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The Design and Manufacture of an Elevating/Articulating Manual Wheelchair Legrest

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THE DESIGN AND MANUFACTURE OF AN ELEVATING/ARTICULATING MANUAL WHEELCHAIR LEGREST

A Thesis

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in

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by

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Abstract

For people bound to a wheelchair, the ability to elevate one’s legs is as much a comfort concern as it is a health concern. The elevation of one’s legs changes the user’s sitting position, thereby increasing their comfort level while at the same time increasing circulation, ultimately aiding in the prevention of pressure sores and lower extremity swelling. Unfortunately, the motion of current legrests on manual wheelchairs does not accurately match the motion of the user’s lower leg. This mismatch of motion causes the legrest to push up on the leg, shortening it while applying torque to the hip. An elevating/articulating wheelchair legrest that consisted of a planar sixbar linkage coupled with a worm gear set was designed and manufactured to address the shortcomings of standard elevating legrests. The legrest prototype elevates and articulates simultaneously from a single user interface, allowing the user’s leg to be straight in the elevated position. The prototype design was evaluated by a potential user, his nurse, and the Director of Rehabilitation Engineering at the Massachusetts Hospital School. The collective response from this evaluation was very favorable. The design was successful in meeting the design specifications. Further modifications are needed before the design is ready for the commercial market.

Acknowledgements

I would like to thank the following people for their help and support throughout this thesis project:

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- Margaret Tomaswick: Manufacturing Engineering Graduate Student - Worcester Polytechnic Institute, Worcester, MA
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- Andy: Student - Massachusetts Hospital School, Canton, MA

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1 INTRODUCTION

Strolling down a beach, hiking up a mountainside trail, simply walking down a flight of stairs – these are things that many of us take for granted. There are, however, a large number of people who do not take these activities for granted. This group is the 1.7 million Americans and 42.5 million people worldwide confined to a wheelchair. Though they may come from all different parts of the world, the reasons they are restricted to a permanent sitting position remain similar. Some well-known reasons include old age, paraplegia, and quadriplegia. Other reasons include those which may be unfamiliar to most people. These reasons include mobility disabilities such as spina bifida, cerebral palsy, and muscular dystrophy. Regardless of their disabilities, these people still need to get up each morning and live life. For most, this can only be possible with the help of a wheelchair.

A wheelchair is a device that can enable and empower a person with a disability to live an independent life. It is important that the design and setup of a wheelchair properly suit the user's needs; the most important being comfort and health. As anyone who has ever sat in a seat for an extended period of time can attest to, in order to provide comfort, continual repositioning of oneself is required. In addition to comfort, the health and well being of the wheelchair user is also of concern. Sitting in one position for a long period of time is not only uncomfortable, but detrimental to one's health as well. Pressure sores, poor circulation, and blood clots are common occurrences in wheelchair users. These concerns can be partially addressed, however, with the simple act of raising the user's leg. Raising the user's lower leg solves the comfort concern by repositioning the user and solves the health concerns by elevating the lower leg closer to the level of the user's heart. This extension of the legs promotes better circulation, deterring the blood from pooling in the lower extremities, as well as spreading out the pressure load on the user's buttocks and upper legs.

Legrests are the assistive devices on wheelchairs that are used to elevate the user's legs. Typically, they are a simple footpad, connected through a rod to a pivot point. The problem faced with this setup is that the pivot point of the legrest is not in line with the center of rotation of the user's knee. If it were, the legrest mechanism would be in the way of the user's transfers into and out of the chair. In general, the pivot point is located a few inches below the user's knee pivot point. Because of this, the arc of motion of the legrest does not match the arc of motion of the user's lower leg (Figure 1).

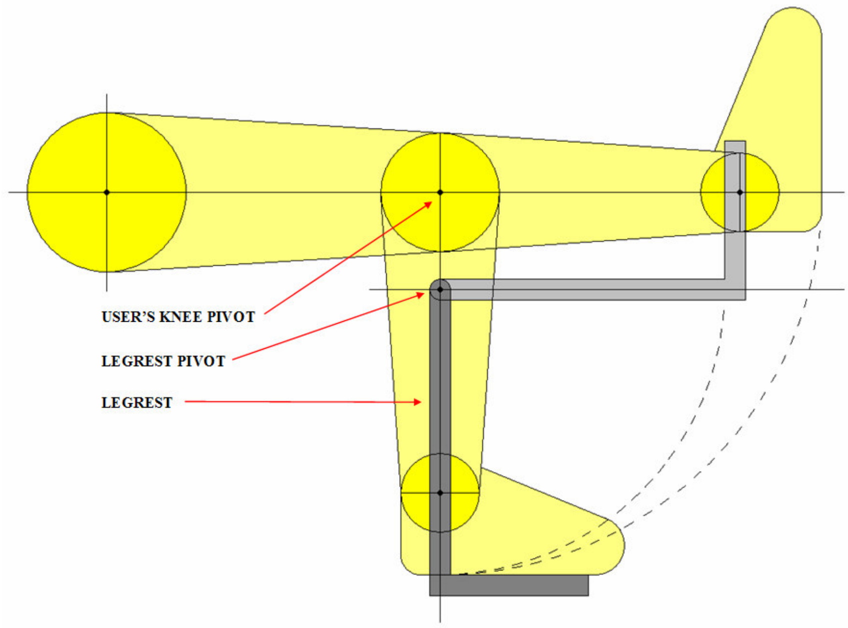


Figure 1: Range of motion difference between legrest and user's leg showing the user's leg, when straight, does not fit on a standard elevating legrest when elevated

In order for the legrest to be fully elevated, the user's leg must bend at the knee (Figure 2 and Figure 3). This action causes the user's leg to be pushed up into him/her, causing flexion at the hip joint. This flexion at the hip joint can be uncomfortable as well as compromise healthy circulation. In addition to causing flexion at the hip joint, the shortening of the leg also causes the leg to turn inward (Figure 4).

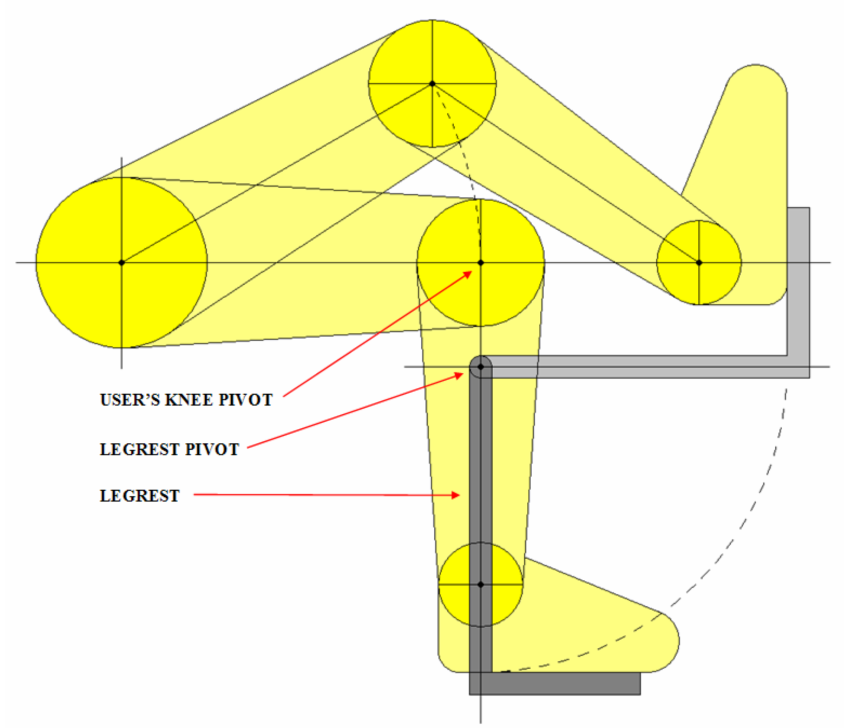


Figure 2: Range of motion difference between legrest and user's leg showing how user's leg must bend to fit on elevated legrest

Figure 3: Side view of user's leg in elevated position showing an obvious bend at the knee

Figure 4: Front view of user's leg in elevated position showing inward rotation of user’s right leg

The goal of this project is to design and manufacture an elevating legrest that accurately follows the natural motion of the user’s leg. It will work to correct the problem of the user’s leg being bent in the elevated position, thus providing comfortable and proper positioning of the user’s leg in the elevated position.

2 BACKGROUND

2.1 History of Project

Three years ago, Gary Rabideau, Director of Rehabilitation Engineering at the Massachusetts Hospital School (MHS), identified a problem in their students' use of their elevating wheelchair legrests. The legrests arc did not match the arc of the students' lower leg. He set out to solve this problem with the aid of Worcester Polytechnic Institute (WPI). For the next two years, two groups of WPI students conducted their Major Qualifying Projects (MQP) in conjunction with Mr. Rabideau and MHS to develop a working prototype of an elevating legrest that would mirror the arc of the user's leg. These two prototypes will serve as preliminary prototypes for this thesis project. Before proceeding with design details, it is important to understand the basics of manual wheelchairs, elevating wheelchair legrests, and which groups of people would require a combination of the two.

2.2 Manual Wheelchairs

Manual wheelchairs have come a long way in the past few decades. Thirty years ago, if a person wanted a manual wheelchair, that person would have to go to a doctor's office and request one. If the individual was indeed found to be in need of a wheelchair, they would most likely receive the standard wheelchair of the time. This wheelchair consisted of a heavy metal frame with dark, solid-colored upholstery.

Times certainly have changed. Today, a person in need of a wheelchair has literally hundreds of options to choose from. Today's wheelchairs come in a wide range of styles and colors, and can be made from new lightweight, composite materials that help reduce the weight. With all these options available, the challenge now is choosing a wheelchair with the right set of options to fit an individual's needs.

The first decision a person in need of a wheelchair needs to make is what kind of wheelchair they require: a manual wheelchair or a powered wheelchair. There are certainly advantages and disadvantages to both – one is not necessarily better than the other. It is important to assess the user's physical ability and lifestyle in order to make this decision. If a person is physically capable of using his/her arms to propel him/herself forward, then a manual wheelchair is most likely the appropriate choice. The relatively simple act of pushing oneself forward is important for a patient's self-reliability and self-confidence. It is also a good source of exercise and athletic activity.

Once the choice of manual wheelchair has been made, the next decision is what kind of manual wheelchair is needed. Manual wheelchairs come in a wide variety of styles; everything from lightweight/sports chairs to standard/everyday chairs. With each different style comes a different purpose and design. Lightweight/sports chairs are usually made of lightweight materials that provide the user with maximum movement for minimum effort. While these chairs are good for people wanting to get around quickly, they're not for everyone. People with obesity may not be able to use this type of chair because the lightweight frame results in a decreased user weight capacity when compared to a standard wheelchair. Standard chairs are 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. This type of chair can be denoted as the descendant of the old standard chair. Still, many people prefer a standard chair over the newer lightweight chair, for its increased strength and durability, allowing for more accessories as well as improving the overall lifespan of the chair.

Standard wheelchairs are fairly straightforward in design (Figure 5). Starting with the base component, the frame can typically be one of two designs: rigid frame or cross-brace frame. A rigid frame is a one-piece frame in which the wheels can detach for storage and travel. A cross-brace frame is a hinged frame with a fabric seat in which the entire frame and chair can fold flat for easy transportation. Outside of special needs schools and people confined to a residential facility, most wheelchair users desire a folding chair for travel, making the cross-brace frame the more popular of the two frames. Attached to the frame are four wheels: two small wheels in the front, known as casters, and two large wheels in the back. The casters typically range from six to eight inches in diameter while the standard size for the rear wheels is 24 inches. As the direct user interface, the seating system plays an important role in the design of a wheelchair. The seating system is often sold separately from the rest of the chair. Other parts of a standard wheelchair include, but are limited to, footrests, armrests, legrests, and brakes.

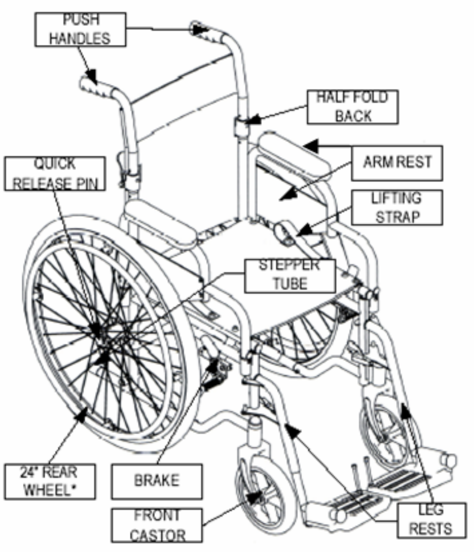


Figure 5: Standard manual wheelchair diagram showing all primary components

The typical price range for a light-midweight manual wheelchair is $1500-2500 while basic models as seen in hospitals can cost as little as $300 and deluxe, customized lightweight chairs can price as high as $3600.

2.3 Wheelchair Legrests

The purpose of wheelchair legrests is to provide support for the lower legs in order to maintain a proper posture of the user. With the amount of time most wheelchair users spend in the sitting position, it is important to ensure they are properly positioned in order to optimize their functional abilities. In addition to providing proper support, legrests can be used to elevate the lower leg of the user to prevent the onset of certain maladies.

Legrests can be divided into two main types: non-elevating and elevating. Non-elevating legrests are nothing more than a vertically-aligned, rigid tube connected to the chair frame with a footrest at the bottom. The footrest at the bottom can be a fixed front end where it does not move or it can be a swing-away/removable style. Swing-away/removable styles help with easier transfers into and out of the chair and thus are more popular.

Elevating legrests differ from non-elevating legrests by having a pivot-point where the non-elevating legrest is securely welded to the chair frame. This pivot-point allows for the user to elevate his/her lower leg to different elevation angles within the user's range of motion. Because of this type of motion, elevating legrests almost always have some type of calf/ankle pad to support the lower leg while it's in an elevated position.

Besides the standard purpose of providing proper sitting support, elevating legrests work to prevent the inception of certain ailments caused by sitting in a single position for an extended period of time. Topping the list of these possible ailments are pressure sores. A pressure sore (bed sore) is an injury to the skin and underlying tissue usually caused by unrelieved pressure (WebMD, 2004). Pressure sores often develop on skin that covers bony areas such as the hips, heels, and tailbone (Figure 6). If untreated, pressure sores can progress through four stages of intensity (Figure 7).

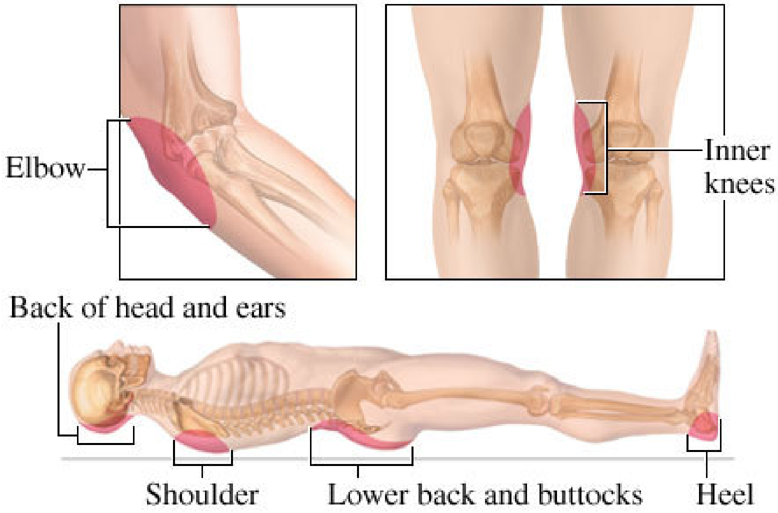


Figure 6: Common areas where pressure sores develop (WebMD, 2004)

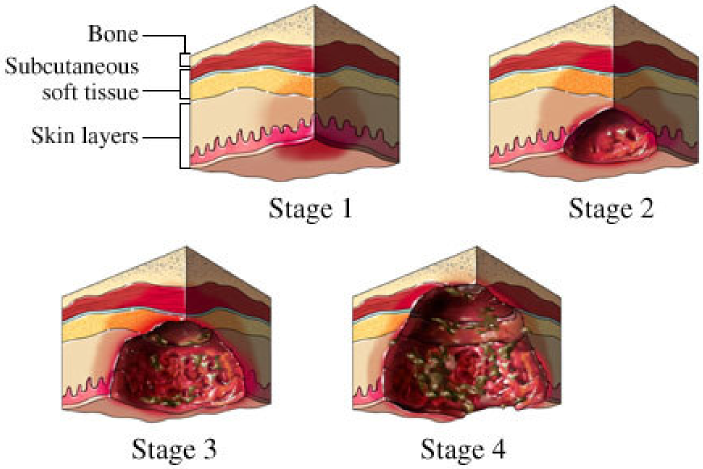


Figure 7: Untreated pressure sore stages showing skin and tissue deterioration (WebMD, 2004)

These sores typically range from a mild redness of the skin to severe tissue damage. Sores develop when there is a continual pressure applied to an area of the body. The pressure reduces blood flow to the skin and tissue, decreasing the amount of oxygen and nutrients to the cells of that area, causing them to die. This breakdown of the skin and tissue eventually leads to an open sore. Without the protection of the skin, these open sores are highly prone to infection.

People confined to a wheelchair are at the greatest risk of developing pressure sores because of the fact that they are sitting down all day. Additionally, these people are highly susceptible to additional pressure sores because of their inability to stay off of the affected area for any length of time. To promote healing, a person who develops a pressure sore on their buttocks may have to lie prone on their stomach for weeks or months depending on the severity of the sore. With the slow and difficult healing process, it is clear why preventative measures must be taken in order to thwart pressure sores before they develop. The simple measure most often taken is the simple elevating of a person’s lower legs. By elevating a person’s lower legs, it repositions them in the seat of the chair such that the pressure on their buttocks and thighs is more evenly distributed. This allows for a lower pressure as well as an increased circulatory flow.

Another malady caused by a person remaining in the sitting position for any length of time is swelling of the lower extremities. This is particularly common in wheelchair patients with neuromuscular disorders. Like all muscles, those of the lower legs and feet become weakened with time if not used on a regular basis. This is the case for most wheelchair users. Their weakened state results in less efficient pumping of blood back to the heart, and the blood ends up pooling in the veins of the lower legs and feet. As the blood pools in the veins, fluid begins to seep out of the veins into the surrounding tissue, causing it to swell (Huberty, 2002).

The simplest and most effective way to relieve swelling in the legs is to elevate the lower legs. Although it is ideal to elevate the swollen legs to a height of six to twelve inches above the heart, any elevation is helpful. Wheelchair legrests typically elevate a patient's legs to a maximum of 0º flexion at the knee joint. Elevating a person's legs several times a day works to enhance the circulation, diminishing the possibility of the blood pooling in the legs and feet.

The problem faced with traditional elevating legrests is that the pivot point of the legrest does not line up with the center of rotation of the user's knee – it is usually located several inches below the knee to allow for transfers into and out of the chair. With the pivot points being misaligned, the arc of the legrest does not mirror the arc of the user's lower leg (Figure 1). Because of this misalignment, the legrest pushes back on the lower leg as it is elevated, causing flexion at the knee and torsion at the hip (Figure 3 & Figure 4). While this awkward elevation will still somewhat help to spread out the pressure load and increase circulation, it leaves the user in an uncomfortable or even painful position.

2.4 Who Needs a Manual Wheelchair with Elevating Legrests?

The fact that a person uses a manual wheelchair does not necessarily mean they require elevating legrests. The function of elevating legrests is repositioning of the user to spread out the pressure load and increase circulation. Three categories of patients require this function: those that can't sense a discomfort in their lower extremities, those that lack the physical strength to reposition themselves, and those that lack the coordination to reposition themselves. Examples of persons in each of these categories are given in the following sections. Persons who can’t sense discomfort in their lower extremities include people with Spinal Cord Injuries (SCI) and Spina Bifida (SB).

2.4.1 Spinal Cord Injuries

The spinal cord is the main neuropathway of the body, extending from the base of the skull down the length of the spine. It carries motor information from the brain to the body’s parts and carries sensory information from the body’s parts to the brain. SCI occur when there is an inordinate level of pressure put on the spine. “The severity of the injury is related to the duration of pressure, the amount of pressure, and the amount of damage to the spinal cord cells” (Duhaime & Gray, 2004). It is estimated the annual occurrence of SCI within the U.S. in approximately 11,000 cases a year. The cause of a SCI can come from almost anything - the most common being falls, automobile accidents, and gunshot wounds.

“Severe SCI often causes paralysis (loss of control over voluntary movement and muscles of the body) and loss of sensation and reflex function below the point of injury, including autonomic activity such as breathing and other activities such as bowel and bladder control” (NINDS SCI, 2001). For the purposes of adjusting oneself in a chair, any injury to the spinal cord in the mid to upper thoracic region (Figure 8) could result in the paralysis of the user’s lower body from the waist down, preventing the feeling of excessive pressure points.

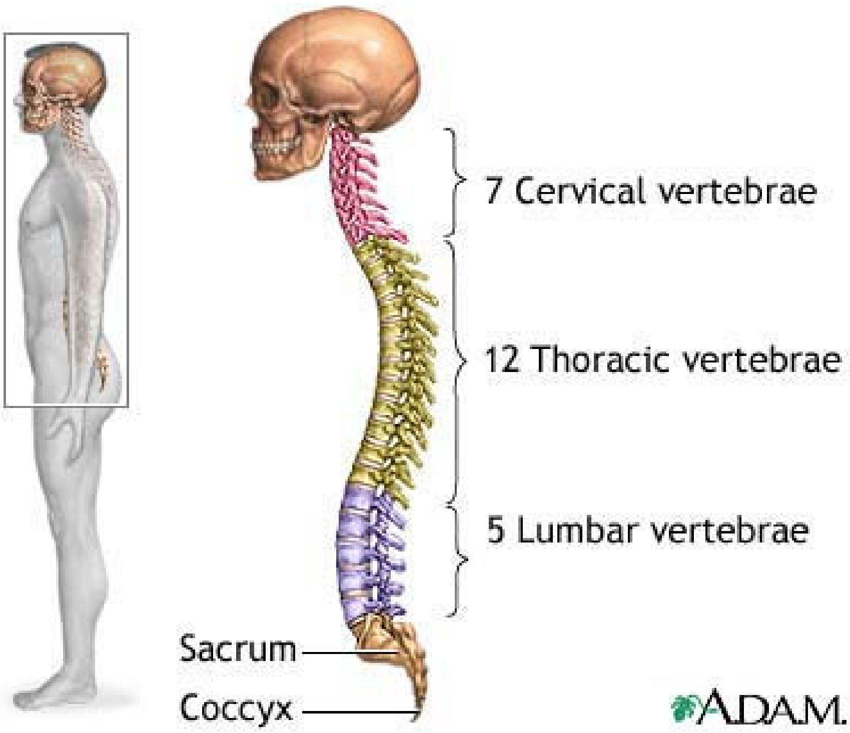


Figure 8: Spinal cord diagram showing different regions

2.4.2 Spina Bifida

Spina bifida is a birth defect in which the vertebrae of the spine do not properly form around the spinal cord (WebMD, 2004). SB is the most common birth defect in a group known as neural tube defects, affecting about 1 out of every 2000 children born in the U.S.

There are two main types of SB: SB occulta and SB manifesta. SB occulta is the mildest and most common form, often not causing problems and not needing treatment. SB manifesta is more rare and severe and can be broken down into two classes: meningocele and myelomeningocele. "In meningocele, fluid leaks out of the spinal canal, causing a swollen area over the baby's spine" (WebMD, 2004). In myelomeningocele, the most severe form, the spinal cord and its protective coverings push out of the spinal canal against the underside of the skin (Figure 9).

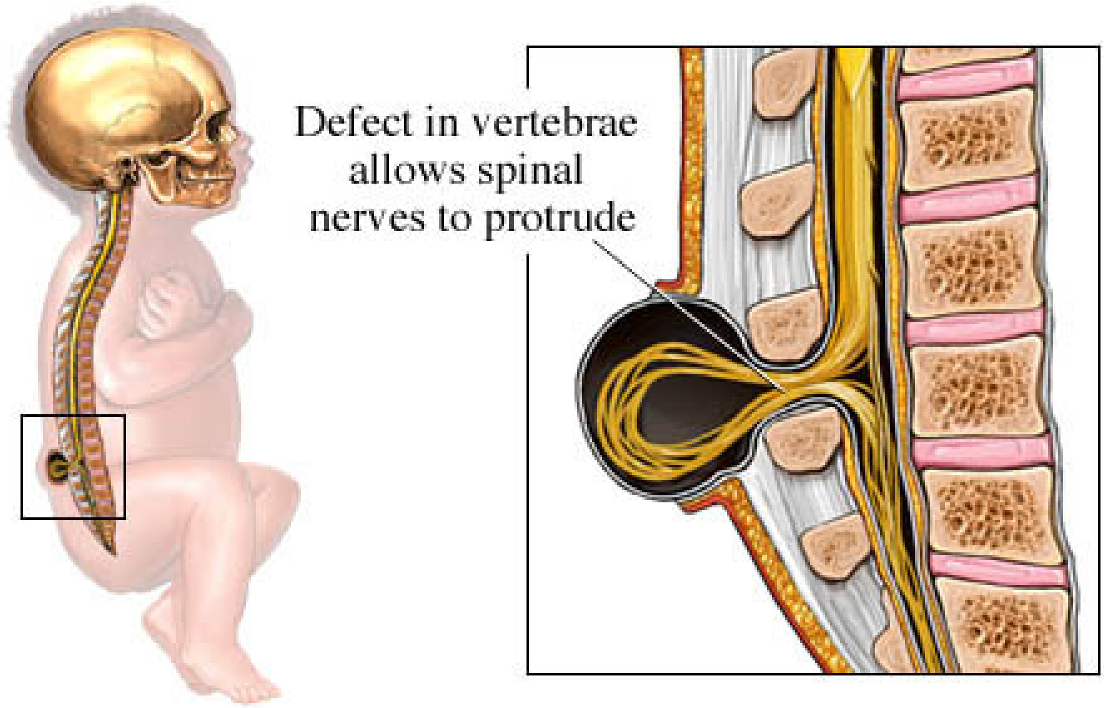


Figure 9: SB diagram showing spinal cord protruding out of spinal canal (WebMD, 2004)

With the spinal cord protruding from the protective spinal canal, the nerves are often permanently damaged, leading to the paralysis of the baby's legs. In the worst cases, the skin is open and the nerves are left exposed to the outside of the body.

2.4.3 Muscular Dystrophy

The second group requiring elevating legrests is people that lack the physical strength to reposition themselves. This group includes the elderly as well as patients with Muscular Dystrophy (MD). As a general rule, the older a person becomes, the more their muscular strength decreases. This decrease in muscular strength can eventually lead to a patient's inability to reposition oneself in a chair.

Muscular dystrophy refers to a group of genetic, degenerative diseases that primarily affect voluntary muscles. The group is known to be genetic based, caused by an irregularity of specific proteins need for proper muscle function. All together, there are nine forms of MD – each one having its own characteristics. Some may have a quick progression while others can span several decades of muscle deterioration. Often, the disease will start in the hip or pelvic region and spread from there - first affecting only the lower half of the body but eventually reaching the heart and breathing muscles. Survival depends on the form and onset time of the disease. Like the elderly, the decrease in muscular strength caused by the deterioration of the muscles will eventually lead to a patient's inability to reposition oneself while in a sitting position.

2.4.4 Cerebral Palsy

The third and final group of people likely to need elevating legrests are those that lack the coordination to reposition themselves. This group includes patients with Cerebral Palsy (CP). CP is a developmental disability grouped in the same set of disorders as Down syndrome, epilepsy, and autism. Appearing very early in childhood, often right after birth, CP is described as a group of chronic conditions affecting body movements and muscle coordination. "It is caused by damage to one or more specific areas of the brain, usually occurring during fetal development, or during infancy" (ACP, 2004). Approximately two out of every 1000 children born in the U.S. are diagnosed with some form of CP. It is important to note that CP is not a disease, but rather a disability occurring at, or around, birth. Thus, CP is not degenerative. It is a stable condition that will remain for the life of the patient.

Symptoms of CP are characterized by inability to fully control motor function, particularly muscle control and coordination (ACP, 2004). Depending on which area(s) of the brain have been damaged, symptoms may include difficulty with fine motor skills, muscle spasms, difficulty maintaining balance, involuntary movements, and seizures. A patient with CP showing these symptoms may lack the coordination to reposition oneself while sitting in a wheelchair.

2.5 Improvements in Elevating Legrests

The problem with elevating legrests has been recognized in the industry for some time. As such, several companies have developed designs that allow the user's leg to be straight when in the elevated position. In order to solve the problem, two main approaches have been used. One method is to have the legrest lengthen as it elevates to compensate for the different pivot points of the user's knee and legrest. Another method is to place the pivot points in line with one another so the arcs of the footrest and the user's foot match.

2.5.1 Articulating Legrests

A patent search was conducted through the U.S. Patent Office's online database to discover the products already available in industry. This search revealed three articulating, elevating legrest design patents.

2.5.1.1 Invacare

The first patent found is for the Invacare articulating legrest (Figure 10). Invacare's articulating legrest, referred to as the "Smart Leg", retails for $320 (Invacare, 2004). Mark J. Quantile developed the legrest (patent no. 5033793 – issued July 23, 1991).

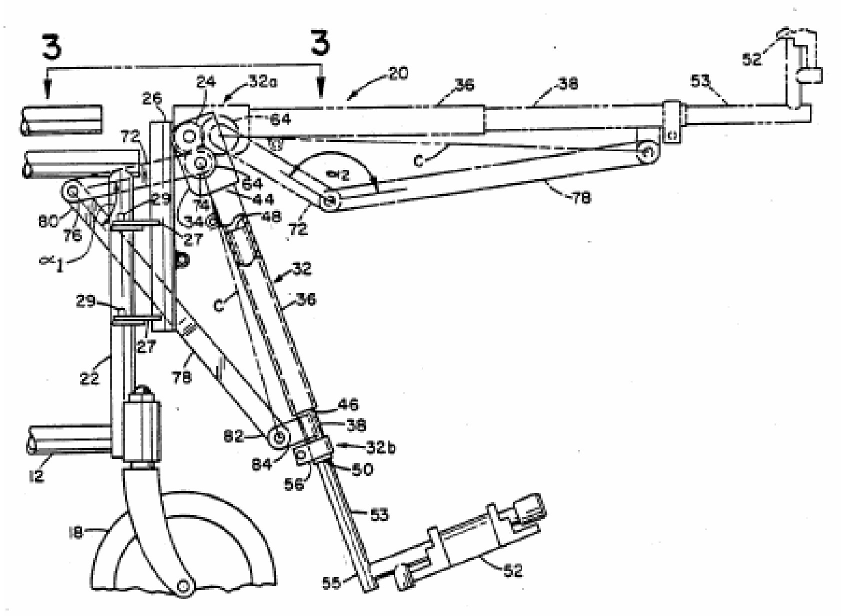


Figure 10: Invacare elevating/articulating legrest (Quintile, 1990)

The legrest is comprised of two gears (24 and 64), two links (72 and 78), and three telescoping cylindrical tubes (32, 36 and 53). The articulation of the legrest is accomplished with a slider-crank mechanism. The first step in the activation process is a manual elevation of the legrest assembly by lifting on tube 32. Gear 24 is located at the pivot point of the legrest at the proximal end of tube 32. As gear 64 rotates counterclockwise around gear 24, link 72, which is rigidly attached to gear 64, rotates counterclockwise about the instant center 65. The counterclockwise motion of link 72 drives link 78 in a clockwise motion about the instant center 76. Link 78 is pinned at the instant center 84, which is connected to tube 38. While link 72 is driving link 78, tube 38 slides away from tube 36, creating the articulating motion.

The footrest (52) is clamped to rod 55 which is welded perpendicular to tube 53. Tube 53 inserts into tube 38 and is clamped in place with a U-clamp. This adjustability of tube 53 into tube 38 allows for various users with different leg lengths.

2.5.1.2 Quickie

The second patent found is for the Quickie articulating legrest (Figure 11). Quickie's articulating legrest retails for $275 (Quickie, 2000). Terrence F. Lovins developed the legrest (patent no. 5328247 – issued July 12, 1994).

The Quickie legrest works similarly to the Invacare legrest, employing a pivot-crank mechanism instead of a slider-crank mechanism to obtain the desired motion. Pins 44 and 78 are ground pins. Link 68 is connected at ground pin 78 as well as the slotted-pin joint 84. Like the Invacare legrest, the Quickie legrest must be manually elevated. When a force is applied to tube 50 in the 52 direction, link 68 rotates counterclockwise about ground pin 78. Link 68 is connected to tube 50 through the instant center 80. As link 68 rotates, tube 50 slides away from tube 48 in the 54 direction, creating the articulating motion.

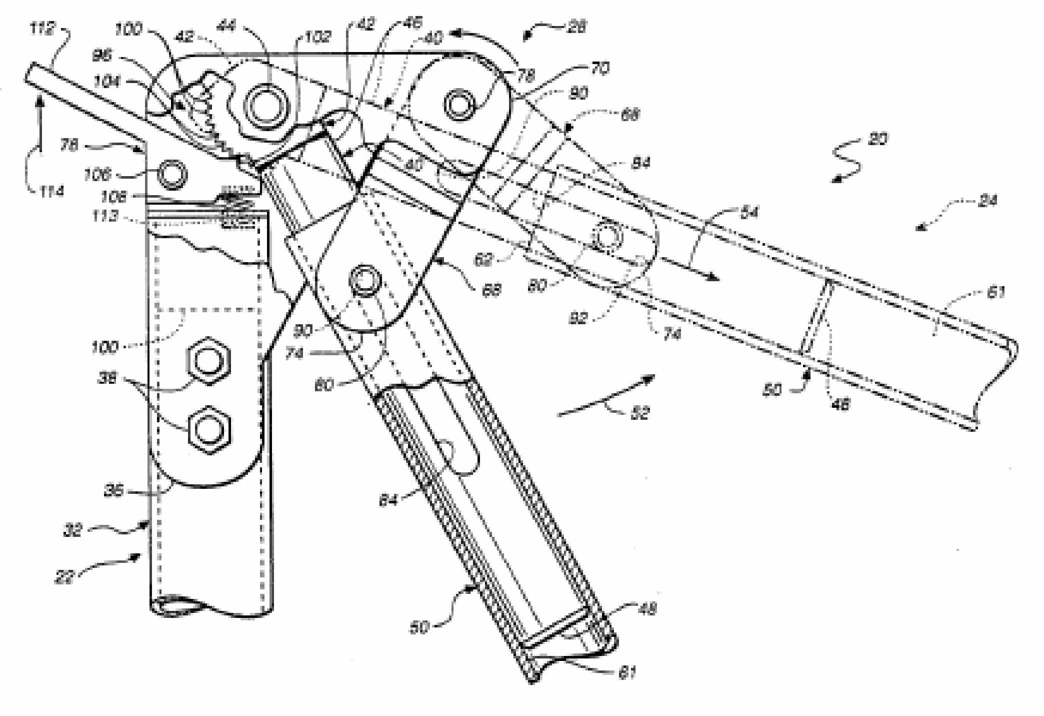


Figure 11: Quickie elevating/articulating legrest (Lovins, 1992)

2.5.2 Pivot-Plus

The third patent found is for the Pivot-Plus legrest (Figure 12). This type of legrest brings with it a different idea of how to accommodate the user's knee pivot and the legrest pivot not aligning. Instead of using an articulating motion like the Invacare and Quickie designs, the Pivot-Plus design adjusts to align the legrest pivot with the user's knee pivot. The legrest pivot can adjust vertically as well as horizontally in respect to the wheelchair. This adjustability allows the user to properly adjust the legrest pivot point in line with his/her own knee pivot, resulting in the legrest's arc of motion being the same as the user's lower leg's arc of motion.

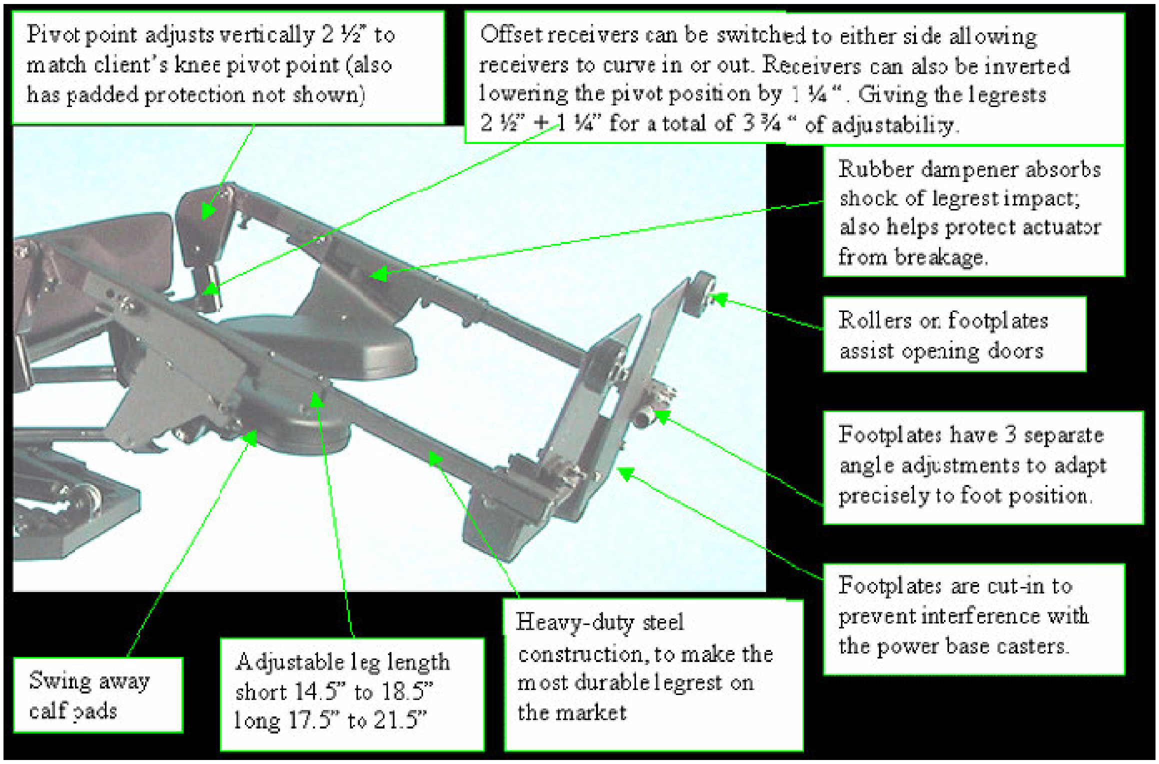


Figure 12: Pivot-Plus legrest (Barlow & Reed, 2003)

While this legrest design is an improvement on the standard legrest design, it does have the drawback of interfering with transfers into and out of the wheelchair. Wheelchair transfers can be performed in a number of ways; one way is to slide off the side of the chair. If the pivot point is adjusted to be in line with the user's knee pivot, it will be at a height above the seat cushion. This will inevitably interfere with transfers into and out of the wheelchair. If the pivot point were lowered, such that it no longer interfered with transfer, it would bring about the same problems as the standard legrest.

2.6 WPI MQP Prototypes

In addition to the improved elevating legrests to come from industry, two WPI MQP projects have developed designs to address the issue of the legrest not following the natural arc of the user's leg as it elevates. Both these designs are classified as articulating legrests, whereby the legrests lengthen as they elevate to compensate for the center of rotation of the user's knee and the pivot point of the legrest not being aligned.

2.6.1 2003 WPI MQP Legrest Design

The first MQP legrest design to come out of WPI was in 2003, created by two undergraduate students: Johanna Barlow and Daniel Reed. The basic function of the design is a gear-incorporated, slider-crank mechanism that works very much like that of the Invacare articulating legrest. To operate the legrest, an external force must first be applied with one hand to ball 33 in direction 48 to manually elevate the legrest (Figure 13). At the same time, the user's other hand must be positioned on the detent mechanism 51 to unlock the legrest. As the legrest is manually elevated, gear 15 rotates clockwise about gear 14. Link 44 is rigidly attached to gear 15 and rotates at the same time. Link 44 is pinned to link 43. As link 44 rotates, link 43 is driven counterclockwise, pushing the lower legrest 37 away from gear 14, creating the articulating motion. When an adequate elevation has been achieved, the user's second hand releases the detent mechanism 51, allowing the pin of the detent mechanism to slide into a hole in rod 49, locking the legrest into place.

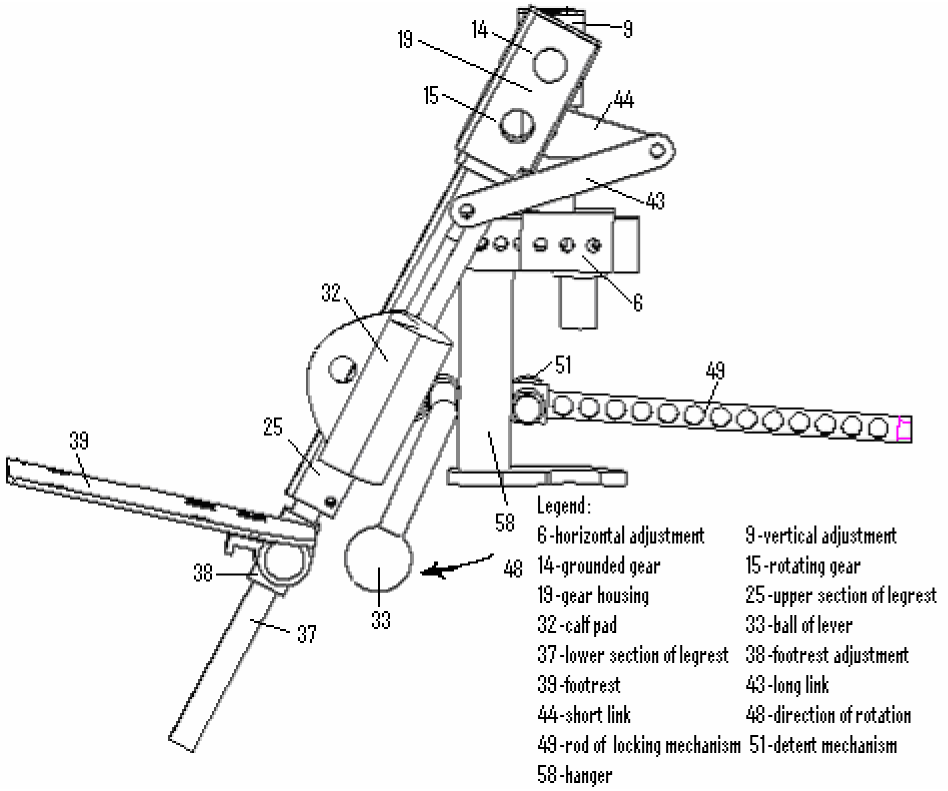


Figure 13: 2003 WPI MQP articulating legrest design (Barlow & Reed, 2003)

2.6.2 2004 WPI MQP Legrest Design

The second MQP legrest design to come out of WPI was in 2004, created by two undergraduate students: Rebecca Duhaime and Amy Gray. This design was a linkage-based mechanism, combining a fourbar linkage with a slider-crank mechanism to create a sixbar linkage system. By having a sixbar linkage system, this design incorporated both elevation and articulation of the legrest under one user operation. To operate the legrest, an external force is applied to the middle link to rotate it about the ground pivot in a counterclockwise direction (Figure 14). The middle link is pinned to the bottom link. The rotation of the middle link pushes against the bottom link, which rotates clockwise and translates forward by means of being pinned to the back link. The back link is pinned to ground. The bottom link extends beyond the middle link and is pinned to the slider mechanism of the legrest. The slider extends outward along the length of the legrest, giving the legrest articulation as well as elevation.

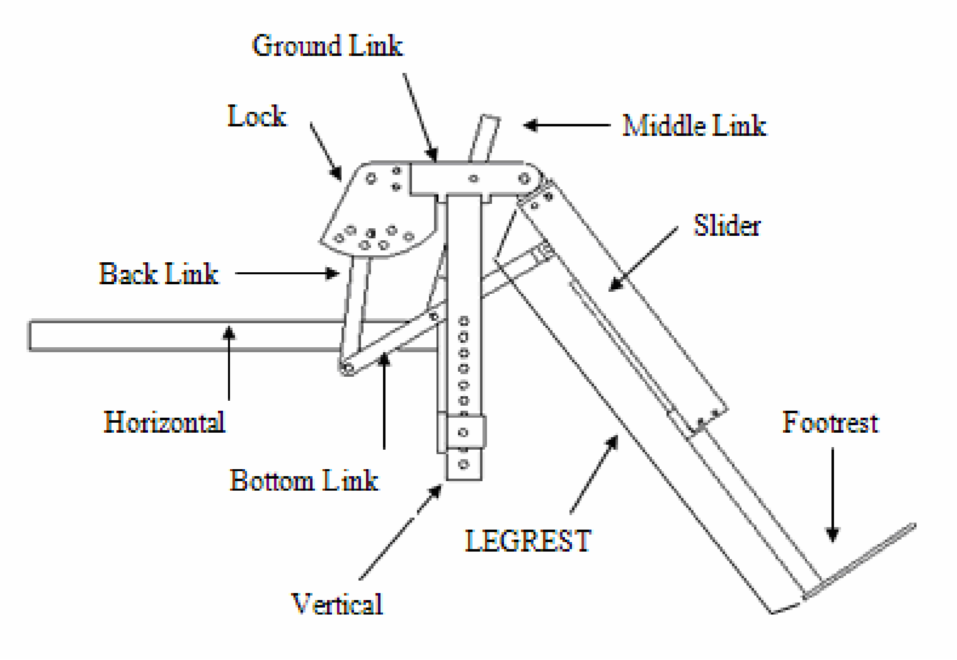


Figure 14: 2004 WPI MQP elevating/articulating legrest design (Duhaime & Gray, 2004)

3 GOAL STATEMENT

The goal of this thesis is to design and manufacture a user-operated, elevating legrest that accurately follows the natural motion of the user's leg as it elevates. The design should minimize the force on the user's upper leg and hip, allowing the user's leg to be straight in the elevated position. In addition, the design should be adjustable for different users and wheelchairs. Finally, the design should follow a strict list of design specifications to include safety, ease of use, and market quality.

4 DESIGN SPECIFICATIONS

A review was conducted of the past MQP designs and the corresponding critiques by Gary Rabideau from MHS. From this review, the basic functions of an elevating legrest design were determined and the following list of design specifications was created:

4.1 Function

- Design must allow user's leg to swing from the down position (80° flexion) to the elevated position (0° flexion).
- Design should be secure at no fewer than 8 positions between the down and elevated positions. The angles at which the legrest is secure should be at even intervals (Barlow & Reed, 2003).
- Once elevated to a certain position, legrest must remain at that position until user or caregiver repositions legrest.

4.2 Adjustability

- Design must be adjustable in increments of 0.5 inches or less to accommodate different leg lengths of users.
- Design must accommodate users with lower leg lengths ranging from 15 to 19 inches.

4.3 Performance/Operation

- Design must be easy for user or caregiver to operate. Design must be able to be operated with less than 15 lbs of applied force.
- Design should incorporate both elevation and articulation in a single user operation.

- Design should operate smoothly. It should not bind or stick at any point in its range of motion.

4.4 Size/Weight

- Design must not interfere with transfers to and from the chair. No parts should extend above the top of the seat cushion.
- Design must not interfere with the propulsion of the wheelchair.
- Design should not extend past the width of the wheelchair frame by more than 2 inches on either side (Barlow & Reed, 2003).
- Weight of design should not exceed 5 lbs.

4.5 Strength/Durability

- Design must be able to support 150 lbs on one footrest while in the down position (RESNA, 1991).
- Design must be able to endure a 1.0 m/s collision with a vertical stationary barrier at an impact angle of 45° (RESNA, 1991).
- While in the elevated position, design must be able to withstand a downward force equal to three times the weight of the lower leg and foot (20 x 3 = 60 lbs) (Woodson et al., 1992).

4.6 Safety

- Design must be safe. No pinch points or sharp edges of any kind are allowed. Any such features must have protective coverings.

4.7 Aesthetics

- Design should be aesthetically pleasing. Final design should be of market quality.

4.8 Parametric Model Prioritization

Once the list of design specifications is complete, it is then necessary to prioritize the list using a parametric model (Table 1). A parametric model is a comparative analysis tool that helps to determine the relative importance of design specifications to one another. The way it works is by first listing the design specification categories along the top and left edges of the table. Next, each row's category is analyzed against each column's category to determine relative importance. In each row-column match-up, a score is recorded to display the row's importance relative to the column: 0 for less important, ½ for equally important, and 1 for more important. Starting with the category of function in the first row, when compared to adjustability in the second column, this design specification category was deemed less important than adjustability and was scored a 0. It is important to note that this is a subjective ranking on the part of the user. Once all the match-ups have been scored, the totals for each row are summed. These total scores are then used to determine the rank of the design specification categories.

Table 1: Parametric model prioritizing design specifications

	Function	**Adjustability**	**Performance/ Operation**	**Size/ Weight**	**Strength/ Durability**	**Safety**	**Aesthetics**	**TOTAL**	**RANK**
Function	■	0	½	½	½	0	1	2.5	10%
Adjustability	1	■	½	½	1	½	1	4.5	20%
Performance/ Operation	½	½	■	½	1	0	1	3.5	15%
Size/ Weight	½	½	½	■	1	0	1	3.5	15%
Strength/ Durability	½	0	0	0	■	0	1	1.5	10%
Safety	1	½	1	1	1	■	1	5.5	25%
Aesthetics	0	0	0	0	0	0	■	0	5%

Table 1 shows that the design specification of safety is this project's most important criteria. Persons with disabilities will someday be using the proposed legrest so it is imperative the device works in a safe manner. The next highest ranked specification is adjustability. The legrest to be designed is for a range of users, not just one. Adjustability of the device is important to suit the size needs of all possible users. The next two highest ranked specifications are performance/operation and size/weight. Smooth operation of the device is essential to keep the operating force at a minimum. Any binding or sticking of the mechanism will cause the operating force to increase. This amplification of force may deter users or caregivers from using the legrests. The other criterion is size/weight. As with all wheelchair components, an ideal design is to be as small and as light as possible. Large or heavy components can be difficult for the user or caregiver to operate. Function and strength/durability were ranked next. Functional specifications such as sufficient angles of flexion are important to a user's comfort level. If the angle of flexion in the down position is not as great as what the user is used to, the user may find discomfort in the use of the legrests. Strength and durability of the design are also important. According to the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) standards, various design components must be able to withstand standard loads. Components not able to withstand these loads indicate a lack of structural strength that can ultimately lead to a deficiency in safety for the user. Finally, the last ranked design specification is aesthetics. While this is not very important in a design prototype, it is very important in a market product. With the hope of someday becoming a marketable product, the design produced in this thesis will strongly consider aesthetics.

5 DESIGN APPROACH ANALYSIS

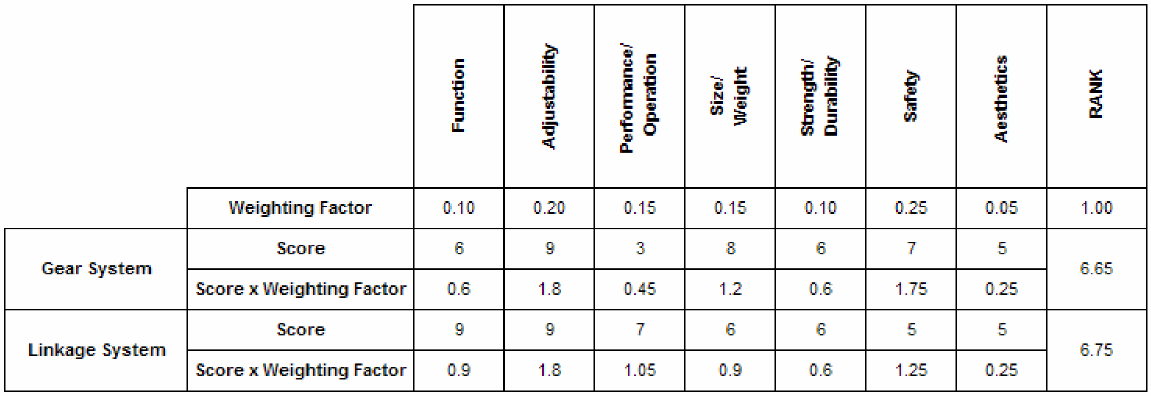
Before the preliminary design synthesis step was undertaken, it was first necessary to investigate the two previous prototypes to come out of WPI as well as commercial designs already available to analyze which aspects of the designs work well and which do not. After studying the designs, it became clear there were two main systems to choose from, each with its own advantages and disadvantages: a gear-based system or a linkage-based system.

A gear-based system typically works like that of the Invacare articulating design (Figure 10) and the 2003 WPI MQP design (Figure 13). The legrest must be manually elevated by the user or caregiver in order for the gear system to turn the crank arm and extend the slider-crank mechanism; there is no user interface mechanism.

The second system option is a linkage-based mechanism like that of the 2004 WPI MQP design (Figure 14). This type of design works by combining a fourbar linkage with a slider-crank to create a 6-bar linkage system, allowing for articulation as well as elevation from a single user interface.

In order to compare the two types of systems, one must employ a decision matrix (Table 2). A decision matrix is another comparative analysis tool that helps the user make a decision after considering a variety of factors in a systematic way. It works by first listing the different designs in rows along the left edge of the table and the design specification categories in columns along the top edge of the table. Each design specification category is assigned a weighting factor, which measures its relative importance. These weighting factors are the ranks calculated with the parametric model (Table 1). The body of the table is then filled with scores (scale of 1 to 10) on how well each design ranks in accordance to the design specification category. It should be noted that the scores assigned in the decision matrix are based on the WPI prototypes as these are the only system models available to this project for testing. Again, like the parametric model, these scores are a subjective ranking on the part of the designer. The scores are then multiplied by the corresponding weighting factor and the totals for each design are summed. The total scores are then used to determine the overall best design.

Table 2: Decision matrix between two primary system designs



		Function	Adjustability	Performance/ Operation	Size/ Weight	Strength/ Durability	Safety	Aesthetics	RANK
	Weighting Factor	0.10	0.20	0.15	0.15	0.10	0.25	0.05	1.00
Gear System	Score	6	9	3	8	6	7	5	6.65
	Score x Weighting Factor	0.6	1.8	0.45	1.2	0.6	1.75	0.25	
Linkage System	Score	9	9	7	6	6	5	5	6.75
	Score x Weighting Factor	0.9	1.8	1.05	0.9	0.6	1.25	0.25	

Beginning with the criterion of function, Table 2 shows the gear-based system received a score of 6 while the linkage-based system received a score of 9. Because both designs were capable of being secure "at no fewer than 8 positions between the down and elevated positions", the scores in this category were based primarily on capable angles of flexion. The gear-based system was only capable of 70° of flexion while the linkage-based design was capable of 80°.

In terms of adjustability, both systems received a score of 9. They both met the adjustability design specifications set forth. The reason they did not receive a perfect score of 10 is there are always improvement possibilities.

For performance/operation, the gear-based system received a score of 3 while the linkage-based system received a score of 7. Starting with the gear-based system, the drawbacks come when one realizes that the legrest takes two hands to operate and must be manually elevated by the user or caregiver in order for the gear-crank arm system to work; there is no easily-operated user interface. This type of design most often requires the assistance of a caregiver to operate the legrests while this project's goal is to create a system that can be easily operated by the user.

Additionally, the assemblage of gears poses another problem. While it may seem trivial, the correct placement and alignment of gears is a delicate art form that is difficult to master. The 2003 WPI MQP group found this out with their own gear box design. Since the gears were not correctly spaced and placed, the gear assemblage had binding and sticking problems throughout its range of motion. Any binding or sticking possibilities in the design are to be avoided in the current work since these problems add to the force necessary to operate the device.

While the linkage-based system does have the advantage of combining both the elevation and articulation of the legrest into one mechanism, it is not without its drawbacks. One such drawback of the 2004 WPI MQP was the sticking points of the linkage – points where the joint pins would hit the housing or another link and cause the linkage's motion to cease. This inconsistent motion is unacceptable in a marketable product.

The next design specification category is size/weight. For this category, the gear-based system received a score of 8 while the linkage-based system received a score of 6. Since both systems are of similar size, the scores in this category were based primarily on weight. The gear-based system is light; however, improvements can be made. The linkage-based system is heavier than its counterpart due to the fact that it requires additional components such as links and pins. Improvements can be made to this system as well – several components can easily be mass-relieved to alleviate the system's total weight.

For the category of strength/durability, both systems received the score of 6. A problem faced by both WPI MQP designs is a lack of durability of system components. RESNA puts forth numerous design specifications to ensure that all wheelchairs and their accessories meet minimal design criteria. Testing performed by the MQP teams on both designs to determine if the designs met these criteria found that a few of the components failed under the applied loads, citing the need for redesign. Upon inspection, it was found that the failed parts were not properly designed for the applied forces and torques. In most cases, a simple redesign of the part geometry will solve the problem. Elsewhere, stronger materials may be needed.

For safety, the gear-based design received a score of 7 while the linkage-based design received a score of 5. While neither design has sharp edges, the scores in this category were based primarily on pinch points. The gear-based design has one pinch point in the slider-crank mechanism, while the linkage-based design, because of the multitude of links, has many pinch points located throughout its mechanism. In both systems, a protective covering of some kind would work to eliminate these pinch points and prevent a user or caregiver from getting their fingers caught in the mechanism as it is in motion. Such a shield will be considered in the current work.

For the final category of aesthetics, both system designs received a score of 5. A good design must not only be designed to be mechanically functional, but also designed to market-ready quality as well. The design must be aesthetically pleasing as well as ergonomically enticing. Both WPI MQP designs were fairly crude, consisting of square-cornered, rectangular shapes with non-fluid edges connecting the parts together. A market-ready product in today's market should consist of fluid-inspired parts that flow into one another with indiscernible seams.

From the analysis of the past MQP prototypes many lessons were learned. Most notably, in order to achieve the goal of a *user-operated* legrest, the linkage-based design method appears to be the prevailing design strategy. Additionally, the linkage-based designs do not incorporate the commonly used slider mechanisms, allowing the designs to be more unique. The following preliminary design synthesis will work to produce several linkage mechanism design possibilities. In addition, elevation methods, user interfaces, and locking methods will also be generated. All design generations will work to eliminate the problems faced by the two previous WPI designs, taking into account the chosen design specifications.

6 PRELIMINARY DESIGN SYNTHESIS & ANALYSIS

With the design specifications defined and the past MQP/industry-patented designs analyzed, the preliminary design options were created. This step of the design process was broken up into four sections:

1) Legrest Linkage
2) Elevation Method
3) User Interface
4) Locking Method

By dividing the preliminary design options into different sections, it allowed each design in each section to be looked at individually as well as combined with any and all other designs to achieve the highest number of complete design choices. The first preliminary designs created were for the "foundation" of the design – the legrest mechanism.

6.1 Legrest Linkage

From the MQP prototype analysis, it was determined that the base mechanism for this thesis design would be linkage-based, primarily for the purpose of achieving the user-operated design goal. Three preliminary linkage mechanisms were considered.

6.1.1 Sixbar linkage with fixed pivot and slider mechanism

The first linkage mechanism considered was that of the 2004 WPI MQP design (Figure 15). This linkage design incorporates both elevation and articulation of the legrest under one user operation. To operate the linkage, an elevation method is combined with link 2 (crank) to rotate the link about the ground pivot O_2 in a counterclockwise direction. Link 2 is pinned to link 3 (coupler) at point A. The rotation of link 2 pushes against link 3, which rotates clockwise and translates forward by means of being pinned to link 4 (rocker) at point B. Link 4 is pinned to ground at point O_4. Link 3 extends beyond link 4 and is pinned to link 6 at point C. In this design, link 6 is the link on which the user's leg would rest. Link 6 slides along the length of link 5, which is pinned to ground at point O_5. To summarize the motion, a counterclockwise rotation of link 2 about point O_2 will cause link 5 to rotate counterclockwise about the fixed ground pivot O_5 as well as cause link 6 to slide outward along link 5, giving the legrest elevation as well articulation.

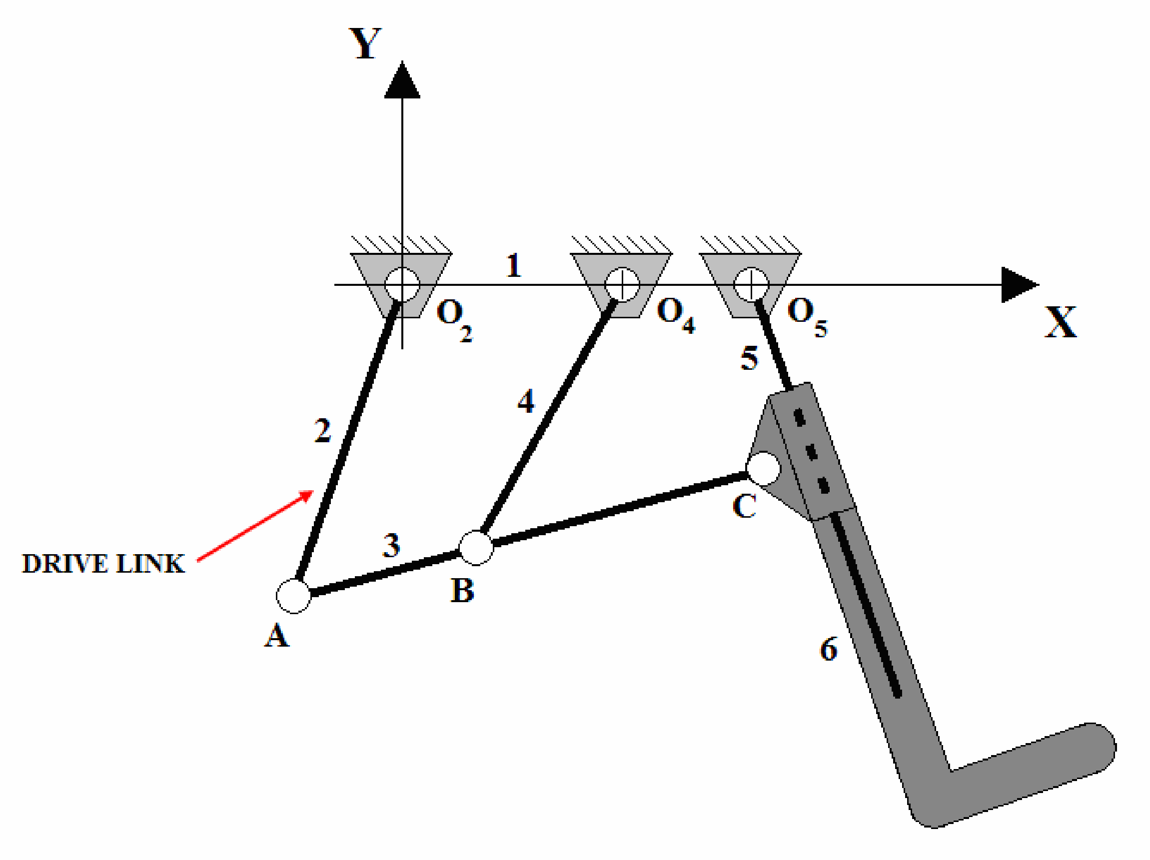


Figure 15: Sixbar linkage with fixed pivot and slider mechanism

6.1.2 Fourbar linkage with floating pivot

The second linkage mechanism considered was a fourbar linkage with a floating pivot about which the legrest link would rotate. This linkage design (Figure 16), like that of the previous sixbar design, incorporates both elevation and articulation of the legrest under one user operation. To operate the linkage, an elevation method is combined with link 2 (crank) to rotate the link about the ground pivot O_2 in a clockwise direction. Link 2 is pinned to link 3 (coupler) at point A (floating pivot). Point A acts as a floating pivot for the legrest link 3 by being the main rotation pivot for the link while translating in the X- and Y-directions. The rotation of link 2 pulls against link 3, which rotates counterclockwise and translates forward by means of being pinned to link 4 (rocker) at point B. Link 4 is pinned to ground at point O_4. By rotating as well as translating, the legrest link, attached to the coupler, achieves the design goal of both elevation and articulation in one user operation.

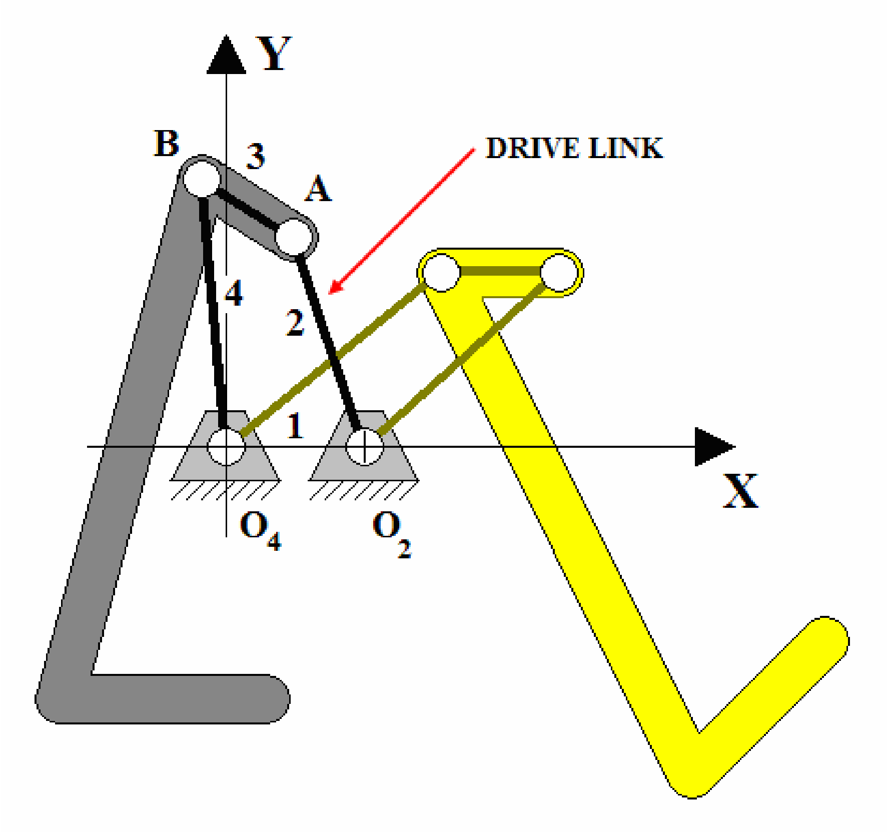


Figure 16: Fourbar linkage with floating pivot

6.1.3 Sixbar linkage with floating pivot

The third and final legrest mechanism considered was a sixbar linkage with a floating pivot about which the legrest link would rotate. Inspired by previous sixbar designs, this floating pivot design (Figure 17) looked to resolve some of the functional problems of the fixed pivot design by removing the slider mechanism entirely.

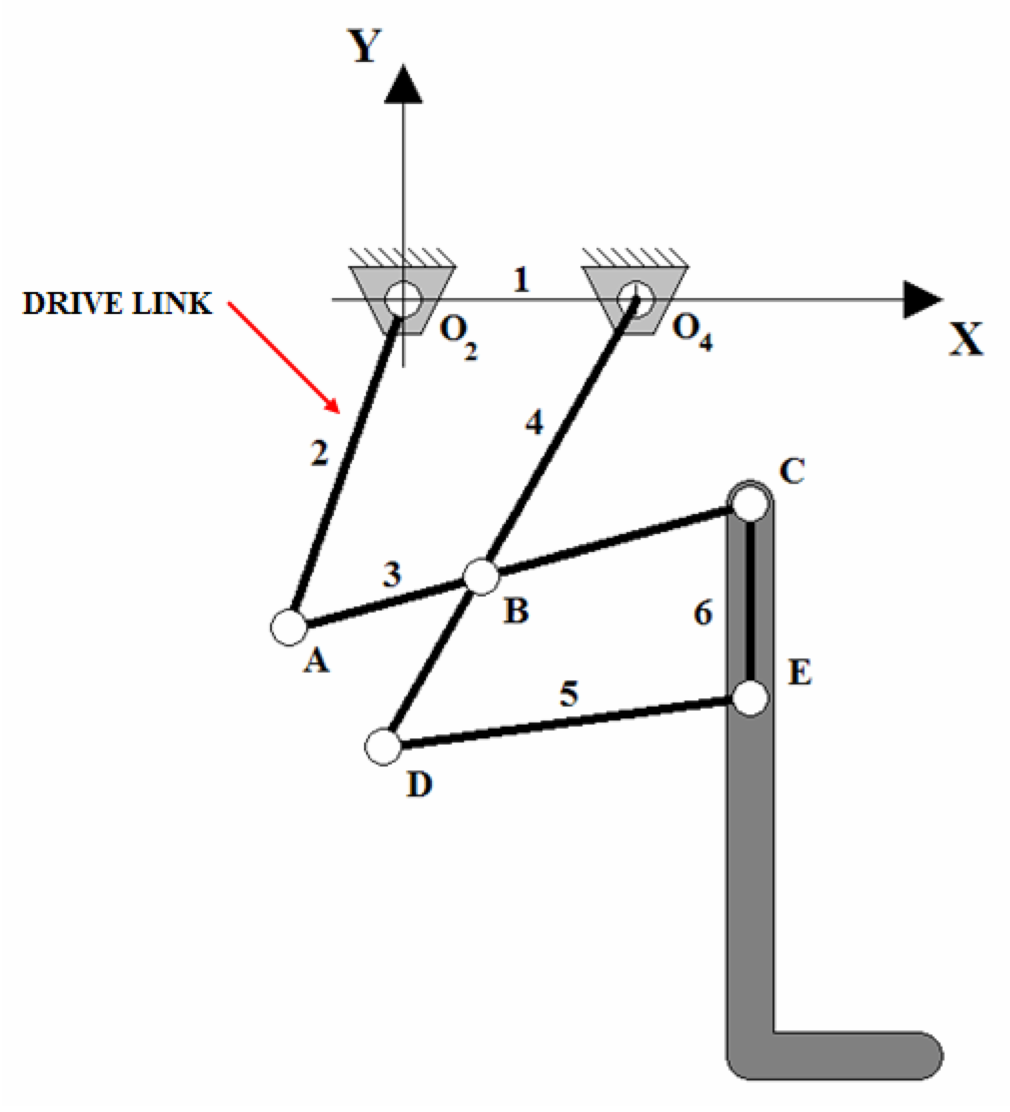


Figure 17: Sixbar linkage with floating pivot

Comparing Figure 17 to Figure 15, one can see several similarities as well as several changes between the two designs. The principal similarity of the design that was inspired by the 2004 WPI MQP design was the fourbar linkage (1-2-3-4) and the accompanying extended coupler link 3. The major diversion from the design was the removal of the slider mechanism. This slider mechanism, needed to achieve articulation as well as elevation, was replaced by an additional interlaced fourbar linkage (3-4-5-6) created by extending links 3 and 4.

To operate the linkage, an elevation method is combined with link 2 (crank) to rotate the link about the ground pivot O_2 in a counterclockwise direction. Link 2 is pinned to link 3 (coupler) at point A. The rotation of link 2 pushes against link 3, which rotates clockwise and translates forward by means of being pinned to link 4 (rocker) at point B. Link 4 is pinned to ground at point O_4. Link 3 extends beyond link 4 and is pinned to link 6 at point C. Link 4 also extends beyond link 3 and is pinned to link 5 at point D. The rotation of link 4 pushes against link 5, which rotates clockwise and is pinned to link 6. In this design, link 6 is the link on which the user's leg would rest. Being pinned in two places at points C and E, link 6 is translated forward while at the same time rotated about its floating pivot point C.

6.2 Elevation Method

With the legrest linkage design choices created, the next set of preliminary designs developed were for the elevation method. Assuming one of the legrest linkages would be chosen, how or by what means should the legrest be elevated (and lowered)? To answer this question, it was important to look at the controlling motion of the legrest linkage designs. In all three cases, it is a rotating motion from a controlling link that moves the linkage from one point to another. Going along with this methodology, five distinct elevation methods were developed.

6.2.1 Lever Handle

The first elevation method considered was the lever handle (Figure 18). This is by far the simplest elevation method possible for this type of design. Used by the 2004

WPI MQP project, the lever handle works by extending the controlling link of the legrest linkage beyond a ground pivot to be within reach of the user. A force applied to the lever handle would apply a proportional force to the controlling link, causing it to rotate.

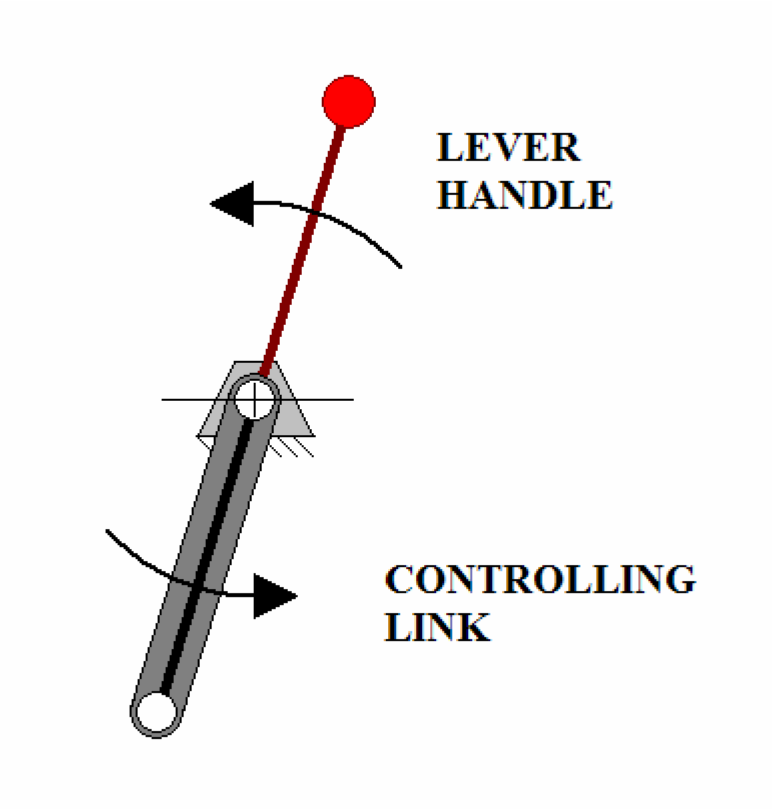


Figure 18: Lever handle elevation method

6.2.2 Gas Springs

The second elevation method considered was the use of a gas spring system (Figure 19). Gas springs work by having a charge of compressed gas, typically nitrogen, push an internal piston within the gas spring outward, causing the overall length of the gas spring to increase. When pinned to ground as well as a chosen point on the controlling link, the gas spring's expansion force would be applied to the controlling link, causing it to rotate about its fixed pivot.

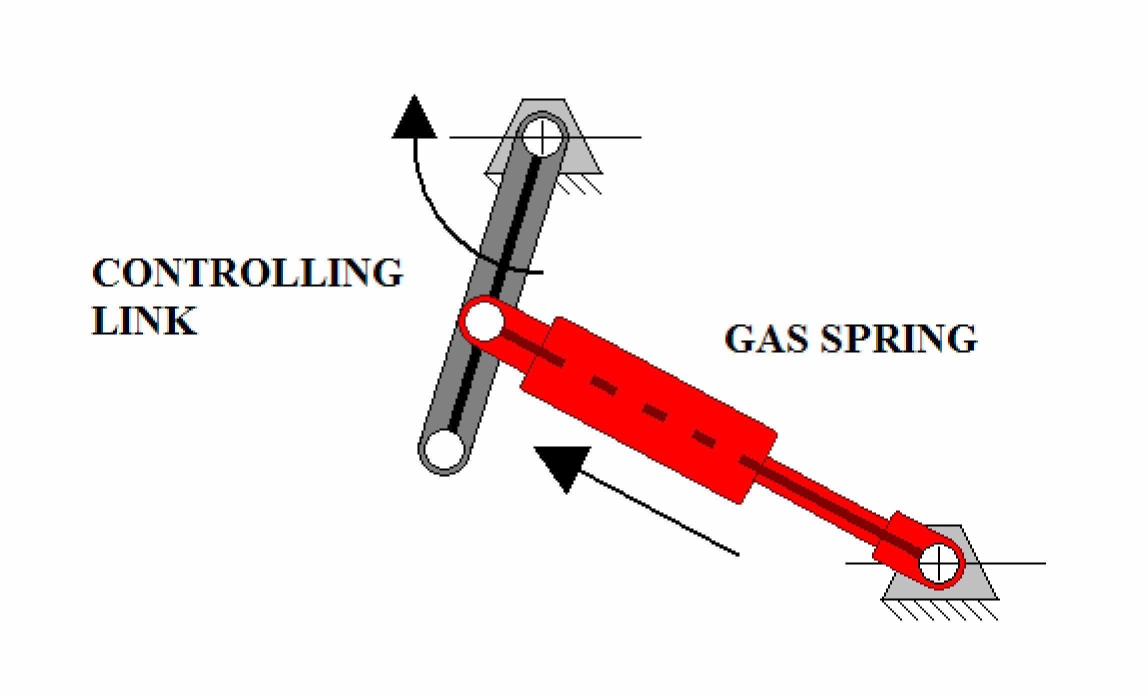


Figure 19: Gas spring elevation method

6.2.3 Worm Gear Set

The third elevation method developed was the use of a worm gear set (Figure 20). A worm gear set consists of the driver gear (worm) and the driven gear (worm gear). A worm is essentially a helical gear with a very high helix angle resulting in the gear having only one tooth wrapped continuously around its circumference a number of times. When meshed with a worm gear, the worm, in essence a screw thread, can transfer a very high gear ratio to the worm gear.

To apply this design to one of the legrest mechanisms, the worm gear would first have to be attached to the controlling link via a shaft and keyway so that the two would rotate together. Next, a worm would be meshed with worm gear by fixing it on a perpendicular shaft to that of the worm gear shaft. When the worm is rotated, it would cause the worm gear to turn and the attached control link to rotate as well.

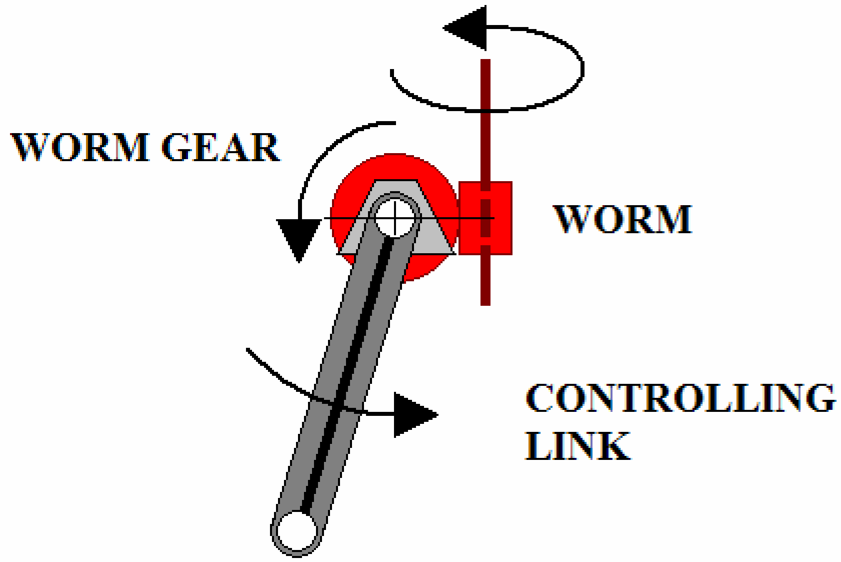


Figure 20: Worm gear set elevation method

6.2.4 Power Screw

The fourth elevation method considered was the use of a power or lead screw (Figure 21). A power screw is a commonly used machine design device used to change angular motion into translation. It is also capable of developing a large amount of mechanical advantage. Familiar applications include vises, presses, and jacks. Opposite to the traditional sense of a screw and threaded hole, a power screw works by holding the threaded hole from rotating while the screw part of the device rotates through it. Holding the position of one end of the screw fixed, the resulting motion would be the threaded hole moving linearly towards or away from the fixed location (depending on screw rotation direction). To apply this device to the legrest mechanism, one would first need a rotating, threaded block pinned to the control link at some point along its length. Next, a power screw would be screwed into the threaded block and have its far end pinned to ground. When the power screw is rotated, the threaded block pinned to the controlling link would travel up (or down) the power screw, causing the controlling link to rotate.

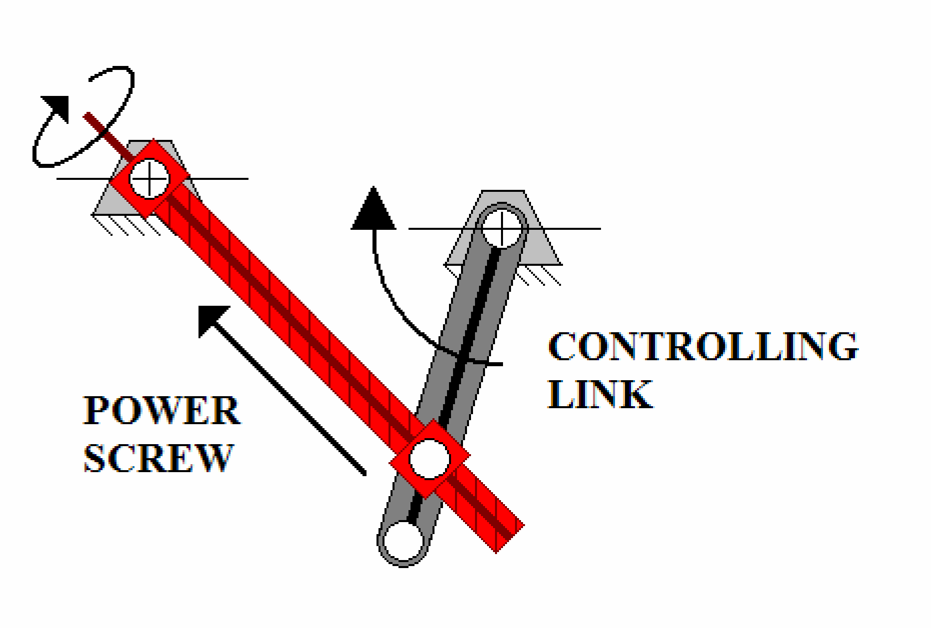


Figure 21: Power screw elevation method

6.2.5 Cam & Follower

The fifth and final elevation method considered was the use of a cam and follower (Figure 22). Cam and follower systems are very common machine design elements used to create a specific motion. The motion created can be simple and regular or complex and irregular. The most common type of cam and follower system used, like that shown in Figure 22, is a radial cam in conjunction with a force-closed, translating roller follower. As the cam rotates about its fixed ground pivot, its profile pushes on the roller follower, causing the follower to compress the spring and move horizontally in its track away from the cam. Having the far end of the follower pinned to the controlling link, any horizontal motion of the follower will cause the controlling link to rotate about its fixed ground pivot.

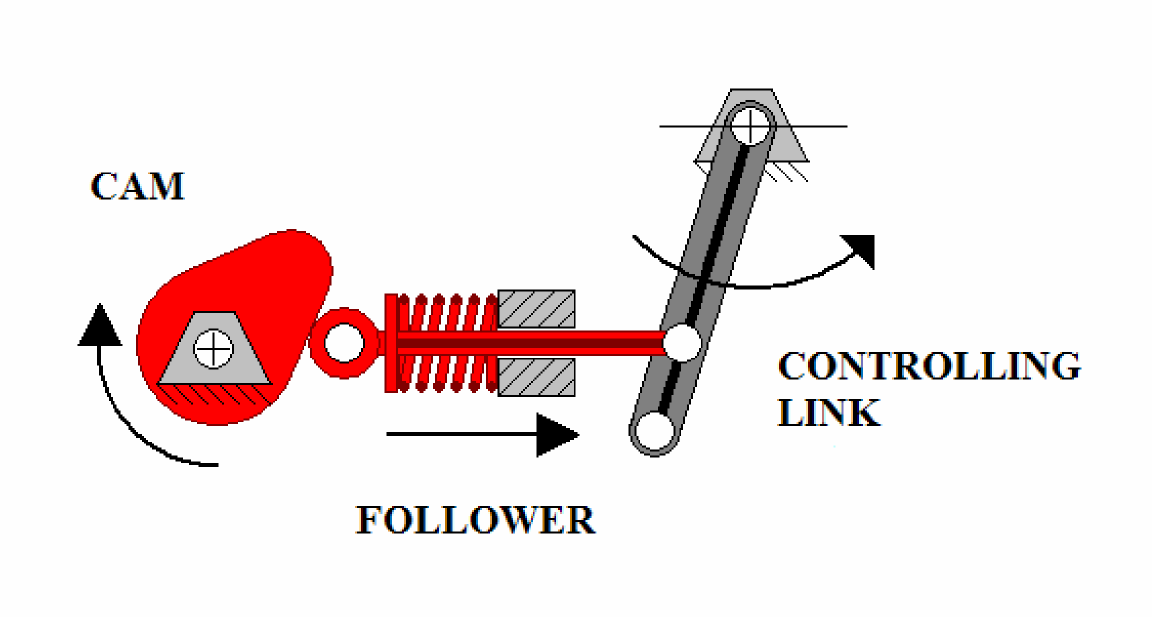


Figure 22: Cam & follower elevation method

6.3 User Interface

After the legrest mechanism and elevation designs were created, the next set of preliminary designs developed were for the user interface. Taking all the elevation method designs into consideration, what kind of interface is the user going to encounter when using the legrest? To answer this question, it was important to examine the input motion necessary for each of the elevation methods to work properly.

6.3.1 Crank Handle

The first user interface considered was a crank handle (Figure 23). For this user interface, the input motion necessary for the different elevation methods would be a rotation motion. Elevation methods that use rotation motion as the input motion include worm gear sets, power screws, and cam/follower systems. Crank handles work by securing the mounting hole onto the shaft which is to be rotated. This is usually done with the combination of a keyway and set screw. Once secure, a perpendicular force applied to the handle will cause the crank handle and attached shaft to rotate. Crank handles come in two forms: stationary handle and fold-away handle.

Figure 23: Different forms of crank handles (McMaster-Carr, 2006)

6.3.2 Handwheel

The second user interface considered was a handwheel (Figure 24). For this user interface, like that of the crank handle, the input motion necessary for the different elevation methods would be a rotation. The same elevation methods that apply to the crank handle interface apply to the handwheel as well. Handwheels work much like crank handles in that they are secured onto the shaft which is to be rotated using the center mounting hole. Once secure, handwheels can rotated two different ways: 1) applying a perpendicular force to the handle, or 2) applying a torque to the handwheel by taking hold of the entire handwheel in one's hand. Handwheels come in various forms: no handle, stationary handle, revolving handle, and fold-away handle.

Figure 24: Different forms of handwheels (Monroe, 2005)

6.3.3 Activation Switch/Button

The third user interface considered was an activation switch or button (Figure 25). For this user interface, the only applicable elevation method is the gas spring method. In a specific type of gas spring known as a "locking" gas spring, the internal gas charge can be released against the piston or it can be locked in the reservoir by means of a two-way gate mechanism. To open and close this gate, some form of activation is required. Various forms of push-buttons and switches, like that shown in Figure 25, are available to be used in conjunction with the locking gas spring's wire/hydraulic release systems.

Figure 25: User interface activation button shown on gas spring (Easylift, 2004)

6.3.4 Lever Handle

The fourth and final user interface developed was the lever handle. This user interface, used by the 2004 WPI MQP project, is only applicable with the lever handle elevation method (Figure 18). As an extension of the controlling link of the legrest, the lever handle would be activated by the user in the form of a pulling or pushing force perpendicular to the handle, causing the controlling link to rotate. Depending on the active lengths of the handle and the controlling link, a variety of mechanical advantages could be achieved. Possible versions of the lever handle include a permanent handle, a fold-away handle, a telescoping handle, and a removable handle.

6.4 Locking Mechanism

After the user interface designs were created, the next set of preliminary designs generated was for the locking mechanism. Assuming a viable design capable of user-activated elevation could be generated from the first three sets of preliminary design sets, the next question to be asked was "How is the legrest going to be securely locked in place?" To find an answer to this question, six locking mechanisms were developed and considered.

6.4.1 Pull Pin

The first locking mechanism considered was the use of a pull pin (Figure 26). Perhaps the simplest locking mechanism possible, this type of locking mechanism was used by the 2004 WPI MQP project. Working as a physical obstacle in the way of the controlling link, the pull pin can be removed and replaced in a different placement hole to achieve a new, locked elevation for the legrest. As a single pull pin, this type of locking mechanism only restricts the movement of the controlling link in one direction. A double U-shaped pull pin that fits over the controlling link would restrict the movement of the link in both directions.

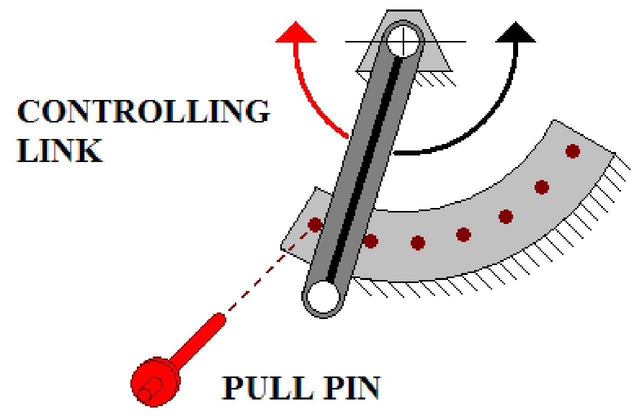


Figure 26: Pull pin locking mechanism

6.4.2 Ratchet & Pawl

The second locking mechanism considered was a ratchet and pawl mechanism (Figure 27). This mechanism works by preventing the rotation of the controlling link in the reverse direction. To work properly, the ratchet is first fixed to the same shaft as the controlling arm so the two parts rotate in unison. The spring-loaded, locking pawl is then positioned so that it prevents the ratchet from reversing direction (clockwise in Figure 27). This type of mechanism is widely used in devices such as winches and ratchet wrenches. Fairly versatile in nature, this type of mechanism could be used in conjunction with most of the elevation method design choices.

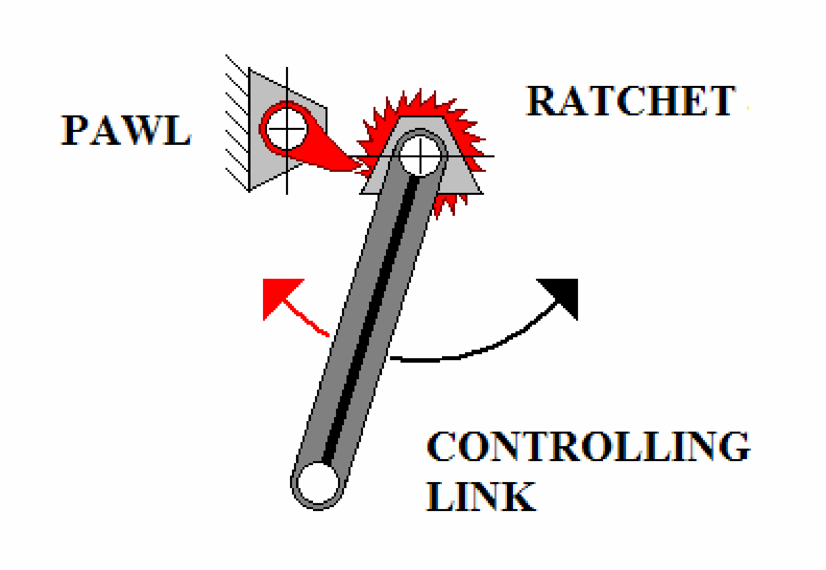


Figure 27: Ratchet and pawl locking mechanism

6.4.3 Worm Gear Set

The third locking mechanism to be considered was the use of a worm gear set. With proper design, a worm gear set can be produced such that it is impossible to backdrive. In other words, a worm gear set can be made such that the worm can turn the worm gear but not vice versa. This is a major advantage of worm gear sets in applications which call for a load to be held in place. The self-locking characteristic comes from the friction angle being greater than the worm lead angle. Generally speaking, if the worm lead angle is less than 5°, there is reasonable expectation of self-locking. For obvious reasons, this locking mechanism option would only be used with the worm gear set elevation method.

6.4.4 Locking Gas Springs

The fourth locking mechanism considered was the use of locking gas springs (Figure 28). Typical gas springs work by having a single charge of compressed gas on one side of an internal piston to provide a continuous pushing force in one direction. Locking gas springs are different in that they have two internal reservoirs separated by a valve. This setup keeps the primary charge of compressed gas in an internal reservoir until it is released into the volume adjacent to the piston. This release of reservoir gas to the piston volume can be started as well as stopped and is usually performed by some kind of user-activated wire/hydraulic release switch or button. This ability of the piston actuation to be stopped and held at different locations is what gives the locking gas spring its locking ability. Again, for obvious reasons, this locking mechanism option would only be used with the gas spring elevation design option.

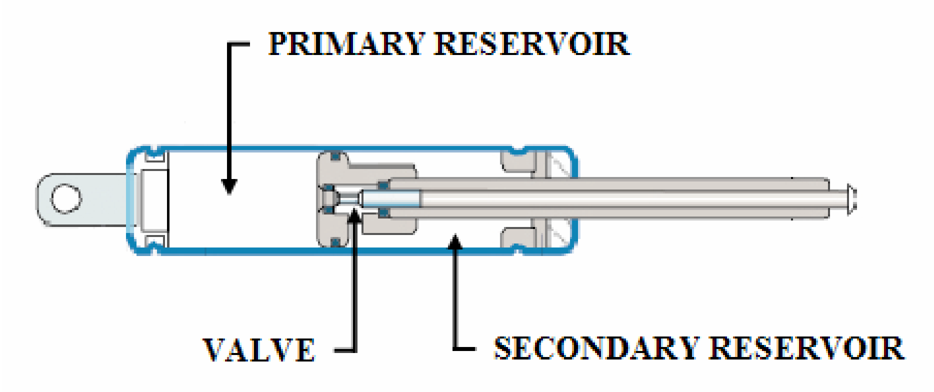


Figure 28: Locking gas spring internal diagram (Easylift, 2004)

6.4.5 Low Lead Angle (Power Screw)

The fifth locking mechanism considered was the use of a power screw with a low lead angle. Working on the same principle as the worm gear set design, the idea behind this design is to use a power screw with a low enough lead angle such that the friction angle would counteract any backdriving ability. A lead angle less than 5° would be enough to expect the power screw to possess a self-locking ability. Because this idea is based on the use of a power screw, it could only be used in conjunction with the power screw elevation method.

6.4.6 Cam Dwells

The sixth and final locking mechanism design produced was the use of a cam and follower system in which the cam profile contains several dwells throughout its function. Working in conjunction with the cam and follower elevation method (Figure 22), the addition of a locking ability could easily be added by including a series of increasing dwells within the cam profile. As the cam rotates about its fixed ground pivot, any rise or fall segment in the cam profile would cause the follower to move one way or another in its horizontal track. When a dwell came along, however, the follower would not move and thus the connecting linkage would also not move. Because no force applied to the linkage and connecting follower can rotate the cam while it is in a dwell, the system will have achieved a locked status.

6.5 Design Evaluations

With all the preliminary design sets created, the next step in the design synthesis process was to evaluate each set to choose the best design to fulfill the user’s needs and design specifications. This evaluation was performed with a “domino effect”, starting with the most important design set and letting that set's design choice affect the next set to be evaluated, and so on. The first design set evaluated was that of the legrest linkages.

6.5.1 *Legrest Linkage*

From the design synthesis section, three legrest linkages were developed:

1) Sixbar linkage with fixed pivot and slider mechanism
2) Fourbar linkage with floating pivot
3) Sixbar linkage with floating pivot

The first linkage to be evaluated was the sixbar linkage with the fixed pivot and slider mechanism (Figure 15). After making use of this design as a possible linkage option, there was minimal enthusiasm to pursue it further. Looking back, it had already been used by the 2004 WPI MQP project group. Not only had it been used, it had also revealed problems, specifically with the slider mechanism. As shown in the Background and Design Approach Analysis sections, slider mechanisms are prone to binding problems and have prevalently been used in articulating legrests. One of the goals of this thesis project was to attempt to develop a new and different design, not just the same or slightly better design. For these reasons, this first linkage design was not chosen for the final design.

The second linkage evaluated was the fourbar linkage with the floating pivot (Figure 16). One can see that the majority of this linkage remains above its fixed pivot points throughout its range of motion. Having these fixed pivot points located at the top level of the wheelchair's frame, one can see that the linkage would operate above the wheelchair frame and most likely above the user's seat cushion. Looking back at the size/weight design specifications, the design must not interfere with transfers to and from the chair. More specifically, no part of the design should extend above the top of the user's seat cushion. For this reason, this second linkage design was not chosen for the final design.

The third design evaluated was the sixbar linkage with the floating pivot (Figure 17). For various reasons, this design seemed to fit the scope of the project perfectly - it was something new and different; never before has an elevating legrest been designed with a sixbar linkage. It did not incorporate a slider mechanism so there was no concern for binding. Finally, possibly most important, it did not interfere with the user's ability to transfer to or from the wheelchair. For these reasons, this third linkage design was chosen for the final design.

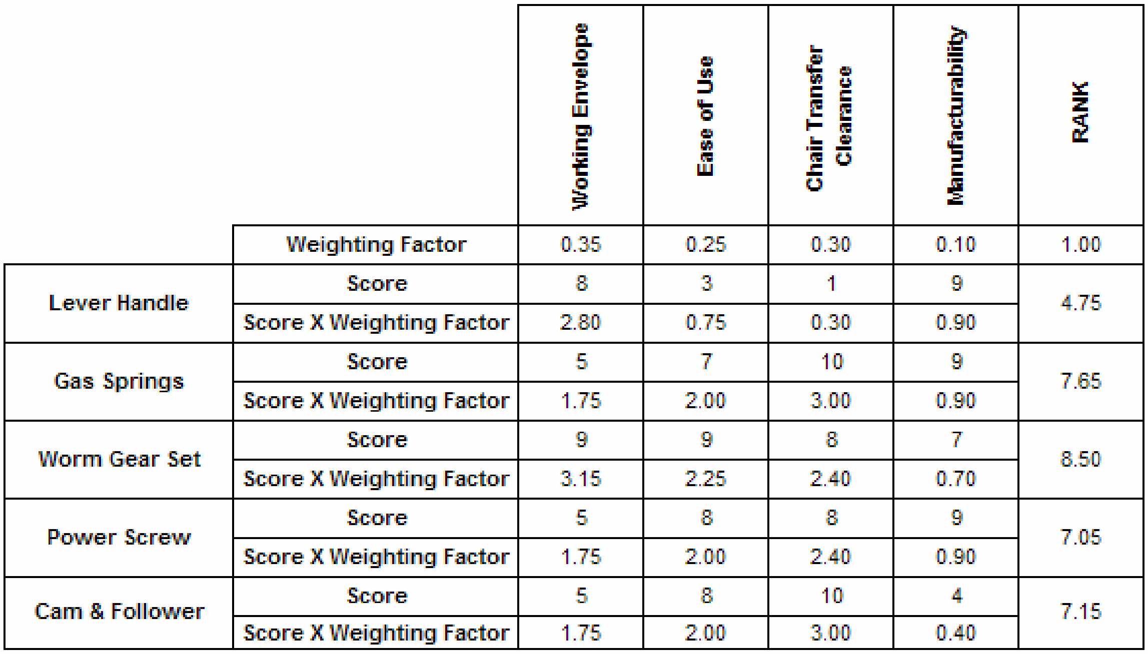
6.5.2 Elevation Method

Once the linkage design was decided upon, the next set of preliminary designs to be evaluated were the elevation methods. From the design synthesis section, five elevation methods were developed:

1) Lever Handle
2) Gas Springs
3) Worm Gear Set
4) Power Screw
5) Cam & Follower

All elevation methods developed were capable of being combined with the legrest linkage chosen; as such, they all had to be evaluated. Because of the high number of elevation methods to choose from, the only practical way to compare them was to employ a decision matrix. Using design specifications pertinent to the elevation method of the legrest, the following decision matrix was established (Table 3).

Table 3: Elevation method decision matrix



		Working Envelope	Ease of Use	Chair Transfer Clearance	Manufacturability	RANK
	Weighting Factor	0.35	0.25	0.30	0.10	1.00
Lever Handle	Score	8	3	1	9	4.75
	Score X Weighting Factor	2.80	0.75	0.30	0.90	
Gas Springs	Score	5	7	10	9	7.65
	Score X Weighting Factor	1.75	2.00	3.00	0.90	
Worm Gear Set	Score	9	9	8	7	8.50
	Score X Weighting Factor	3.15	2.25	2.40	0.70	
Power Screw	Score	5	8	8	9	7.05
	Score X Weighting Factor	1.75	2.00	2.40	0.90	
Cam & Follower	Score	5	8	10	4	7.15
	Score X Weighting Factor	1.75	2.00	3.00	0.40	

Starting with criterion of working envelope, the worm gear set received a score of 9, followed by the lever handle with a score of 8, and finally the gas springs, power screw, and cam/follower system tied with a score of 5. As the smallest in size, the worm gear set warranted the highest score. The gas springs, power screw, and cam/follower system are all large or have a high number of parts, causing their respective working envelopes to be large and hence received lower scores.

In terms of ease of use, the worm gear set took the top spot with a score of 9, followed by the power screw and cam/follower systems with a score of 8, and finally the gas springs with a score of 7 and the lever handle with a score of 3. Having a relatively low torque requirement, the worm gear set was given the highest score. The power screw also has a relatively low torque requirement; however the user interface would need to move with the power screw during its operation, causing some difficulty for the user. The cam/follower system was given a slightly lower score than the worm gear set for the reason that it would require more torque to operate. Gas springs were given a score of 7 due to the fact that the user would have to manually push the legrest down to lower it after elevation. The lever handle was given the lowest score as it would require the highest amount of user-supplied force to operate the legrest.

For chair transfer clearance, the gas spring and cam/follower systems received a score of 10, followed by the worm gear set and power screw systems with a score of 8, and finally the lever handle with a score of 1. The gas spring and cam/follower systems were given the top score of 10 for the fact that neither has any part of its system extend beyond the fixed ground points. The worm gear set and power screw systems were given a slightly lower score because they have components which extend just beyond the ground pivots. The lever handle was given a score of 1 for the fact that the entire system exists above the ground pivots.

The final criterion to be looked at was manufacturability. For this category, the power screw, lever handle, and gas spring systems received the high score of 9, followed by the worm gear set with 7, and finally the cam/follower system with 4. The number of parts and required assemblage of parts directed the scores for this category. Having the least number of parts, the power screw, lever handle, and gas spring systems took the top spots. The demanding placement of the worm and gear in the worm gear set caused that design to score lower. The high number and machining-difficulty of the parts in the cam/follower system caused it to obtain the lowest score. Adding all the category scores up, the worm gear set obtained the highest score. For this reason, it was chosen as the elevation method of choice for the final design.

6.5.3 User Interface

With the elevation method chosen, the next set of preliminary designs to be evaluated were the user interfaces. From the design synthesis section, four user interfaces were developed:

1) Crank Handle
2) Handwheel
3) Activation Switch/Button
4) Lever Handle

Because the user interface had to work with the (already chosen) elevation method, some of the user interface design options had to be removed from the selection. The activation switch/button and the lever handle user interfaces were eliminated as design choices due to their inability for horizontal plane rotation, leaving only the crank handle and handwheel as user interface options.

The decision between the crank handle and handwheel interfaces was a relatively easy one as it came down to which had the smaller working envelope; more specifically, which had the smaller rotational diameter. After several product searches, it was determined that handwheels have smaller working envelopes than crank handles. For this reason, the handwheel was chosen for the final design.

6.5.4 Locking Mechanism

With all other aspects of the design already chosen, the locking mechanism design set was the last to be evaluated. From the design synthesis section, a total of six locking mechanisms were developed:

1) Pull Pin
2) Ratchet & Pawl
3) Worm Gear Set
4) Locking Gas Springs
5) Low Lead Angle (Power Screw)

6) Cam Dwell

Continuing with the "domino effect" of already having chosen an elevation method, all but one of the locking mechanism choices were automatically eliminated. The one remaining locking mechanism design choice was that of the worm gear set. It made the most sense that if one already has a worm gear set in place to elevate the legrest, one might as well use it to lock the legrest in place as well. For this reason, the worm gear set locking mechanism was chosen for the final design.

6.5.5 Complete Design Choice

To summarize, the design choices made in this preliminary design synthesis include the sixbar linkage with the floating pivot for the legrest linkage, the worm gear set for the elevation method, the handwheel for the user interface, and the worm gear set again for the locking mechanism. The next section will take the reader through the final design details where all the design choices are brought together.

7 FINAL DESIGN

7.1 Overview of the Final Design

The final design is shown in Figure 29. The elements making up the final design were chosen for the reason of being the best suited for the user's needs and for their high compatibility with one another. To operate the legrest, the user first turns the handwheel connected to the worm gear set. The worm gear within the worm gear set is connected to the controlling link of the sixbar legrest linkage such that when the worm gear turns, the controlling link turns with it and the entire linkage is moved through its pre-described motion. Acting also as the locking mechanism for the assembly, the worm gear set's self-locking ability allows for the linkage to be locked in place at any required elevation.

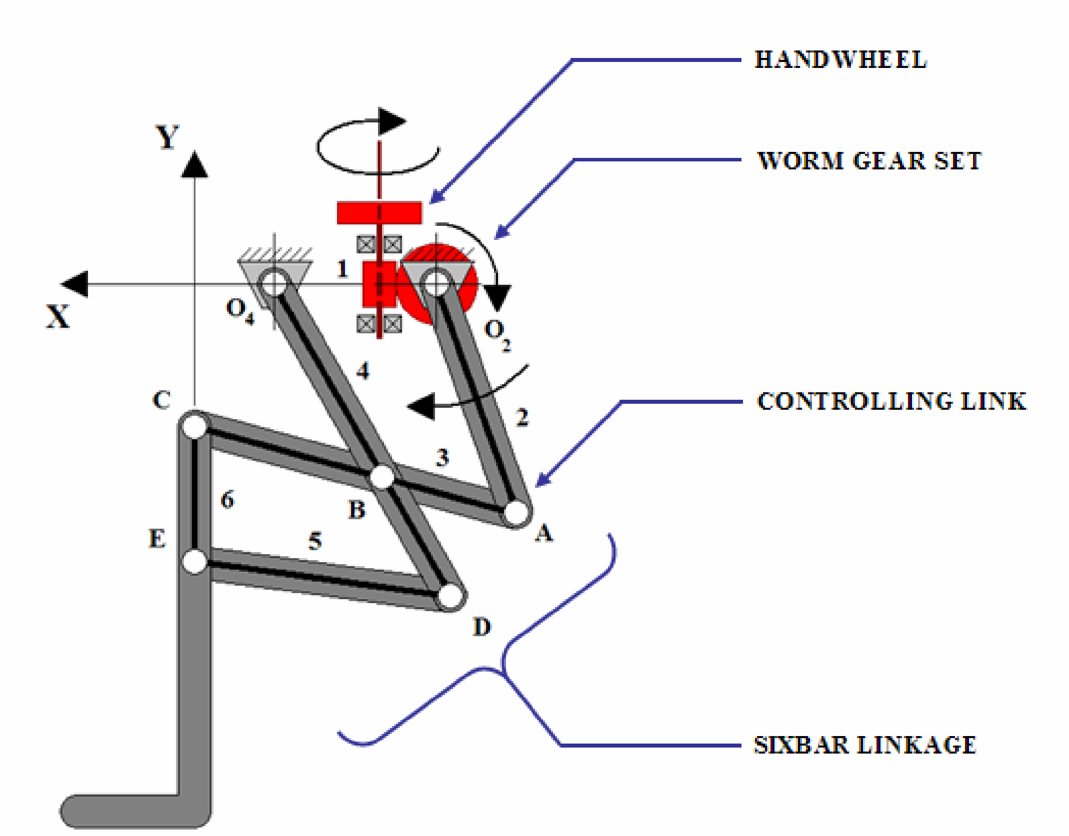


Figure 29: Final design showing chosen design elements: handwheel, worm gear set, controlling link, and sixbar linkage

The final design CAD model (Figure 30) also shows the chosen design elements of the handwheel user interface, worm gear set, and sixbar linkage in addition to the gear set housing. Another viewpoint of the final design CAD model (Figure 31) depicts other design aspects such as the wheelchair attachment assembly, footrest assembly, and calf support assembly.

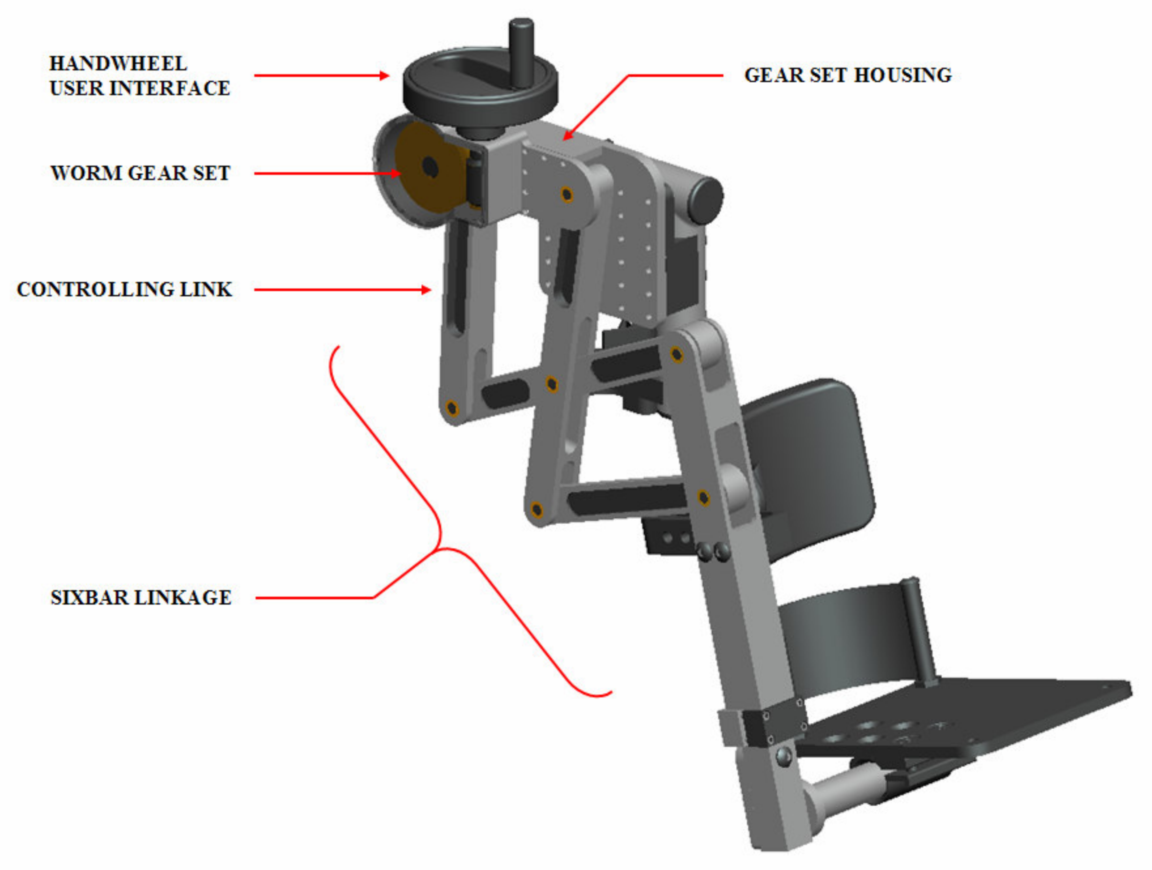


Figure 30: Final design CAD model (outboard view) showing handwheel, worm gear set, sixbar linkage, and gear set housing

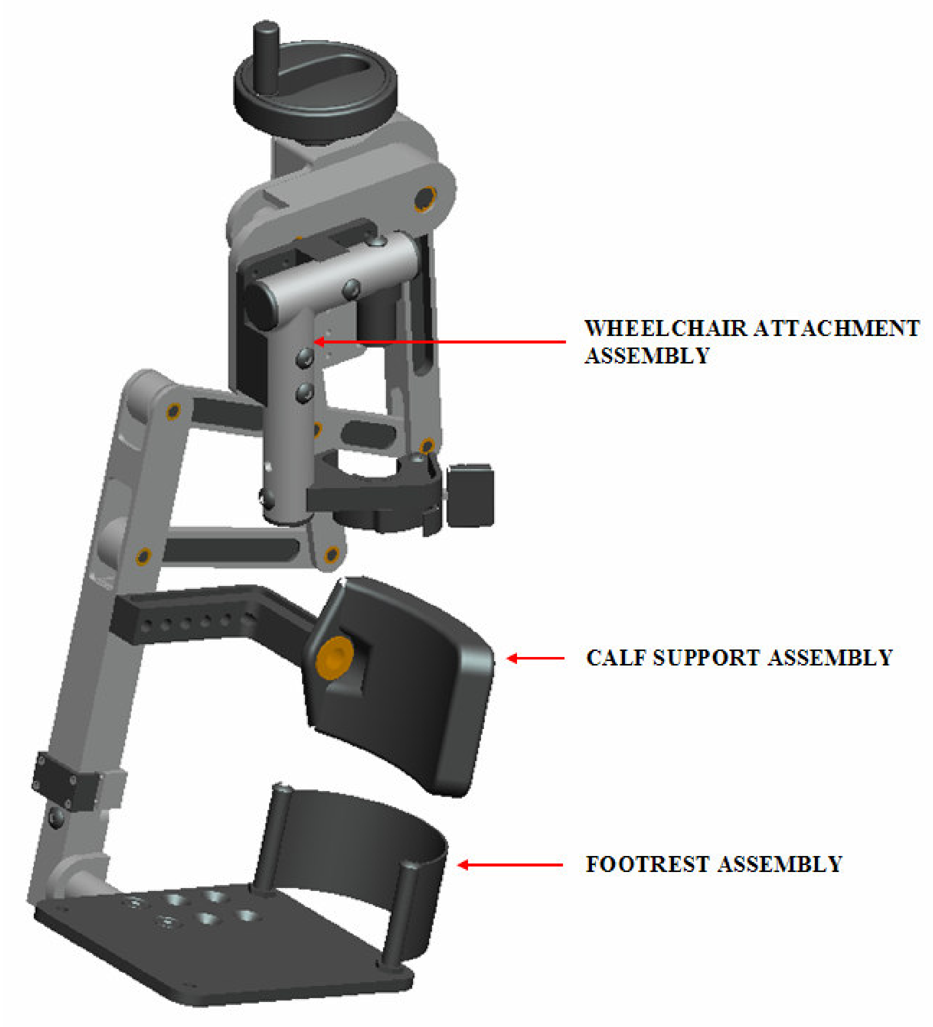


Figure 31: Final design CAD model (inboard view) showing wheelchair attachment assembly, calf support assembly, and footrest assembly

7.2 Sixbar Linkage Design

7.2.1 Position and Needed Extension of Linkage

The first parameter that needed to be determined when designing the sixbar linkage was the position of the virtual legrest pivot relative to the position of the user's knee pivot. The term *virtual* is used to signify that the legrest pivot point is not a physical object but rather a point in space about which link 6 of the linkage rotates (Figure 32). More specifically, this virtual pivot point is the instant center of link 6 with respect to the ground link. While this point starts and ends at the same position during the lowered and elevated positions of the legrest, it traverses slightly in between these end positions as the assembly elevates. For a linear articulation of the legrest link, the instant center 1-6 moves through a small teardrop motion during the elevation of the linkage (Figure 51 in Chapter 8).

Once the position of the virtual pivot point was determined, the extension needed from the legrest could be solved for as it is a direct product of the difference in the location of the pivot points. Based on the previous research performed by the two WPI MQP prototypes as well as this project's current clearance research, the position chosen for the legrest pivot point was four inches directly below the user's knee pivot (Figure 32). This distance gives the user plenty of chair transfer clearance over the legrest linkage and its attached assemblies.

Based on the chosen position of the virtual legrest pivot relative to the user's knee pivot, the amount of extension needed from the legrest linkage was determined through simple trigonometry. From these calculations, it was concluded that an extension of four inches was required (Figure 32).

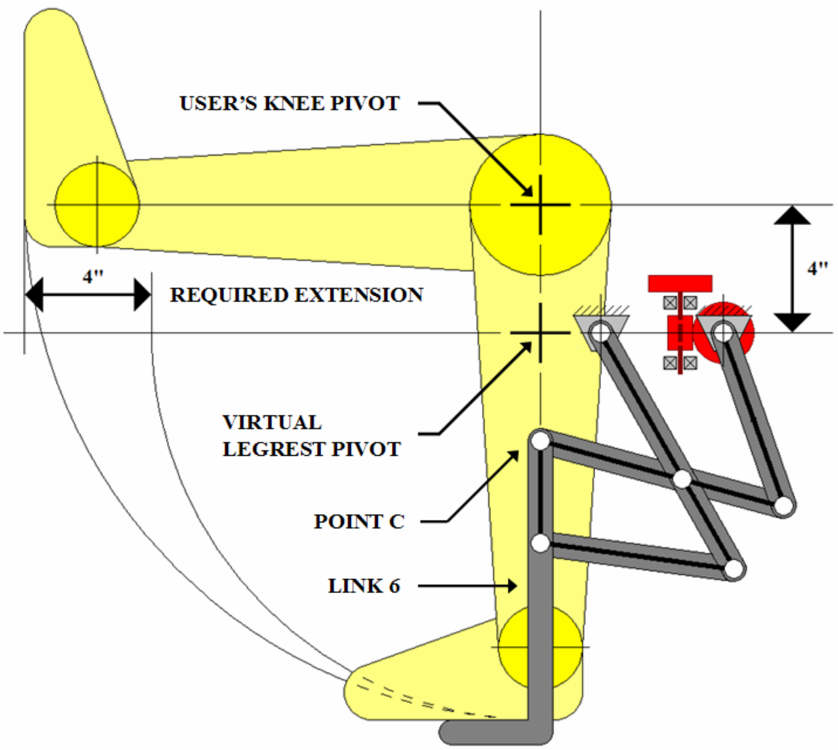


Figure 32: Position of legrest linkage relative to user's knee pivot

7.2.2 Primary Fourbar Linkage Design

With the position and extension of the legrest resolved, the actual design of the sixbar linkage was undertaken. Beginning with a fourbar linkage with an extended coupler link, a two-position graphical synthesis was used design the linkage. The synthesis method employed made sure that the linkage's range of motion included the sequential elevated and lowered positions such that the required level of extension was achieved (Figure 33). This was done by carefully choosing the start and end positions of point C on the linkage. Point C is later joined to link 6 (Figure 32), the link which the user's leg rests on, such that the position and movement of the point C is directly related to that of link 6.

In the lowered position, point C (C1 in Figure 33) starts two inches directly below the virtual legrest pivot. In the elevated position, point C (C2 in Figure 33) is located six inches directly in front of the virtual legrest pivot. As link 6 of the legrest linkage rotates 90° between the lowered and elevated positions, point C on link 6 must move from its starting position of two inches away from the virtual legrest pivot to its ending position of six inches away from the virtual legrest pivot, thus obtaining the required four inches of extension.

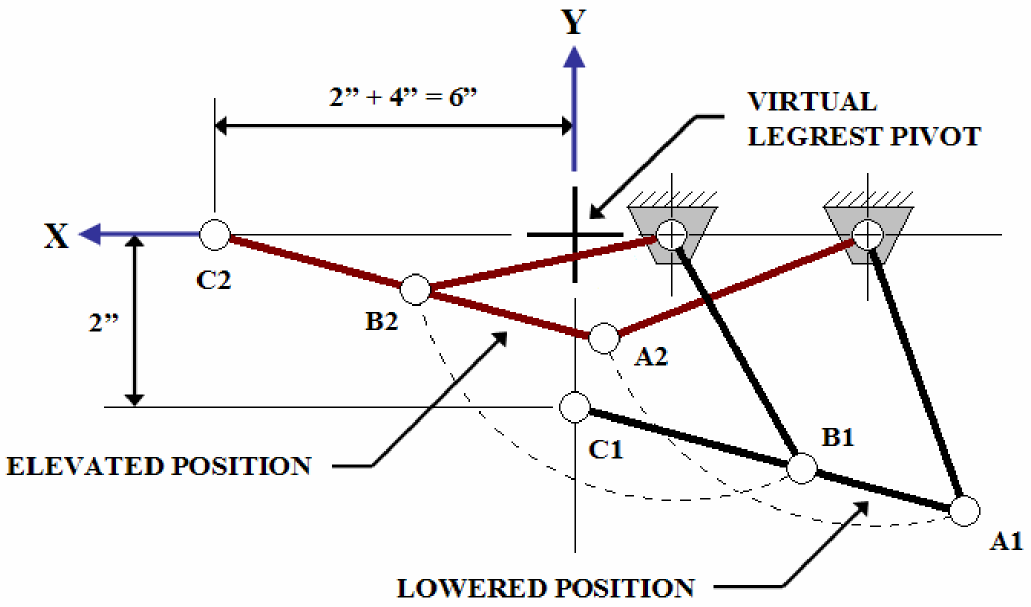


Figure 33: Graphical position synthesis of primary fourbar linkage

7.2.3 Interlacing Fourbar Linkages into Sixbar Linkage

After the primary fourbar linkage was designed, the next step in the process was to interlace another fourbar linkage into the existing design to complete the sixbar linkage design. This step was done by adding links 5 and 6 as well as extending link 4 (Figure 34). Having chosen the length of link 6 as a design decision, the only other lengths needed were the length of link 5 and the extended length of link 4. Knowing the angles of the other links in both the elevated and lowered positions, these two lengths were found by writing vector loop equations and solving the system of equations using the computer program MathCad® (Appendix A). With the addition of these links, two interlaced fourbar linkages (1-2-3-4 & 3-4-5-6) were combined to form one sixbar linkage. Having only two ground pivots, this linkage design can be classified as a Watt's sixbar inversion I.

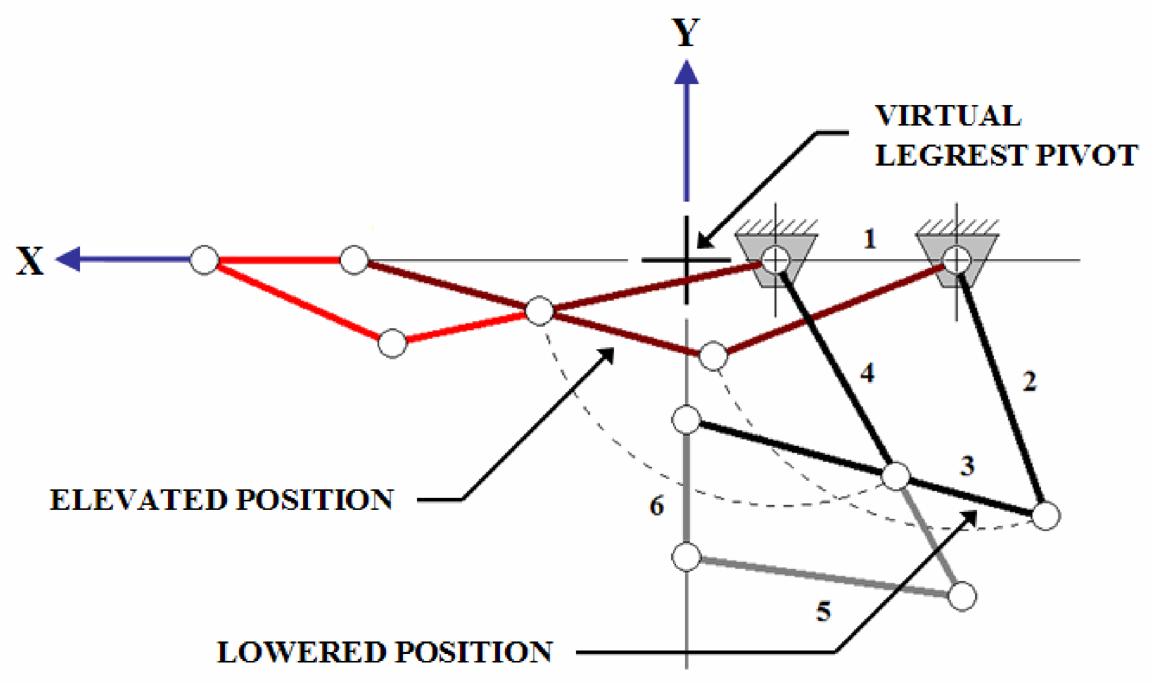


Figure 34: Sixbar legrest linkage formed by interlacing two fourbar linkages

7.3 Worm Gear Set Design

7.3.1 Elevation and Locking Ability

As previously stated in the preliminary design synthesis and analysis section, a worm gear set was chosen as a final design element for two reasons: elevation method and locking mechanism. In terms of elevation method, it was chosen primarily on the basis that it can be packaged in a very small volume and it required a very low input force. For a locking mechanism, the worm gear set was chosen for the convenience of its dual-use as an elevation method as well as its self-locking ability, allowing for infinite locked, elevated positions.

7.3.2 Selection

The selection of the worm gear set required it to have a small working envelope and a high gear ratio to keep the input torque low. These two requirements were somewhat difficult to satisfy as it turns out the higher the gear ratio, the larger the worm and worm gear are likely to be. Other factors included the worm gear hub diameter and the worm gear set materials. The hub diameter had to be large enough to encase a shaft capable of supporting the applied loads while the appropriate worm gear set materials of steel for the worm and bronze for the worm gear were only available in certain size ranges. After many iterations between size and gear ratio constraints, a worm gear set was chosen. The chosen design had a gear ratio of 30:1 with the worm gear and worm diameters being 1.875 inches and 1 inch, respectively.

7.4 User Interface

With the sixbar linkage and worm gear set designs in place, the user interface was the next design item to be decided upon. From the preliminary design synthesis and analysis section, the final design's user interface was chosen to be a handwheel – but what kind of handwheel? There are many different forms of handwheels to choose from: no handle, stationary handle, revolving handle, and fold-away handle. The first aspect needed in the chosen handwheel was a handle so that if the user did not possess the dexterity to grasp and turn the entire handwheel, he/she could at least apply a horizontal force to the handwheel's vertical handle. The other design aspect required of the handwheel was a low profile. Remembering that the handwheel will be positioned at the top of the legrest assembly where chair transfers will take place, the overall height of the handwheel had to be kept to a minimum. Taking both design aspects into consideration, the fold-away handle handwheel (Figure 35) was the best choice.

Figure 35: Fold-away handle handwheel shown in the folded position (Monroe, 2005)

7.5 Wheelchair Attachment Assembly

7.5.1 Overview

The wheelchair attachment assembly (Figure 36) is an assembly that mounts to various wheelchair frames to provide a mounting for the legrest assembly. The design of this assembly should allow for easy removal and attachment to the wheelchair frame as well as provide adjustability to the legrest assembly.

7.5.2 Swing-away Hanger System

The design for this attachment assembly was chosen to be a swing-away hanger system, allowing for the legrest assembly to be easily attached and detached from the wheelchair. The method of attachment was modeled after the standard Quickie swing-away hanger system as this design would most likely be used in accordance with a Quickie wheelchair.

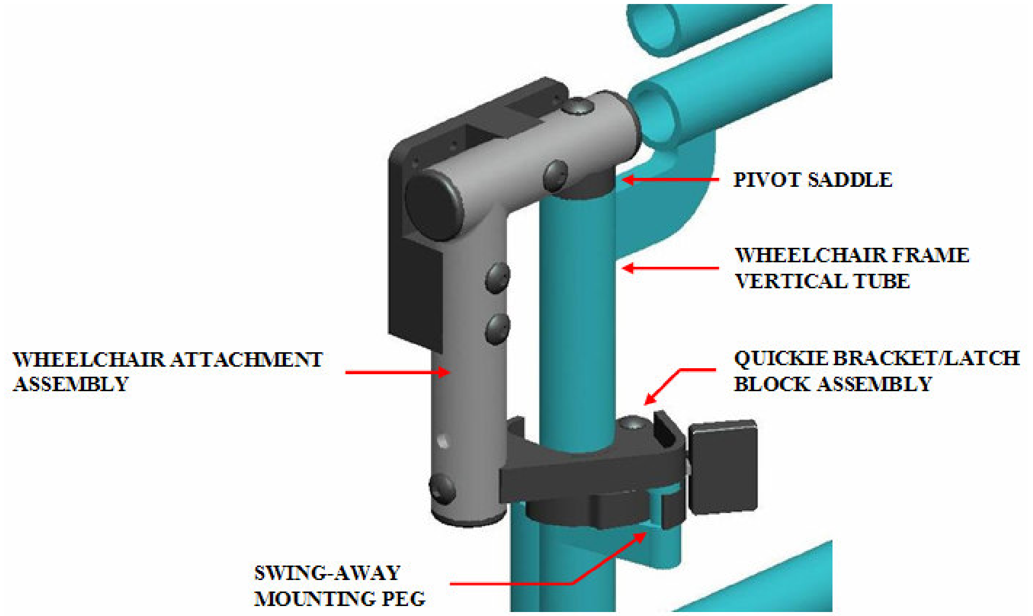


Figure 36: Wheelchair attachment assembly shown on Quickie wheelchair frame

To attach the swing-away hanger system to the wheelchair frame, the pivot saddle (Figure 37) is first inserted into the open end of the wheelchair frame's vertical tube (Figure 36). Next, the entire hanger system is rotated until the mounting peg on the wheelchair frame reaches the swing-away latch block, snapping into a locked position by means of the spring-loaded release lever. To detach the mounting system from the wheelchair, the process is reversed: first the release lever is pushed to unlock the latch block from the mounting peg, and then the assembly is rotated and lifted off the frame's vertical tube.

To attach the legrest assembly to the swing-away hanger system, the legrest mount (Figure 37) is employed. Acting as a bridge between the hanger system and the legrest system, the legrest mount part is secured first to the legrest assembly by means of (8) #6-32 screws and then to the hanger system by means of (3) 1/4"-20 screws.

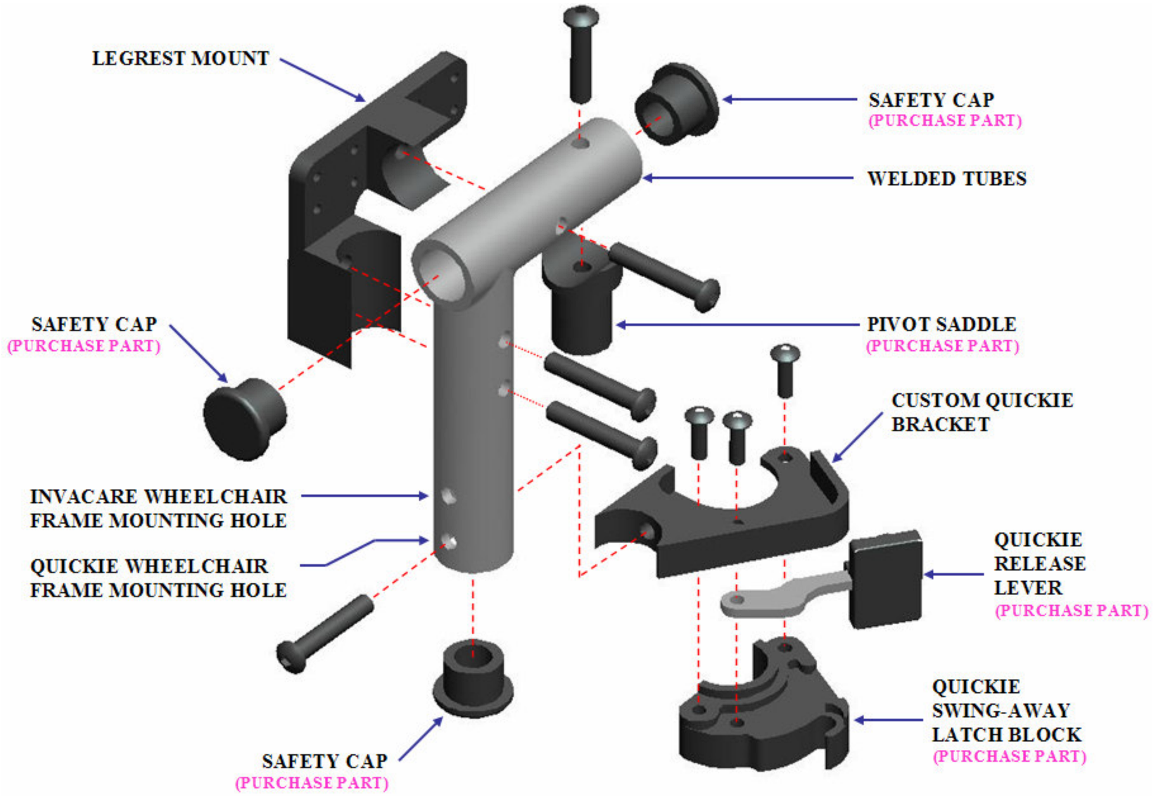


Figure 37: Wheelchair attachment assembly - swing-away system (exploded) for attachment to standard Quickie manual wheelchair

7.5.3 Adjustability

As one of the most important design specifications for this project, adjustability was a major concern, especially in the design of the legrest attachment system. As explained in the sixbar linkage design section and shown in Figure 32, the accurate positioning of the user's knee joint in reference to the legrest assembly is critical to the correct operation of the legrest. Though the general position of the user's knee pivot could be adjusted through the use of different seat cushions and back padding, its typically best to be thought of as fixed. Therefore, the position of the legrest pivot point must be adjustable to fit various leg sizes and positions. This is accomplished with the interface of the legrest mount and ground link 2 (Figure 38).

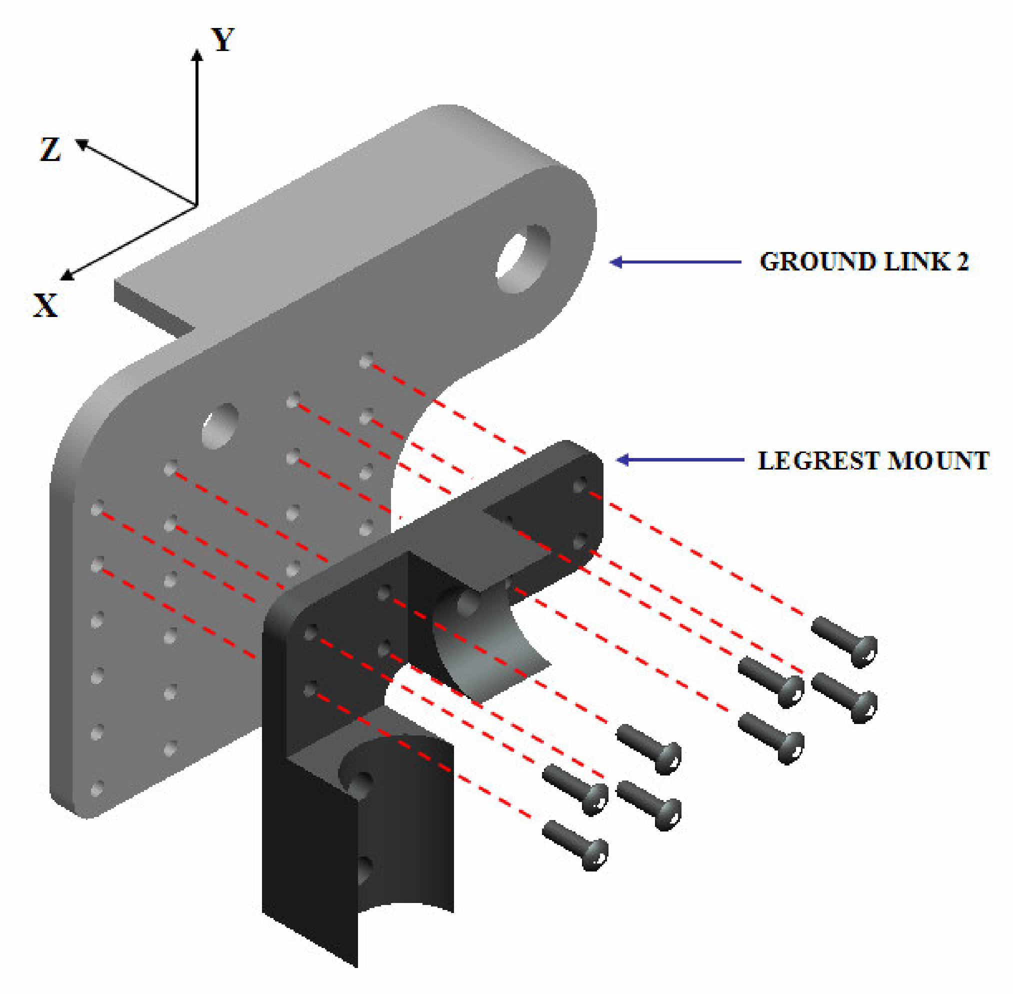


Figure 38: Adjustable attachment interface between ground link 2 and legrest mount

Employing a matrix of tapped holes, the ground link 2 can be adjusted in both the X- and Y-directions in reference to the legrest mount. Capable of 2” of travel in the Y-direction (5 securing positions) and 1.5” of travel in the X-direction (3 securing positions), the legrest pivot point may be adjusted using any of the 15 different securing positions. This adjustability range was shown to be adequate for the majority of users.

In addition to the adjustability of the legrest pivot point, the mounting system also has the ability to fit wheelchairs from different manufacturers. As one of the primary manual wheelchair manufacturers in the country, the Quickie wheelchair was the main focus of this mounting system setup. However, in addition to Quickie, Invacare is also a major manufacturer of manual wheelchairs. While the wheelchair frames for each company do possess a similar swing-away mounting peg, small variances prevent the interchangeability of the legrest assembly from one wheelchair frame to another. The main difference between the two designs is the length of the wheelchair frame vertical tube from the top end where the pivot saddle fits into down to the swing-away mounting peg (Figure 36); the length of the Invacare vertical tube is shorter than that of the Quickie vertical tube. Because of this, the mounting system used on the Quickie wheelchairs does not fit on the Invacare wheelchairs. As a simple and quick fix, an additional hole is drilled in the welded tubes (Figure 37) to allow for the attachment of an Invacare bracket/latch block assembly at the correct height. To adjust between a Quickie wheelchair and an Invacare wheelchair, the user would simply have to remove the Quickie bracket/latch block assembly (Figure 36) from the lower mounting hole and attach the Invacare bracket/latch block assembly to the upper mounting hole.

7.6 Gear Set Housing

Attached to the legrest mount is the gear set housing (Figure 39) which is the main assembly of the legrest and has two primary functions: 1) provide a solid foundation for the linkage's ground pivots and 2) provide a structured combination of bearing surfaces for the worm gear set.

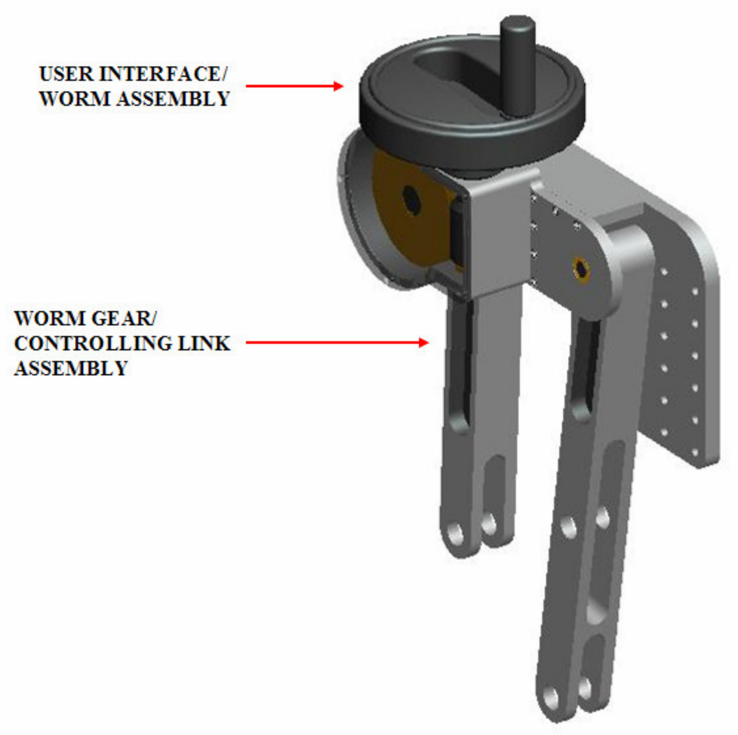


Figure 39: Gear set housing showing major assemblies: user interface/worm assembly and worm gear/controlling link assembly

7.6.1 Linkage Ground Pivots

The gear set housing assembly is comprised of numerous parts (Figure 40). In terms of linkage ground points, the parts of interest are the two ground links, the controlling link 2, link 4, the worm gear shaft, the bronze collar bushings and the dowel pin. Starting with the forward ground pivot, pivot O_4 in Figure 29, the bronze bushings are press-fit into the ground links and act as bearings for the dowel pin which, in turn, is press-fit into link 4, allowing for free rotation of link 4.

The rear ground pivot, pivot O_2 in Figure 29, is assembled in a similar way to that of the forward ground pivot but instead of a dowel pin, link 2 is attached to the worm gear shaft via a keyway and set screw. The rotation of link 2 is dictated by the rotation of the worm gear attached to the other end of the worm gear shaft. The two ground links are held together with thirteen #2-56 screws, not shown in Figure 40.

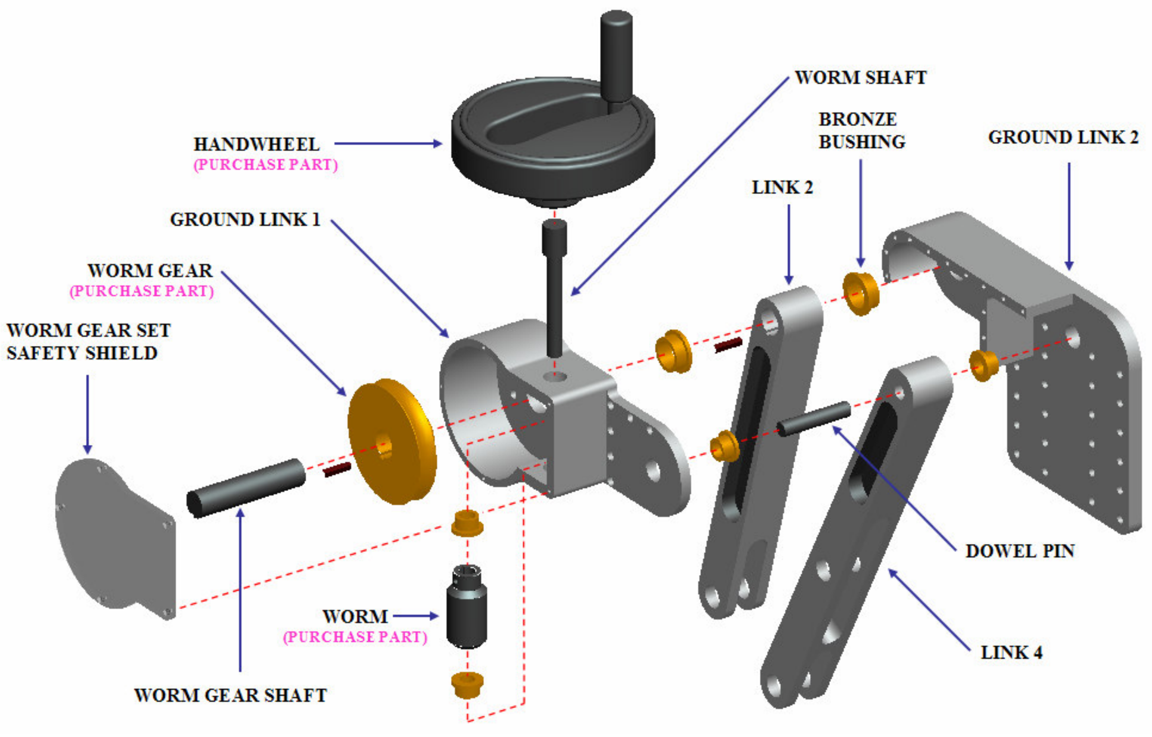


Figure 40: Gear set housing assembly (exploded) showing all major components

7.6.2 User Interface/Worm Assembly

The worm gear set assembly is comprised of two smaller assemblies: the user interface/worm assembly and the worm gear/controlling link assembly. Each assembly by itself is a rigid structure with no moving parts, whereas the main worm gear set assembly has the ability to move. When a force is applied to the user interface, the interface/worm assembly rotates and forces the worm gear assembly to rotate as well.

The user interface/worm assembly (Figure 41) is made up of the handwheel, the worm shaft, and the worm. Like the ground pivots, two bronze bushings are press-fit into the ground link 1 to act as bearing surfaces for the worm shaft. Both the handwheel and the worm are secured to the worm shaft via keyways and set screws.

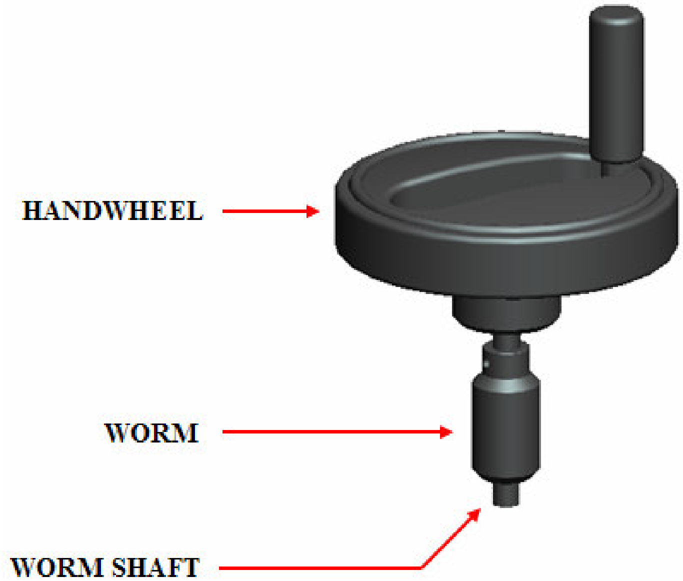


Figure 41: User interface/worm assembly showing handwheel, worm, and worm shaft

7.6.3 Worm Gear/Controlling Link Assembly

The worm gear/controlling link assembly (Figure 42) consists of the worm gear, the worm gear shaft, and the controlling link 2. The worm gear is first assembled onto the end of the worm gear shaft via a keyway and set screw. Next, the other end of the worm gear shaft is fed through the ground link 1 where the controlling link 2 is assembled onto the shaft in the same way. Again, bronze bushings are press-fit into the ground links to act as bearing surfaces.

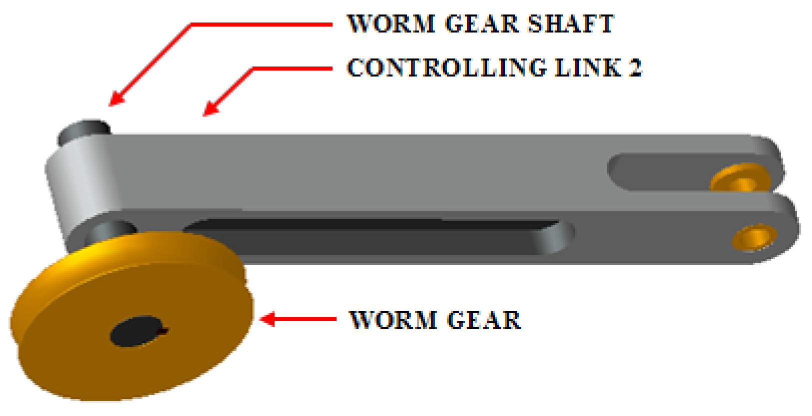


Figure 42: Worm gear/controlling link assembly showing worm gear shaft, controlling link 2, and worm gear

The final piece to the gear set housing assembly is the worm gear set safety shield (Figure 40). Secured in place with #0-80 screws, the safety shield keeps the user and/or caregiver safe from getting anything caught in the gear set.

7.7 Links

As the principal design element of the overall legrest, the linkage and its associated links had to be designed correctly so they would perform well. In order to perform well, it was important that the linkage stayed in one plane throughout its range of motion, that it didn't have any slop or binding in the joints, and that the links were as light as possible.

7.7.1 Single Plane Linkage

Starting with the first criterion, keeping the linkage in a single plane was important to the smooth operation of the legrest. Any offset between the links would cause the overall linkage to incur some bending due to the moment loads. To achieve this goal of the linkage remaining in one plane, the links were designed to fit and move through one another. In Figure 43, links 2, 4, and 6 are wider than links 3 and 5. By having slots cut into the wider links, the narrower links have room to fit into them, keeping the centerlines of all the links within the same plane.

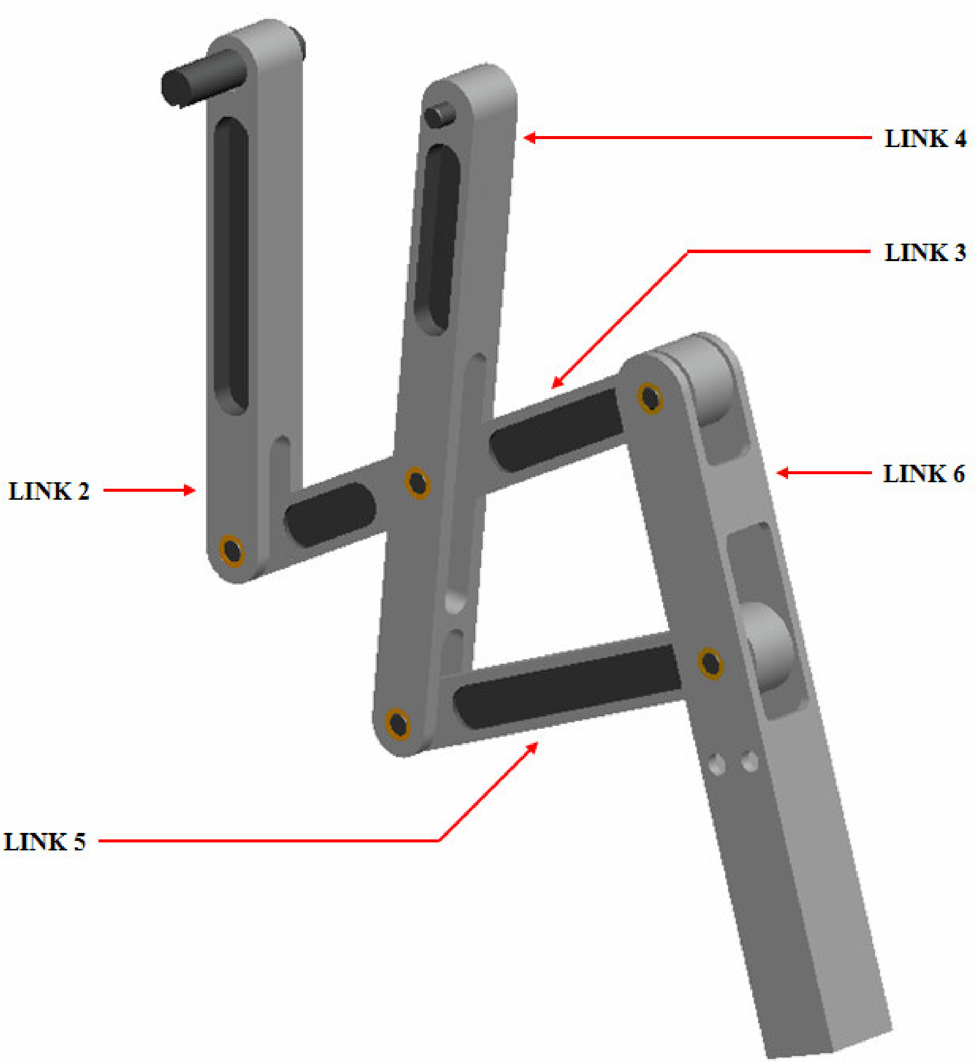


Figure 43: Moving links of legrest sixbar linkage

7.7.2 Joint Construction

The second criterion for the linkages was to make sure the links didn't have any slop or binding in the joints. In the past, WPI MQP groups have had trouble designing secure joints between links that operated smoothly without binding. Smooth operation was a key design specification in this project so it was important to design the joints correctly. As with the ground pivots, the first step in designing the joints was press-fitting bronze bushings into the wider of the two links to be joined. Next, the narrower of the two links was positioned into the slot of the wider link and a stainless steel dowel pin was press-fit into the narrower of the two links (Figure 44). The combination of stainless steel and bronze gave the joint smooth rotation while the careful tolerancing and manufacturing of the press-fit gave the joint a good, compact fit.

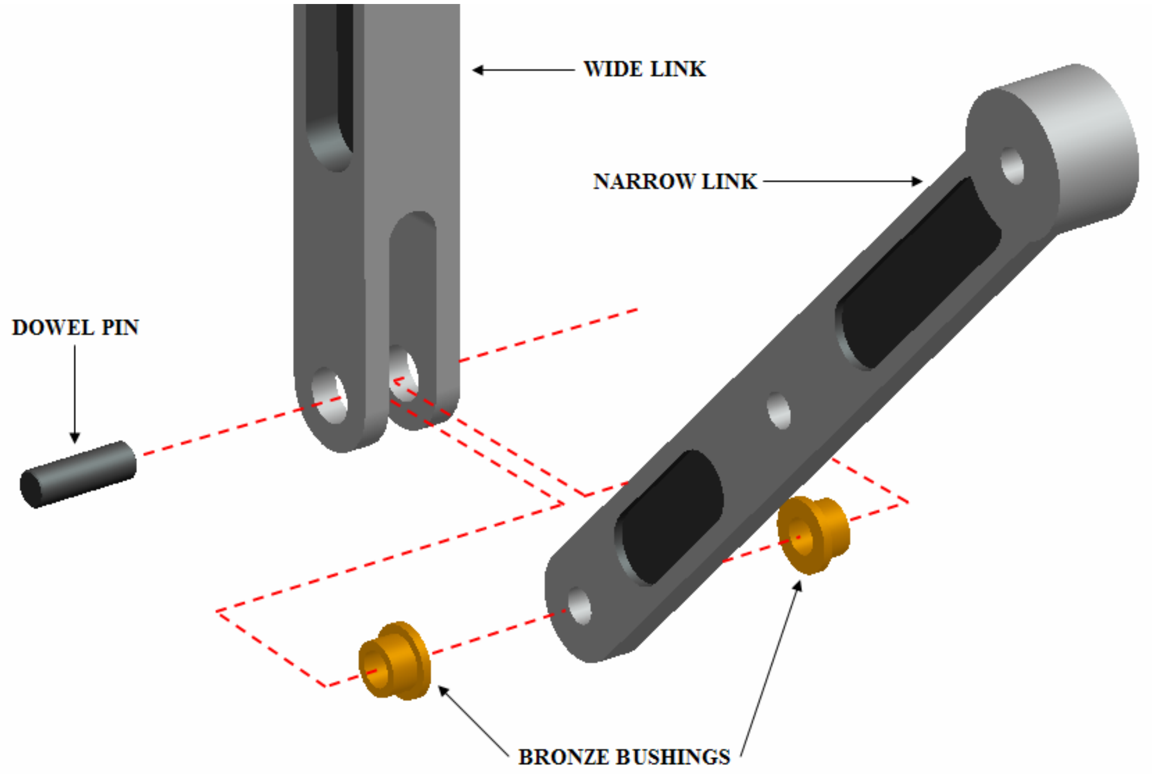


Figure 44: Joint construction between links

7.7.3 Weight Reduction

The final design criterion for the links was to keep them as light as possible. In addition to the weight of the user's leg, the worm gear set elevation method would also have to lift the weight of the legrest itself. Thus weight was always a factor to consider. After each link was designed to be functional, mass relieves were machined to lessen each link's weight as much as possible while not compromising the structural integrity (Figure 45).

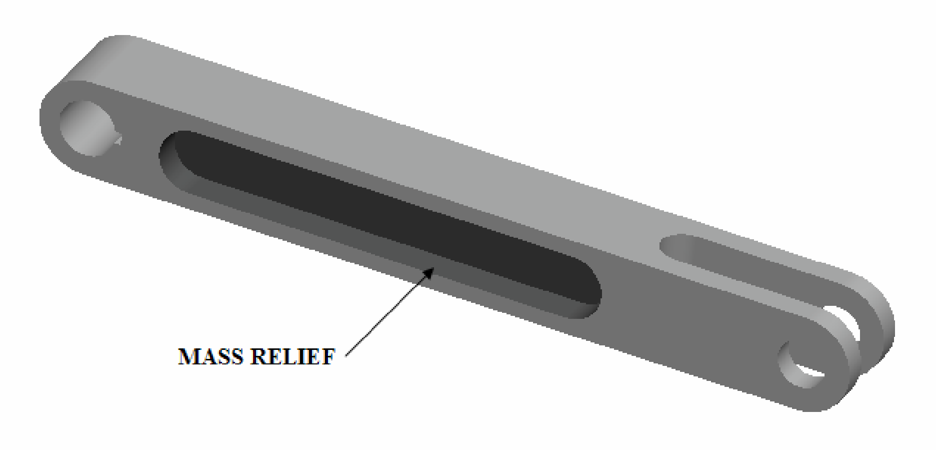


Figure 45: Mass relief of controlling link 2

7.8 Footrest Assembly

The footrest assembly (Figure 46) is attached to link 6 and acts as a support for the user's lower leg and foot in the lowered as well as elevated positions. The primary connection of the footrest assembly to the rest of the linkage is the adjustable square tube. This part was designed such that it can slide in and out of link 6 in the local X-direction and is secured in place using the square tube clamp assembly. Pinned to this adjustable square tube part is the footrest hanger. This part was designed such that it can pivot about the local Y-axis, allowing the footrest assembly to swing up and away to aid in chair transfers. Attached to the footrest hanger is the footrest clamp which is further secured to the actual footrest itself. The footrest clamp, when not tightly held in place, has the ability to rotate in the local Z-axis direction, allowing for some footrest angle adjustability. Fastened at the back edge of the footrest clamp is the footrest strap, which keeps the user's foot from slipping off the back of the footrest in the lowered and elevated positions.

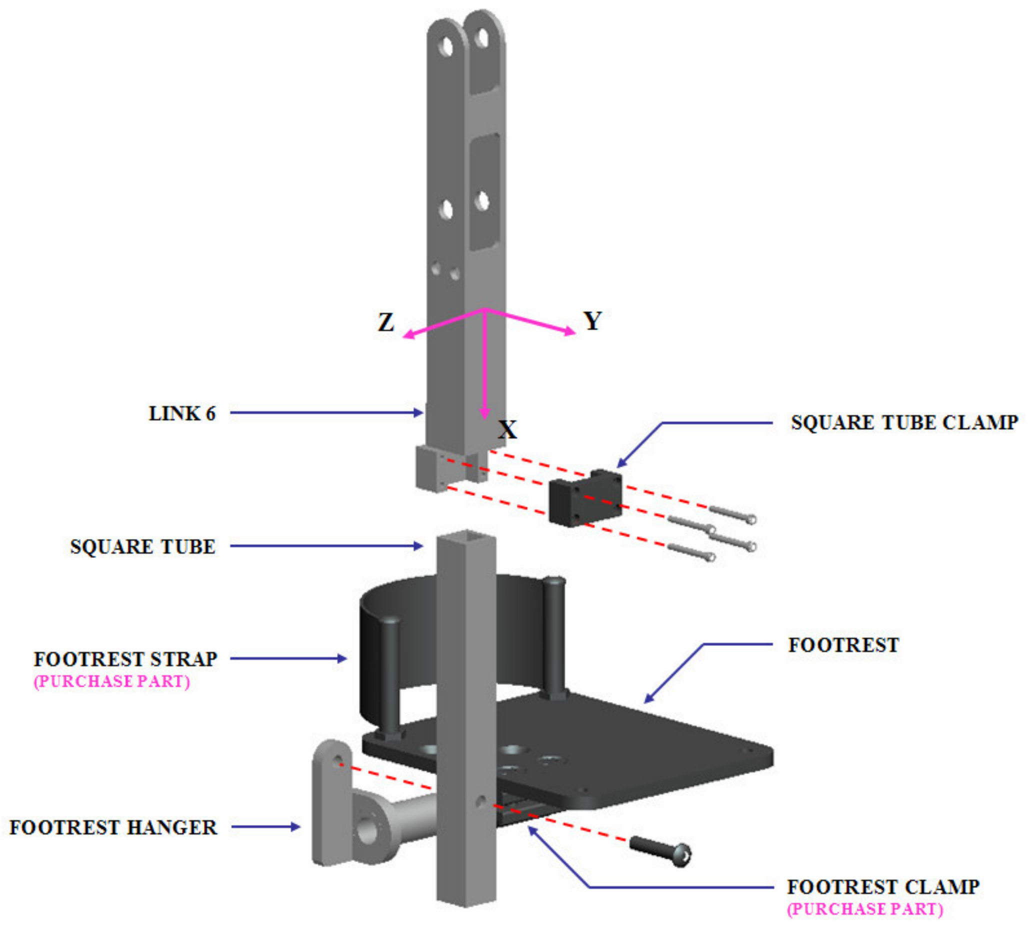


Figure 46: Footrest assembly (exploded) showing all major components

7.9 Calf Support Assembly

In addition to the footrest assembly, the calf support assembly is also critical to the proper support of the user's lower leg. In the elevated position, the calf pad and accompanying assembly support almost the full weight of the user's lower leg. The footrest strap supports the remaining weight.

Like the footrest assembly, the calf support assembly (Figure 47) had to be designed such that it would move with the user's leg throughout the full motion of the legrest. To accomplish this, the calf support part is attached to link 6 with a pair of ¼"-20 bolts. Through an array of taps along the length of the part, the calf support is capable of adjustment in the local Y-direction. The calf pad is secured to the other end of the calf support with a single bolt. By only having one attachment point, the calf pad has the ability to swivel about the local Z-axis, allowing for further fine adjustments.

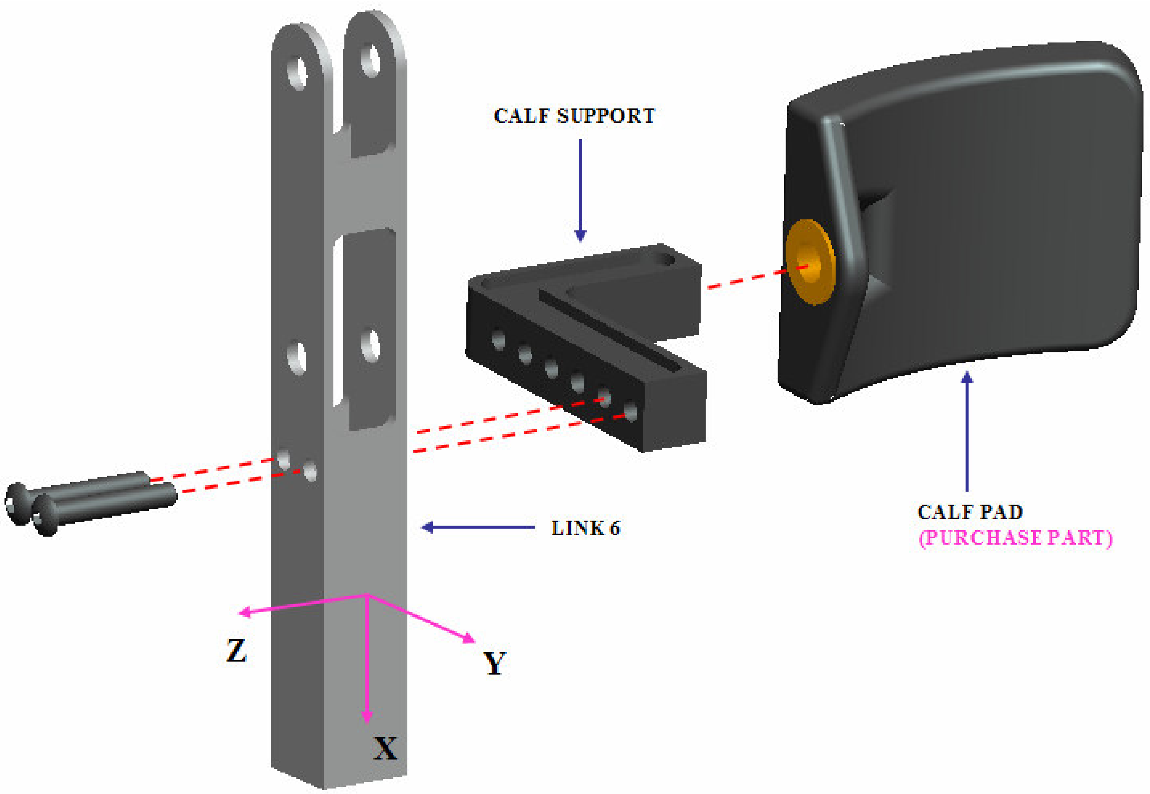


Figure 47: Calf support assembly (exploded) showing calf support, link 6, and calf pad

7.10 Safety

Safety was the most important design specification for the legrest. The following safety measures were incorporated into the design: all the exposed parts throughout the assembly have rounded edges and corners; there are no pinch points accessible to the user during the operation of the device; safety caps (Figure 37) were implemented on the welded tube parts of the wheelchair attachment assembly; and finally, a safety shield (Figure 40) was integrated into the gear set housing to keep the user and/or caregiver safe from getting anything caught in the gear set.

7.11 Final Legrest Assembly

With all sub-assembly designs in place, the final design in its complete form was assembled. Mounted to a standard Quickie manual wheelchair (Figure 48), one can get a general sense of the actual size of the legrest assembly.

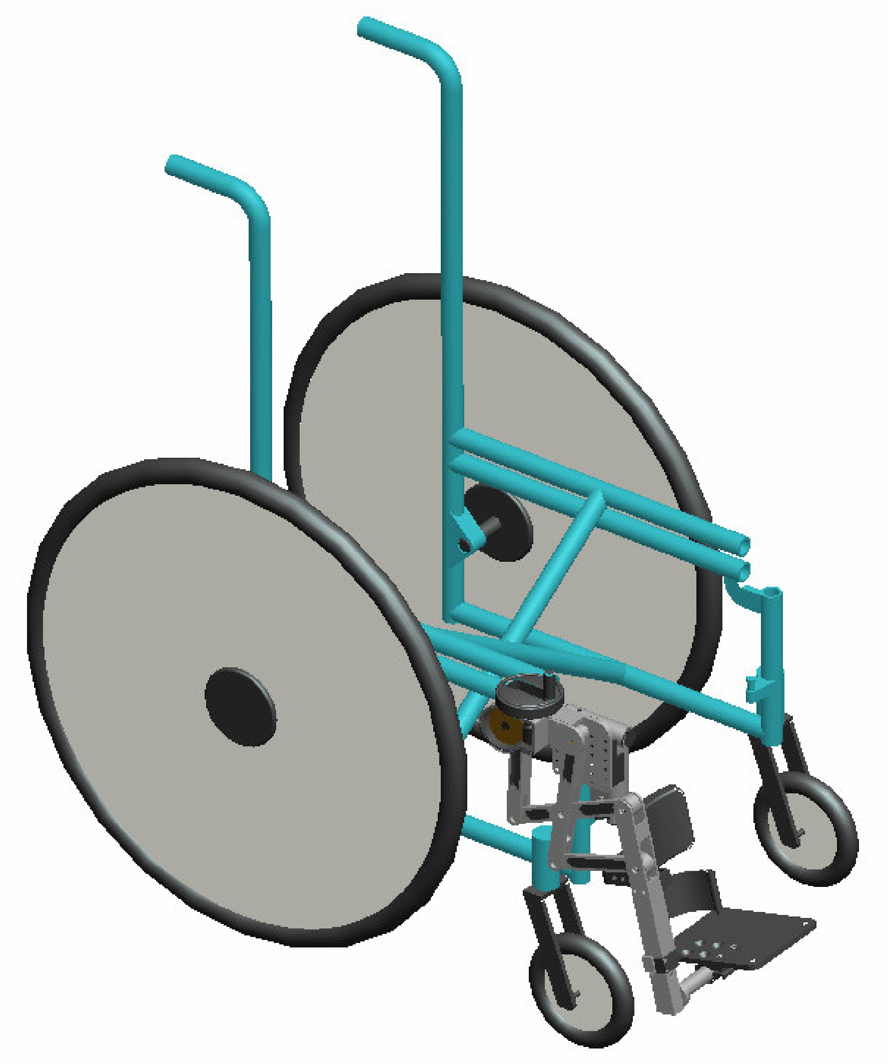


Figure 48: Final legrest assembly mounted on Quickie wheelchair (outboard view)

8 ANALYTICAL LOAD ANALYSIS OF FINAL DESIGN

8.1 Overview

After finalizing the design, the analysis step of the design process was undertaken. This step was divided into three sections:

1) Kinematic analysis
2) Kinetic analysis
3) Stress analysis

Each section is unique and must be analyzed in the order shown. Kinematic analysis, also known as position analysis, must first be performed in order to determine the exact position of all points of interest in the mechanism. The kinetic analysis, also known as force analysis, then implements the results of the kinematic analysis into virtual work equations to determine the forces associated with operating the mechanism. Finally, the stress analysis is performed using the established forces from the kinetic analysis to calculate the stresses in the components. The overall goal of the analysis is to determine whether the system components will fail under the applied loads.

8.2 Kinematic Analysis

The kinematic analysis of a mechanism is typically understood to be the development of equations describing the position, velocity, and acceleration of all points of interest in the mechanism in relation to a chosen primary variable. For this part of the analysis, several assumptions were made:

1) No friction
2) Rigid bodies
3) No backlash
4) Massless members

Starting with position analysis, the primary variable in this case was the angle of the controlling link 2 to the horizontal plane (angle ‘q’ in Figure 49). The primary point of interest was the footrest (point 'I' in Figure 49), and how far that point articulated as the mechanism was activated. Vector loop equations were written such that the primary point of interest was a function of the primary variable. The position analysis was performed using the computer program MathCad® (Appendix A). This allowed one to easily change variables within the mechanism to obtain the desired result. In addition, MathCad's graphical capabilities allowed the user to visually verify that the position analysis was correct (Figure 50 and Figure 51). Figure 51 shows the position of instant center 1-6 as the linkage moves through its range of motion.

After completing the position analysis, the velocity and acceleration analyses were performed. Once the vector loop equations were written in MathCad®, it was very easy to obtain the velocity and acceleration equations as they are the direct time derivatives of the vector loop equations. Again, MathCad's graphing capabilities were used to visually analyze the velocity and acceleration of the mechanism.

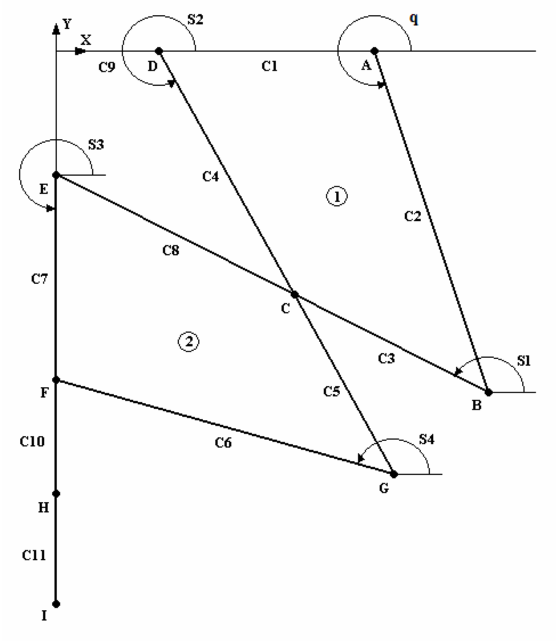


Figure 49: MathCad analytical analysis diagram showing the system's primary variable (q) and the primary point of interest (I)

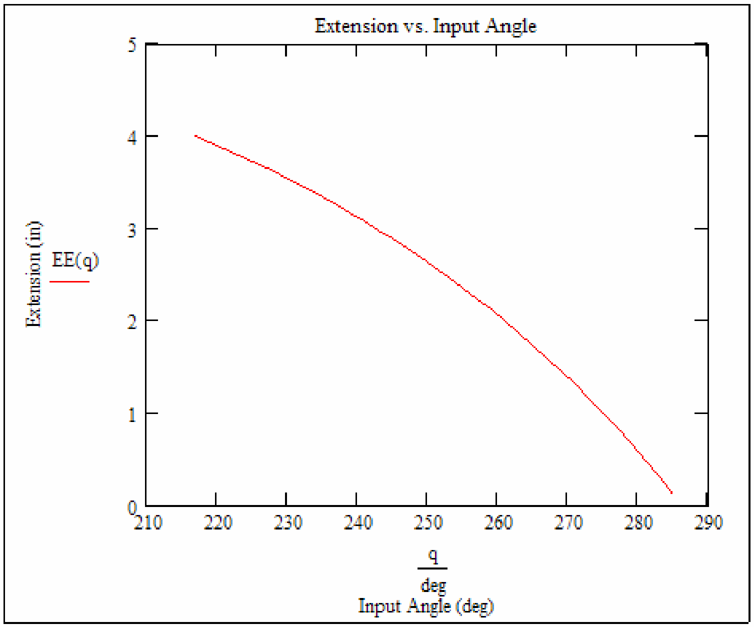


Figure 50: Legrest extension versus input link angle obtained from MathCad® computer program

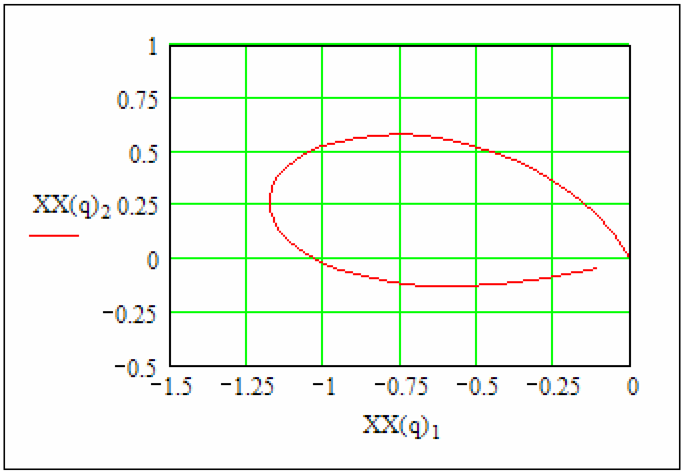


Figure 51: Trace of instant center 1-6 location through entire motion of legrest – starting in the down position and moving in a clockwise motion (inches)

8.3 Kinetic Analysis

8.3.1 Overview

Once the kinematic analysis was complete, the next step in the analysis of the design was kinetic analysis. Kinetic analysis, also known as force analysis, is used to determine the forces associated with the mechanism's movement. Most importantly, this analysis was used to determine the input torque necessary to activate and operate the system throughout its range of motion for a given loading condition. The two loading conditions analyzed in this design were a normal load from a 50th percentile human and a maximum load contingent on design specifications for a wheelchair legrest. The principle of virtual work was used for this analysis.

8.3.2 Virtual Work

The principle of virtual work is an energy solution method which works by turning a dynamic system into a static system and then solving the system of equations for the input force. Work is defined as the dot product of force and displacement. Modifying this definition, *virtual work* can be defined as the dot product of force and *virtual displacement*. "The term virtual work comes from the concept of each force causing an infinitesimal, or virtual, displacement of the static system element to which it is applied over an infinitesimal delta time" (Norton, 2004). At this minute level, these virtual work terms can be categorized as the instantaneous power of the system. Power is further defined as the time rate of change of energy. Working backwards, at an infinitesimal delta time, work can be considered instantaneous power which can further be considered instantaneous energy. Under the law of conservation of energy, energy can neither be created nor destroyed, only converted from one form to another. Therefore, the work done by external forces and torques on the system must be matched by the input force or torque on the system. Only external forces and torques are considered with this solution method as these are the only ones doing work; forces at the pin joints between links have no relative displacement between them and thus do no work on the system.

The MathCad® computer program calculated the force needed not only to activate the mechanism, but to operate it throughout its range of motion as well. For this part of the analysis, the same assumptions as the kinematic analysis applied except for the massless members assumption; in this part of the analysis, the masses of the links and their adjoining structures were considered.

8.3.3 Normal Torque Loadings

Anthropometric data was used to determine the weight of an average human. Using 50th percentile data, the average weights of an adult man and an adult woman were found to be 171-lbf and 130-lbf, respectively (Seireg, 1989). The average of these weights calculates out to be 150.5-lbf. This figure was used as the weight of a typical manual wheelchair user under normal operating conditions.

Using the concept of virtual work, the torque loadings on the worm gear shaft and worm shaft were calculated for an average user using the legrests. A linear system of equations which took into account all external forces and their corresponding virtual displacements was implemented and solved. External forces included the weight of the individual link assemblies, found using Pro/Engineer's *model analysis* function, and the weight of the user's lower leg (Figure 52).

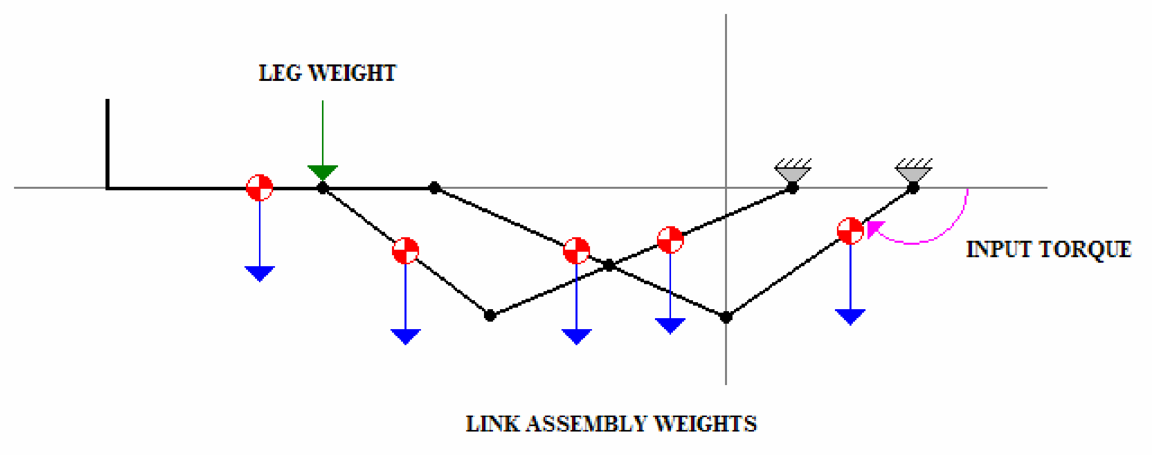


Figure 52: Virtual work diagram showing external forces and input torque

The weight of the user's leg was calculated from the following equation (Seireg, 1989):

$$Weight_{leg} \cong 0.06 * Weight_{user} \tag{1}$$

For the predetermined 150.5-lbf average user, the weight of that user's lower leg would be approximately 9-lbf. With all variables in place, the torque on the worm gear shaft assembly was found to be 64.9 in-lbf in the lowered position and 159 in-lbf in the elevated position (Appendix A). Knowing the gear ratio within the worm gear set, the torque on the worm shaft assembly was found to be 2.16 in-lbf in the lowered position and 5.28 in-lbf in the elevated position (Table 4). It is important to note that this required input torque of 5.28 in-lbf from the user falls well below the imposed design specification limit of less than 15 lbf, which should make the design easy to use.

8.3.4 Maximum Torque Loadings

The design specifications contain additional loading requirements: 1) a wheelchair legrest must be able to withstand a vertical force of 150-lbf in the lowered position (Figure 53) (RESNA, 1991) and 2) a wheelchair legrest must be able to withstand a downward force equal to three times that of a user's lower leg (60-lbf maximum) in the elevated position (Figure 54) (Woodson et al., 1992). Two additional virtual work equations were developed to test these maximum loading conditions. Initial analyses showed that the 60-lbf elevated loading condition caused a more severe torque on the controlling link and worm gear shaft than the 150-lbf lowered loading condition. To save time and space, only the 60-lbf loading condition will be discussed and shown in Appendix A.

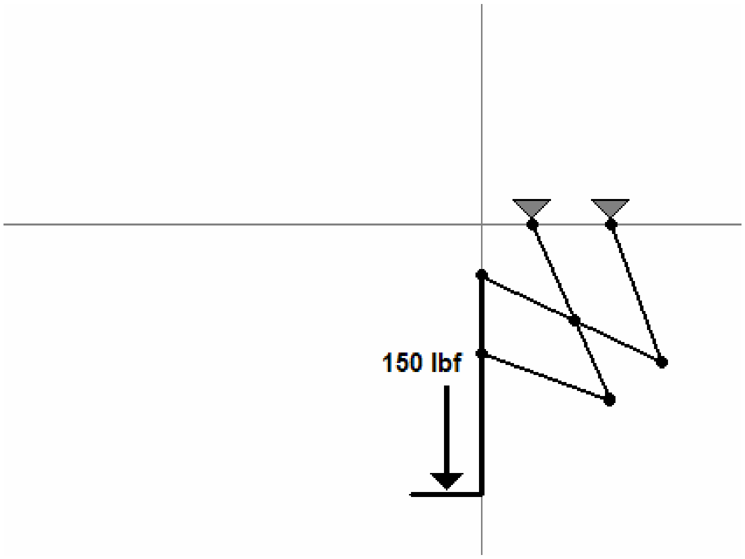


Figure 53: Maximum loading condition #1: 150 lbf in lowered position

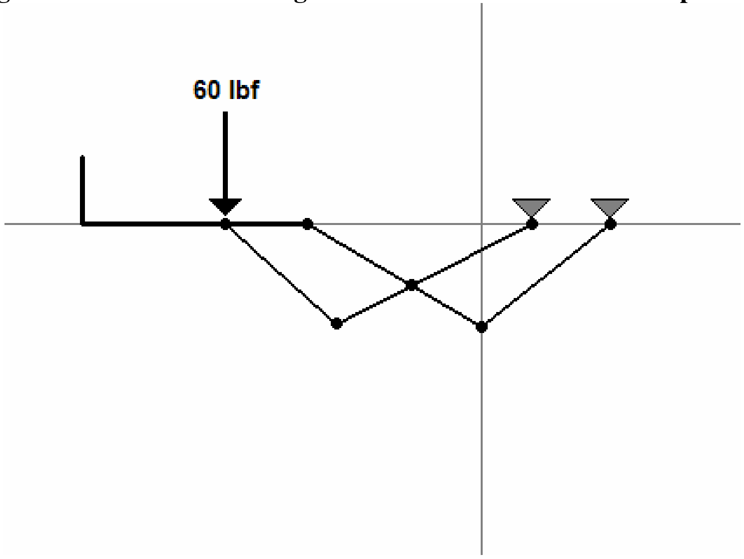
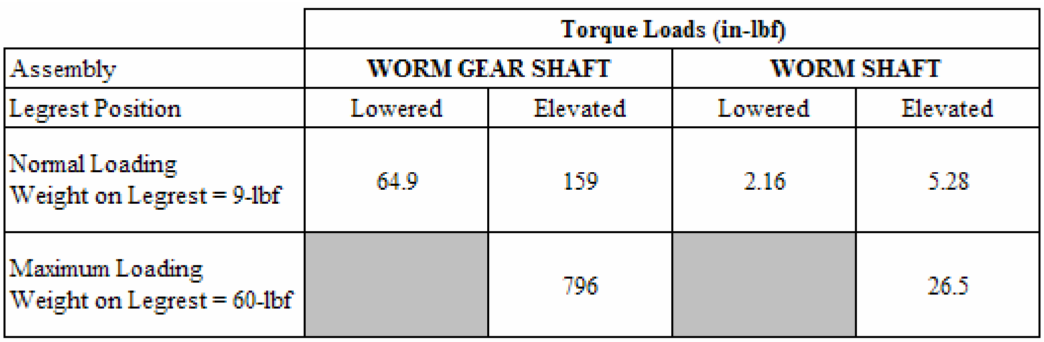


Figure 54: Maximum loading condition #2: 60 lbf in elevated position

With the maximum load of 60-lbf in place of the original 9-lbf normal load, the new system of equations for the torque on the worm gear and worm assemblies was once again solved. From these equations, it was found that the torques on the worm gear shaft and worm shaft in the elevated position were 796 in-lbf and 26.5 in-lbf, respectively (Table 4).

Table 4: System loading conditions and the resultant torque loads on system components



	Torque Loads (in-lbf)			
Assembly	**WORM GEAR SHAFT**		**WORM SHAFT**	
Legrest Position	Lowered	Elevated	Lowered	Elevated
Normal Loading Weight on Legrest = 9-lbf	64.9	159	2.16	5.28
Maximum Loading Weight on Legrest = 60-lbf		796		26.5

8.4 Stress Analysis

Once the kinetic analysis was complete, the final step in the analysis of the design was stress analysis. Stress analysis plays an important role in mechanical design as it determines if the applied loads to the system are large enough to cause a failure in any of the system components. The legrests are only going to be used a few times per day. Thus, for the stress analysis of this legrest design, one can consider the applied loads to be static. The total number of cycles over the product’s lifecycle does not warrant a fatigue analysis.

Preliminary analyses were performed on the linkage part of the design to determine whether any of the links would fail or have a low safety factor under the maximum loading condition. Static two-dimensional and three-dimensional force analyses were performed on the linkage to determine the pin forces at the joints and the torque on the legrest link 6 (Appendix B). The pin forces were then used to determine the loading conditions on the links. Links 3 and 5 were specifically analyzed because of their smaller cross-sectional areas. Link 5 was shown to incur a compressive force of 94.5-lbf while link 3 was shown to have a bending moment of 189 in-lbf. Safety factors of 98.8 and 5.53 for link 5 and link 3, respectively, were determined knowing the material yield strength. Both these safety factors were high enough to consider these components non-critical. Link 6 was analyzed for its torque loading. Under the maximum loading condition of 60 lbf of applied force, link 6 incurred a torsional load of 300 in-lbf due to the fact that the weight of the leg is supported by the calf support and footrest which are inboard of link 6 (Figure 31). The factor of safety under this torsional load was determined to be 28.71. This safety factor was high enough to consider link 6 non-critical. The following components were considered critical due to their low factors of safety.

8.4.1 Gear Shaft Stress Analysis

The torsional shear stresses on the gear shaft were determined from the applied torque loads from the kinetic analysis. For the normal loading setting with the legrest in the elevated position, the torque load applied to the worm gear shaft was found to be 159 in-lbf. Combining this information with the shaft's geometry components of radius and polar moment of inertia, the torsional shear stress was found to be 9.64 ksi. Taking into account the shaft material's yield strength, the safety factor against yield failure from this load was found to be 7.99.

For the maximum loading setting, the torque load applied to the worm gear shaft while the legrest was in the elevated position was found to be 796 in-lbf. The resulting torsional shear stress and ensuing safety factor against yield failure for the shaft were found to be 48.4 ksi and 1.59, respectively (Table 5).

8.4.2 Worm Shaft Stress Analysis

The torque load applied to the worm shaft during the normal loading setting with the legrest in the elevated position was found to be 5.28 in-lbf. Knowing the worm shaft's geometry, the torsional shear stress under this torsional load was found to be 3.97 ksi. Again, taking into account the worm shaft material's yield strength, the safety factor against yield failure from this load was found to be an impressive 19.4.

For the maximum load setting, the torque load applied to the worm shaft while in the elevated position was determined to be 26.5 in-lbf. The resulting torsional shear stress and yield strength safety factor for the shaft were found to be 19.9 ksi and 3.87, respectively (Table 5).

8.4.3 Gear Hub Stress Analysis

The final component to be analyzed for possible torsional shear stress failure was the hub portion of the worm gear. The torsional shear stress on the hub was found to be 2.16 ksi for the normal loading condition and 10.9 ksi for the maximum loading condition. The safety factors against yield failure were determined to be 21.7 for the normal loading condition and 4.33 for the maximum loading condition (Table 5).

Table 5: Torsional shear stress and yield strength safety factors for system components

System Component	WORM GEAR SHAFT		WORM SHAFT		WORM GEAR HUB	
Material	Steel		Steel		Bronze	
Yield Strength (ksi)	77		77		47	
	Torsional Shear Stress (ksi)	Yield Strength Safety Factor	Torsional Shear Stress (ksi)	Yield Strength Safety Factor	Torsional Shear Stress (ksi)	Yield Strength Safety Factor
Normal Loading Weight on Legrest = 9-lbf	9.64	7.99	3.97	19.4	2.16	21.7
Maximum Loading Weight on Legrest = 60-lbf	48.4	1.59	19.9	3.87	10.9	4.33

The normal loading safety factors for the critical components were very respectable, ranging from 7.99 for the worm gear shaft to 21.7 for the worm gear hub (Table 5). Under the maximum loading conditions, the worm gear shaft and hub safety factors ranged from 1.59 to 4.33, respectively. These lower safety factors are considered to be adequate given that the maximum loading condition is an extreme case which would not occur often, if ever. Most standard wheelchairs are designed for a maximum user weight of 265-lbf. A legrest loading of 60-lbf corresponds to a user weight of approximately 333-lbf. A person of that weight would likely be using a specially designed chair called a bariatic chair which can support a user weight up to 450-lbf.

9 PROTOTYPE CONSTRUCTION

The prototype construction phase of the project was undertaken after the completion of the final design analysis. A primary goal of producing a design prototype was to have a manual wheelchair user test the legrests and provide some important feedback. A secondary goal of producing a prototype was to expose any inherent design problems that had not been previously revealed in the analysis phase. A prototype was built and assembled to meet these goals.

9.1 Manufacturing

By this point in the design process, all of the system parts and assemblies had been modeled using the CAD software Pro/Engineer. From the individual part files, drawings were produced for each part specifying all necessary dimensions, materials, and tolerances (Appendix B). The majority of parts to be machined were made from wrought aluminum alloy (6061-T6 or 7075-T6 grade) while a few of the parts such as the worm and worm gear shafts were made from carbon steel (AISI 1045).

To manufacture the individual parts, one of two machining methods were implemented: manual machining or computerized numerically controlled (CNC) machining. The majority of the system's parts were manually machined using a Bridgeport 3-axis manual milling machine or a 36" manual lathe in the WPI machine shop located in Higgins Laboratories. The remainders of parts were CNC-machined using a HASS 3-axis CNC milling station in the WPI machine shop located in Washburn Shops. These parts, which included the two ground links, Quickie wheelchair attachment bracket, and gear set shield, were chosen to be CNC-machined due to the curved profiles and features each possessed. The computer-aided manufacturing (CAM) software

GibbsCam was used in partnership with Pro/Engineer to produce the G-code needed by the CNC milling machine.

9.2 Assembly

Once all the individual parts were machined, the assembly process began. This procedure consisted of first bringing together individual parts into sub-assemblies and then combining those sub-assemblies into the fully-completed, final assembly (Figure 55 & Figure 56).

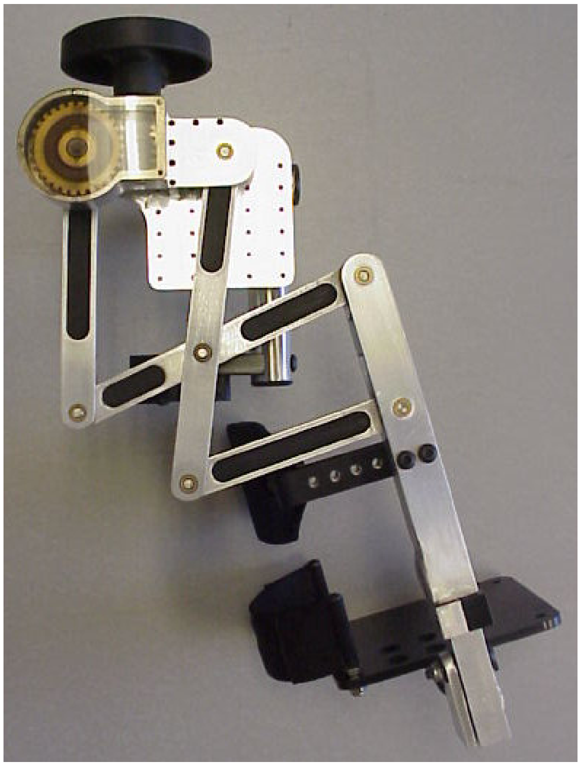


Figure 55: Prototype assembly - right legrest, outboard view

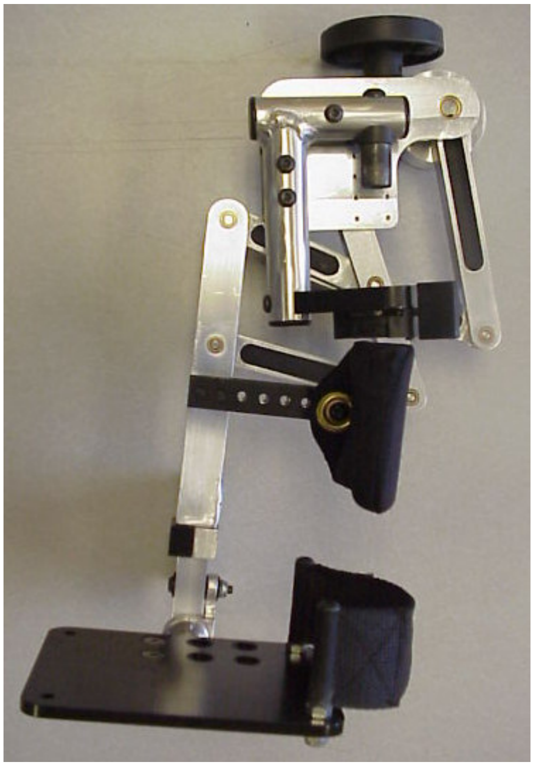


Figure 56: Prototype assembly - right legrest, inboard view

The bulk of the design was assembled using standard screw fasteners and dowel pins; very few weld joints were used and only in the case where screw fasteners were impossible or impractical. Screws are a lot easier and faster assembly method than welding aluminum and they also offer a cleaner final look.

Once assembled, the legrest prototypes were attached to a standard Quickie wheelchair to check for form, fit, and function (Figure 57 through Figure 60). The legrests were attached to the chair and then individually elevated and lowered to be sure there were no interferences with the wheelchair frame, casters, or wheel locks.

Figure 57: Standard Quickie wheelchair with legrest prototypes attached in the lowered position

Figure 58: Quickie wheelchair with legrest prototypes attached - one lowered, one elevated

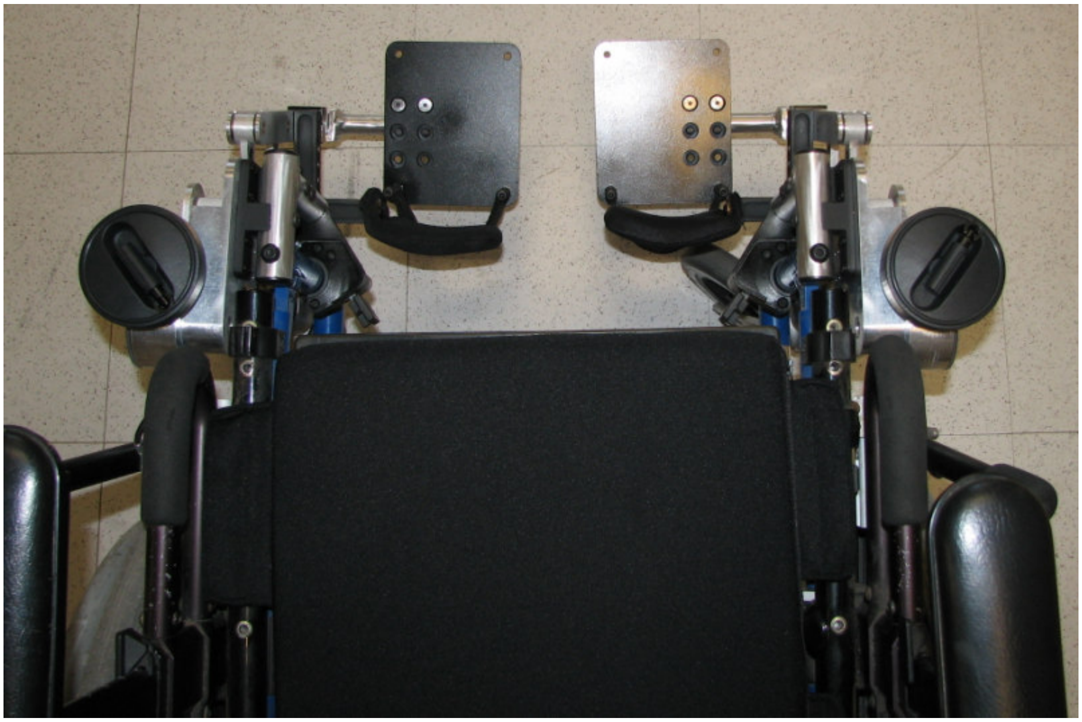


Figure 59: User's view of legrest prototypes attached to Quickie wheelchair in the lowered position

Figure 60: Standard Quickie wheelchair with legrest prototypes attached in the lowered position - front view

9.3 Cost

The total cost of the materials for the legrest prototypes was $367.63. The overwhelming majority of this cost came from the purchased hardware with the biggest contributions coming from the handwheels and worm gear sets. The only stock materials purchased were the aluminum square tubes and the various key stocks for the shaft keyways; all other materials were acquired from the WPI machine shops. All individual purchases are included in the bill of materials (BOM) (Appendix C).

10 MHS TESTING & EVALUATION

10.1 Overview

Upon completion of the prototypes, the testing and evaluation stage of the project was carried out. Accurate real life feedback can only be obtained from a test client familiar with the everyday use of typical elevating legrests. With the help of Gary Rabideau from the Massachusetts Hospital School (MHS), a student named Andy was chosen to be this project's test client. Andy is a young man afflicted with spina bifida, leaving him with no control of his legs and a minimized functional dexterity of his upper body. He is a day student at MHS and currently uses a Quickie II manual wheelchair with standard, elevating legrests.

To obtain the needed feedback, Andy was asked to use the legrest prototypes for a period of no less than five days. Seemingly enthusiastic at the opportunity, Andy graciously agreed. The legrest prototypes were dropped off at MHS on Wednesday, February 8, 2006 to be tested the following week. On Monday, February 13, 2006, Gary met with Andy in the morning to set up the legrests on Andy's wheelchair. To obtain some direct comparative feedback, Gary only set up the left legrest prototype on Andy's chair, leaving the standard Quickie elevating legrest on the right (Figure 61). This allowed Andy to compare and contrast the two designs as he used them throughout the week.

Several adjustments had to be made to the legrest prototypes before Gary could let Andy use them. First, some standard vertical and horizontal adjustments were made to the mounting system so that the pivot point of the linkage matched the user's knee pivot. Next, blocking was added to the footrest to provide the same cushioning as his original legrest and to reduce the overall leg length (Figure 61). Andy was somewhat of a unique test case in that the lengths of his lower legs are very short and the position of his knees was well above the wheelchair frame. Third, in order to provide more leg support, the calf pad was substituted with a larger calf pad similar to that of Andy's original legrest. The final adjustment was a reconfiguration of the wheel lock. Andy's original wheel lock was a push-to-lock system which interfered with the user interface for the prototype when in the locked position. Gary substituted this with a pull-to-lock system which kept the user interface obstacle-free.

Figure 61: Test client Andy with original elevating legrest on his right and the adjusted legrest prototype on his left (including footrest blocking, larger calf pad, and pull-to-lock wheel lock)

Throughout the week from February 13, 2006 to February 17, 2006, Andy used the legrest prototype on a daily basis during school hours. Gary did not feel comfortable leaving the legrest prototype on full time so he kept it on during the day and took it off in the afternoon when Andy left the school. On February 17, 2006, a return trip was made to MHS in the late afternoon to collect the legrest prototypes and obtain some feedback from both Gary and Andy.

10.2 Positive Feedback

After one week of testing, both Gary and Andy had several positive feedback points on the legrest prototypes. Gary identified the biggest and most important advantage of the prototype's design over that of commercial designs as the independent activation by the user. Gary mentioned that most commercial elevating legrest designs require the additional aid of a caretaker to elevate and lower the legrests. By giving the users the ability to operate the legrests themselves, they are more likely to do it more often and it gives them a sense of independence. Andy seconded this point, saying that on a daily basis he would elevate the legrests himself about four times, each time for approximately fifteen minutes.

Another point made by Gary and Andy was the smooth, consistent elevation of the legrests as well as their functional articulation. Andy said that the legrest was easy to use and that he could fully elevate it with one hand, though it got "a little tougher as it got higher." In terms of functional articulation, Gary was very pleased with the design. He liked how it accommodated the true leg extension while elevating. Andy agreed saying his knee was able to stay straight when elevated on the prototype legrest, while his other knee was bent when elevated on the original legrest. In addition to being bent, Andy's knee also rotated inward as a result of his original legrest pushing back on his leg (Figure 62). An important point to be made is that because of Andy's unusually short lower leg lengths and knee position with respect to the wheelchair frame, the correct placement of the prototype legrest was unobtainable. For these reasons, the arc of the legrest extension was slightly skewed from the correct position and caused Andy's foot to be away from the footrest in the elevated position. Gary did not feel this was a problem since the leg was still fully supported by the calf pad. He further indicated that too much extension is far better than too little extension.

Figure 62: Test client Andy with legrests in elevated positions - the leg on the prototype legrest is able to stay straight while the leg on the original legrest is bent and rotated inward

Additional positive feedback from Gary and Andy included the adjustability of the legrest. Gary felt the knee axis adjustment was very useful as it is important for the correct and effective elevation of the user's leg. Andy also mentioned the angle of the legrest in the lowered position was an improvement as it could be positioned even lower than his original legrest (Figure 63). One final positive point made was on the aesthetics of the design. Gary felt it was a very thoughtful, user friendly design that was well fabricated. Andy said it "looked cool."

Figure 63: Test client Andy with prototype legrest (foreground) shown to have greater flexion than original legrest (background)

10.3 Points for Improvement

Besides positive feedback, Gary and Andy as well as Andy's nurse had some constructive criticism to offer as well. The biggest point for improvement they all saw was the swing-away legrest attachment system. Typical swing-away legrest attachment systems work by swinging the legrest outward, away from the user's legs. This, unfortunately, was not possible with this project's attachment system due to the Quickie attachment bracket being in the way of the linkage's movement if placed on the outboard side of the mounting system. Instead, what was done was to move the attachment bracket to the inboard side of the mounting system, causing the swing-away system to swing inward towards the user's legs to be removed. Unfortunately, this caused difficulty for the various personnel working with Andy throughout the week who needed to remove the legrest for transfers.

Another point for improvement was the interference between the user interface handwheel and the push-to-lock style wheel lock. As was stated earlier, the original wheel lock on Andy's wheelchair was a push-to-lock system which got in the way of the user interface handwheel when in the locked position. Gary had to substitute for this with a pull-to-lock system in order to be able to lock the wheels and operate the handwheel at the same time. Andy's nurse noted in her questionnaire (Appendix D) that she had to remind Andy a couple times of the different style brake action. Though this isn't a major problem, an ideal design should be able to accommodate all standard wheel lock systems and not be restricted to just one.

While the legrest's elevation was smooth and consistent, the lowering was found to have some intermittent chatter. This was most likely caused by a combination of the torque applied to the legrest linkage from the weight of the user's leg and the dry friction and/or backlash of the worm gear set. All those interviewed described it in their own way: Gary described it as "occasional choppiness going down"; Andy's nurse described it as "an awkward bounce during lowering"; Andy himself described it as "a little jiggly going down." Though they all mentioned it, none found it diminishing to the function of the design, just a little unusual.

One final point for improvement mentioned by Gary in his questionnaire (Appendix D) was a minor concern regarding the durability and/or protection of the legrest system if a significant frontal impact were to occur. Specifically, he was concerned about how the linkages would fare when impacted by another wheelchair user. Andy's nurse also noted this, questioning the overall durability of the legrest system.

10.4 Overall Assessment

The overall assessment from MHS was very positive. One important result was that the test client Andy expressed considerable satisfaction with the legrests. One could have a seemingly flawless design but if the eventual end user doesn't like it, it's not going to be used or be successfully commercially. Gary had a lot of positive things to say about the design as well. He thought it was a well thought-out design: creative, functional and potentially very beneficial to the user. He really appreciated the advantage of the independent elevation by the user in addition to the functional articulation and adjustability. Conversely, he felt the one significant impediment to the market application of this design was the swing-inward feature. This would need a revision before the design could be finalized. Andy's nurse echoed the remarks of Gary stating the self-elevation feature offers excellent benefits while the swing-inward feature would need to be changed.

11 SUMMARY

The goal of this thesis was to design and manufacture a user-operated, elevating legrest that accurately follows the natural arc of the user's leg. The final design elevates and articulates simultaneously from a single user interface, allowing the user's leg to be straight in the elevated position. The ability for the user's leg to be straight when elevated increases one's comfort level as well as prevents certain ailments such as pressure sores and lower extremity swelling from developing.

Careful consideration was paid to all aspects of the design to ensure the design specifications were met. In terms of function, the final design's worm gear set allows for the legrest to be locked securely in place at an infinite number of locations between the lowered and elevated positions. Adjustability of the design accommodates users with lower leg lengths ranging from 15 to 19 inches. Additional adjustments to the legrest pivot location in the horizontal and vertical directions allow for different sized seat cushions and femur lengths between users. For performance/operation, the design is easy for the user to operate, requiring less than 5.3 in-lbf of torque under normal loading conditions. In terms of size, the final design has no components that extend beyond the top of the seat cushion. In addition, the design remains within the width of the wheelchair wheels, keeping the overall width of the chair the same. For weight, each legrest prototype weighs approximately 4.93-lbf, staying under the self-imposed 5-lbf limit. In terms of strength, the final design's key components (gear shaft, worm shaft, gear hub) were strong enough to withstand the maximum imposed loading conditions and still retain a reasonable safety factor against yield failure. The final design is safe, having no pinch points or sharp edges of any kind. Additionally, the worm gear set and circular pipe ends are shielded with protective plastic coverings. Finally, the design is aesthetically pleasing, having a marketable quality.

Beyond design specifications, the final design was tested by a wheelchair user named Andy. A student at Massachusetts Hospital School (MHS), Andy tested the legrest design for a period of one week. Afterwards, Gary Rabideau, the Director of Rehabilitation Engineering at MHS had several points of positive feedback to make on the design. Gary felt the user-operated elevation aspect of the design was a big advantage over other elevating legrests, giving the user a sense of independence as well as encouragement to elevate their legs more often. He also liked the smooth, consistent elevation of the legrests in addition to their functional articulation. Andy really liked the design as well, saying it was easy to use and “looked cool.”

Besides positive feedback, some constructive criticism was offered as well. Gary felt the biggest problem with the design was the swing-inward feature of the wheelchair mounting system. He saw this as the biggest market-impediment of the design and that would have to be changed. In addition, there was some interference between the design’s user interface and the push-to-lock style brake on Andy’s chair. Though Gary was able to switch the brake to a pull-to-lock style to resolve the problem, he felt a revision to the working envelope of the design may be necessary to allow for all brake styles. Lastly, there was some mild concern from Gary as well as Andy’s nurse regarding the durability of the legrests. They were worried about how the linkage components would fare if a frontal impact with another wheelchair were to occur.

12 FUTURE WORK/RECOMMENDATIONS

Based on the feedback received from Gary, Andy, and Andy's nurse from MHS, several improvement recommendations were developed for future revisions of the design. The first and most important needed improvement was the swing-inward mounting system. As was described in chapter 10, the typical swing-away mounting system used by most Quickie manual wheelchair legrests had to be altered for this design. Due to the Quickie attachment bracket being in the way of the linkage's movement if placed on the outboard side of the mounting system, it was moved to the inboard side of the mounting system, causing the swing-*away* system to become a swing-*inward* system. This caused some difficulty for those trying to remove the legrests from Andy's chair for transfers during the week of testing at MHS. To solve this problem, Gary suggested switching the mounting system from a swing-away hanger design to a lift-off hanger design (Figure 64).

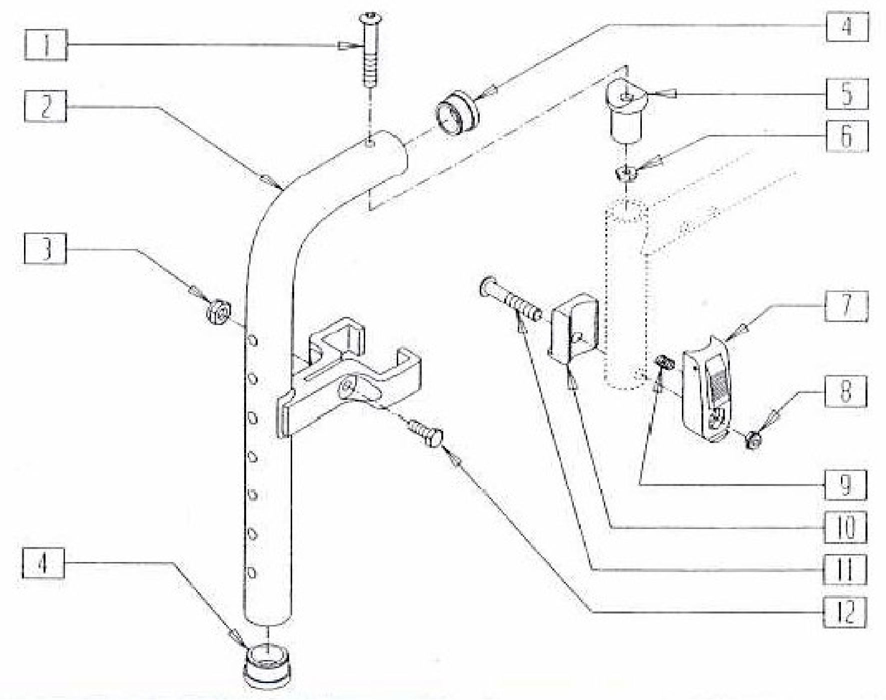


Figure 64: Quickie lift-off frame hanger (exploded) (Quickie, 2004)

The lift-off hanger design differs from the swing-away hanger design by removing the rotate-to-lock-in-place feature. The design works by vertically lowering the hanger bracket over the spring-loaded blocks (#7 & #10 in Figure 64) secured to the wheelchair frame. Once the hanger bracket gets beyond a certain point, the spring-loaded locks snap into place, securing the assembly (Figure 65). To remove the hanger assembly, the user or caregiver pushes in the spring-loaded locks and lifts the assembly off. This type of mounting system would stay out of the way of the linkage's movement and be easy to remove at the same time.

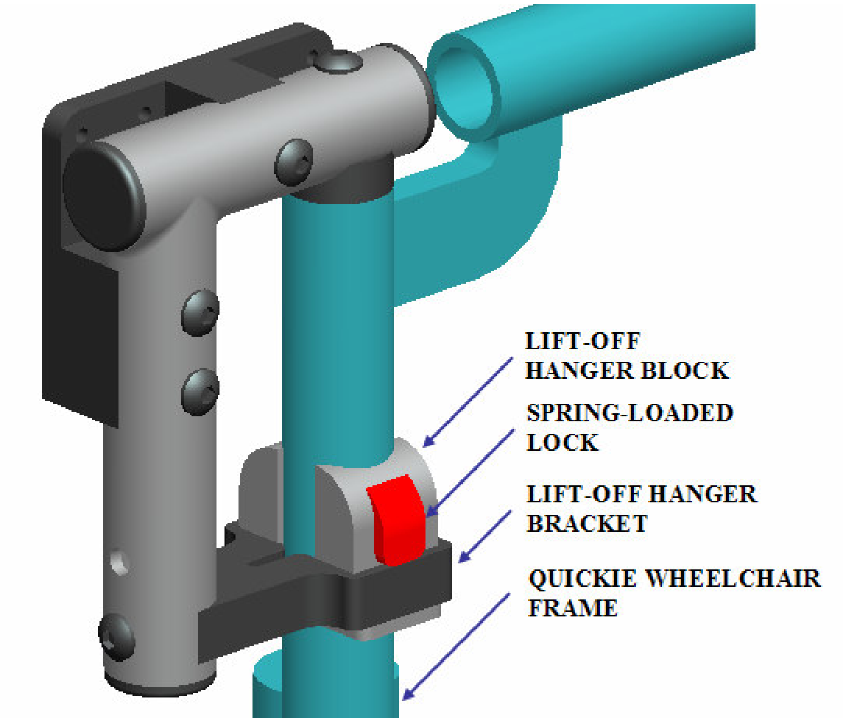


Figure 65: Quickie lift-off hanger system CAD model shown attached to a Quickie wheelchair frame

Another opportunity for improvement is the design of the legrest's linkage. Currently, the links are somewhat long and slender, posing not only working envelope problems, but a durability problem as well. Redesigning the linkage to achieve the same articulation as the current setup while using shorter links would improve the design.

Shorter links would shrink the working envelope of the system and because the links are shorter, they could be made thicker without affecting the overall weight. Thicker links would help improve the overall durability of the linkage.

One final improvement opportunity could be in the worm gear set design. A gear set with a higher gear ratio could be used to lessen the required input torque to the system, making it even easier for the user to operate. Since the worm already has the minimum number of teeth (one), it would be necessary to find a worm gear with a higher number of teeth than the current design possesses. As noted in Chapter 7, the greater the number of teeth on a worm gear, the greater the diameter of that worm gear tends to be. A careful search would need to be conducted to find a suitable worm gear set that had a higher gear ratio but didn’t increase the working envelope of the system.

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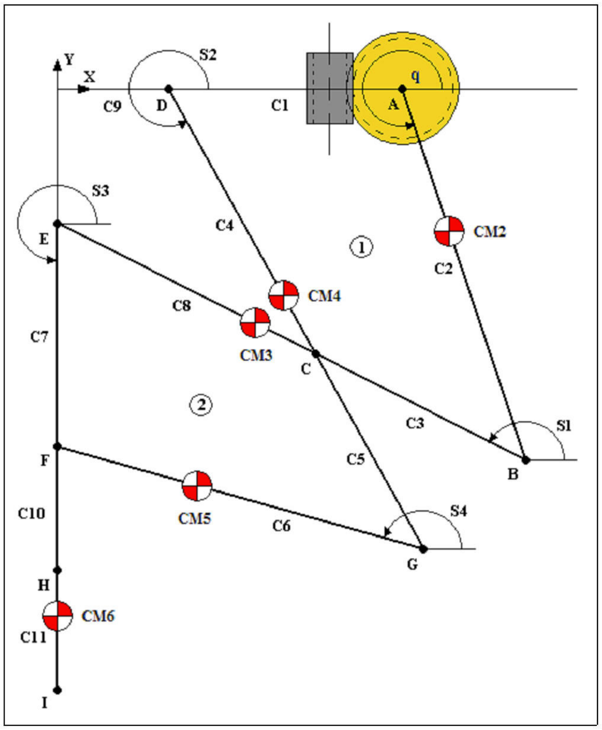
APPENDIX A – MATHCAD ANALYTICAL ANALYSIS

Kinematic Analysis

In this section of the analysis, all the system variables and constants are defined. The vector loops for the linkage are written and the system variables are determined. Velocity coefficient equations are also written. These will be used in the virtual work equations in the Kinetics Analysis section.

Diagram



Primary Variables:

$q := 286.1177948 \cdot deg$

Secondary Variables: s1, s2, s3, s4

Constants:

$C1 := 3.106389876$

$C2 := 5.575590232$

$C3 := 3$

$C4 := 4.392233453$

$C5 := 2.861$

$C6 := 4.919$

$C7 := 3$

$C8 := 3.875$

$C9 := 1.345753589$

$C10 := 0$

$C11 := 11$

$CM2 := 1.0151306$

$CM3 := 4.0870484$

$CM4 := 3.3285077$

$CM5 := 3.1326963$

$CM6 := 7.0022511$

$F_{CM2} := 0.59058567$

$F_{CM3} := 0.18182671$

$F_{CM4} := 0.2935833$

$F_{CM5} := 0.13592756$

$F_{CM6} := 2.1301624$

$qmin := 217.0122793 \cdot deg$

$qmax := 286.1177948 \cdot deg$

$W_{person1} := 150.5$

$F_{leg1} := W_{person1} \cdot 0.06$

$F_{total1} := 1 \cdot F_{leg1}$

$W_{person2} := 333.333$

$F_{leg2} := W_{person2} \cdot 0.06$

$F_{total2} := 3 \cdot F_{leg2}$

Assumptions

No friction
Rigid bodies
No backlash

Governing Equations

Vector Loop Equations

Loop 1: (ABCD)

$$f_1 = C2\cdot\cos(q) + C3\cdot\cos(s_1) - C4\cdot\cos(s_2) + C1 = 0$$
$$f_2 = C2\cdot\sin(q) + C3\cdot\sin(s_1) - C4\cdot\sin(s_2) = 0$$

Loop 2: (CGFE)

$$f_3 = C5\cdot\cos(s_2) + C6\cdot\cos(s_4) - C7\cdot\cos(s_3) - C8\cdot\cos(s_1) = 0$$
$$f_4 = C5\cdot\sin(s_2) + C6\cdot\sin(s_4) - C7\cdot\sin(s_3) - C8\cdot\sin(s_1) = 0$$

Position Solution

$s_1 := 150\cdot deg \qquad s_2 := 295\cdot deg \qquad s_3 := 265\cdot deg \qquad s_4 := 135\cdot deg$

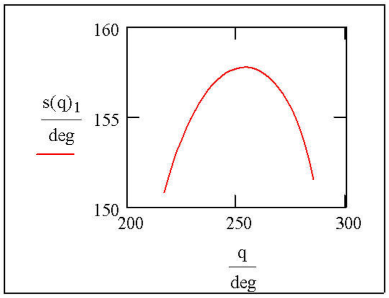
Given

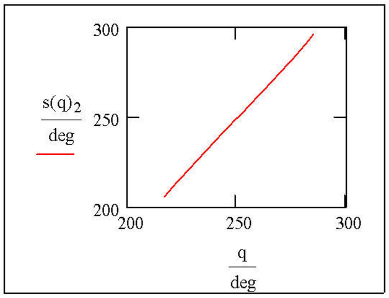
$$C2\cdot\cos(q) + C3\cdot\cos(s_1) - C4\cdot\cos(s_2) + C1 = 0$$
$$C2\cdot\sin(q) + C3\cdot\sin(s_1) - C4\cdot\sin(s_2) = 0$$
$$-C5\cdot\cos(s_2 - \pi) + C6\cdot\cos(s_4) + C7\cdot\cos(s_3 - \pi) - C8\cdot\cos(s_1) = 0$$
$$-C5\cdot\sin(s_2 - \pi) + C6\cdot\sin(s_4) + C7\cdot\sin(s_3 - \pi) - C8\cdot\sin(s_1) = 0$$
$$s_3 \geq 100\cdot deg$$

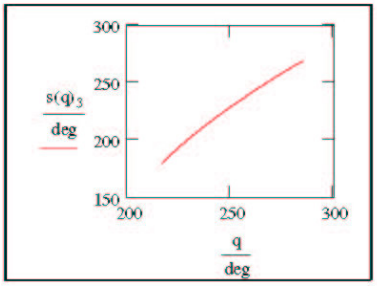
$s(q) := \mathrm{Find}(s_1, s_2, s_3, s_4)$

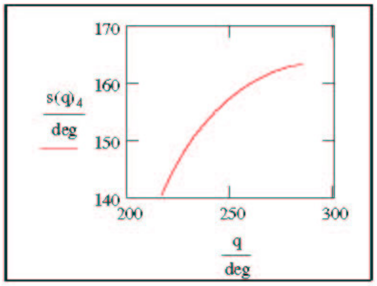
$s(q)_1\cdot\frac{180}{\pi} = 150.777 \quad s(q)_2\cdot\frac{180}{\pi} = 297.617 \quad s(q)_3\cdot\frac{180}{\pi} = 270.011 \quad s(q)_4\cdot\frac{180}{\pi} = 163.138$

$q := 217deg, 219\cdot deg \,..\, 286\cdot deg$









Jacobian and B matrix

$$J(q) := \begin{pmatrix} -C3\cdot\sin\left(s(q)_1\right) & C4\cdot\sin\left(s(q)_2\right) & 0 & 0 \\ C3\cdot\cos\left(s(q)_1\right) & -C4\cdot\cos\left(s(q)_2\right) & 0 & 0 \\ C8\cdot\sin\left(s(q)_1\right) & -C5\cdot\sin\left(s(q)_2\right) & C7\cdot\sin\left(s(q)_3\right) & -C6\cdot\sin\left(s(q)_4\right) \\ -C8\cdot\cos\left(s(q)_1\right) & C5\cdot\cos\left(s(q)_2\right) & -C7\cdot\cos\left(s(q)_3\right) & C6\cdot\cos\left(s(q)_4\right) \end{pmatrix} \qquad B(q) := \begin{pmatrix} C2\cdot\sin(q) \\ -C2\cdot\cos(q) \\ 0 \\ 0 \end{pmatrix}$$

Velocity Coefficients

$$K(q) := J(q)^{-1}\cdot B(q)$$

Partial Loop for Various Points

Base Coordinates:

$$E(q) := \begin{bmatrix} C9 + C1 + C2\cdot\cos(q) + (C3 + C8)\cdot\cos\left(s(q)_1\right) \\ C2\cdot\sin(q) + (C3 + C8)\cdot\sin\left(s(q)_1\right) \end{bmatrix}$$

$$F(q) := \begin{pmatrix} C9 + C1 + C2\cdot\cos(q) + C3\cdot\cos\left(s(q)_1\right) + C5\cdot\cos\left(s(q)_2\right) + C6\cdot\cos\left(s(q)_4\right) \\ C2\cdot\sin(q) + C3\cdot\sin\left(s(q)_1\right) + C5\cdot\sin\left(s(q)_2\right) + C6\cdot\sin\left(s(q)_4\right) \end{pmatrix}$$

$$ext(q) := \frac{-4}{69}\cdot\frac{q}{deg} + \frac{1282}{69}$$

$$XX(q) := \begin{bmatrix} C9 + C1 + C2\cdot\cos(q) + (C3 + C8)\cdot\cos\left(s(q)_1\right) - ext(q)\cdot\cos\left(s(q)_3\right) \\ C2\cdot\sin(q) + (C3 + C8)\cdot\sin\left(s(q)_1\right) - ext(q)\cdot\sin\left(s(q)_3\right) \end{bmatrix}$$

$$I(q) := \begin{bmatrix} C9 + C1 + C2\cdot\cos(q) + (C3 + C8)\cdot\cos\left(s(q)_1\right) + (C7 + C10 + C11)\cdot\cos\left(s(q)_3\right) \\ C2\cdot\sin(q) + (C3 + C8)\cdot\sin\left(s(q)_1\right) + (C7 + C10 + C11)\cdot\sin\left(s(q)_3\right) \end{bmatrix}$$

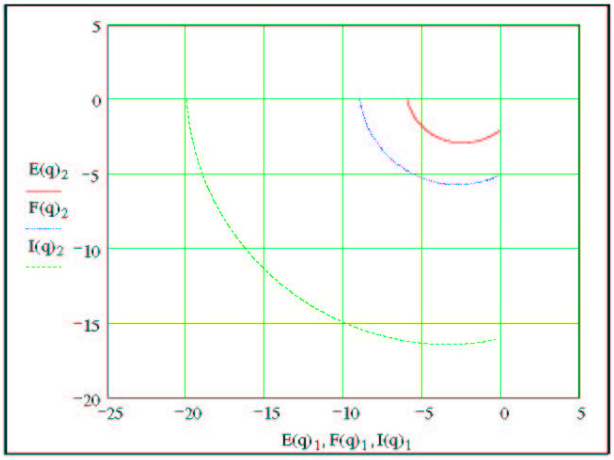
$$CM22(q) := \begin{pmatrix} C9 + C1 + CM2\cdot\cos(q) \\ CM2\cdot\sin(q) \end{pmatrix}$$

$$CM33(q) := \begin{pmatrix} C9 + C1 + C2\cdot\cos(q) + CM3\cdot\cos\left(s(q)_1\right) \\ C2\cdot\sin(q) + CM3\cdot\sin\left(s(q)_1\right) \end{pmatrix}$$

$$CM44(q) := \begin{pmatrix} C9 + CM4 \cdot \cos\left(s(q)_2\right) \\ CM4 \cdot \sin\left(s(q)_2\right) \end{pmatrix}$$

$$CM55(q) := \begin{bmatrix} C9 + (C4 + C5) \cdot \cos\left(s(q)_2\right) + CM5 \cdot \cos\left(s(q)_4\right) \\ (C4 + C5) \cdot \sin\left(s(q)_2\right) + CM5 \cdot \sin\left(s(q)_4\right) \end{bmatrix}$$

$$CM66(q) := \begin{pmatrix} C9 + C4 \cdot \cos\left(s(q)_2\right) + C8 \cdot \cos\left(s(q)_1\right) + CM6 \cdot \cos\left(s(q)_3\right) \\ C4 \cdot \sin\left(s(q)_2\right) + C8 \cdot \sin\left(s(q)_1\right) + CM6 \cdot \sin\left(s(q)_3\right) \end{pmatrix}$$



Velocity Coefficients:

$$Kf(q) := \begin{pmatrix} -C2 \cdot \sin(q) - C3 \cdot K(q)_1 \cdot \sin\left(s(q)_1\right) - C5 \cdot K(q)_2 \cdot \sin\left(s(q)_2\right) - C6 \cdot K(q)_4 \cdot \sin\left(s(q)_4\right) \\ C2 \cdot \cos(q) + C3 \cdot K(q)_1 \cdot \cos\left(s(q)_1\right) + C5 \cdot K(q)_2 \cdot \cos\left(s(q)_2\right) + C6 \cdot K(q)_4 \cdot \cos\left(s(q)_4\right) \end{pmatrix}$$

$$Km2(q) := \begin{pmatrix} -CM2 \cdot \sin(q) \\ CM2 \cdot \cos(q) \end{pmatrix}$$

$$Km3(q) := \begin{pmatrix} -C2 \cdot \sin(q) - CM3 \cdot K(q)_1 \cdot \sin\left(s(q)_1\right) \\ C2 \cdot \cos(q) + CM3 \cdot K(q)_1 \cdot \cos\left(s(q)_1\right) \end{pmatrix}$$

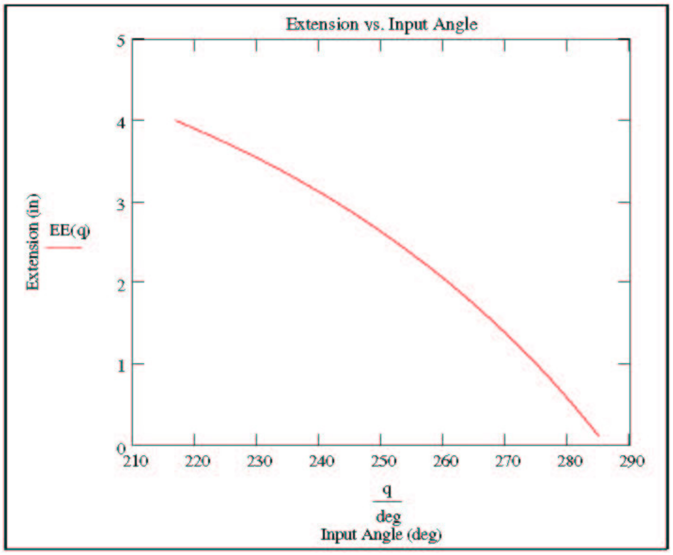
$$Km4(q) := \begin{pmatrix} -CM4 \cdot K(q)_2 \cdot \sin\left(s(q)_2\right) \\ CM4 \cdot K(q)_2 \cdot \cos\left(s(q)_2\right) \end{pmatrix}$$

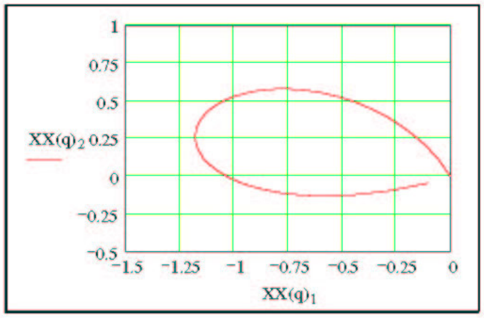
$$Km5(q) := \begin{bmatrix} -(C4 + C5) \cdot K(q)_2 \cdot \sin\left(s(q)_2\right) - CM5 \cdot K(q)_4 \cdot \sin\left(s(q)_4\right) \\ (C4 + C5) \cdot K(q)_2 \cdot \cos\left(s(q)_2\right) + CM5 \cdot K(q)_4 \cdot \cos\left(s(q)_4\right) \end{bmatrix}$$

$$Km6(q) := \begin{pmatrix} -C4 \cdot K(q)_2 \cdot \sin\left(s(q)_2\right) - C8 \cdot K(q)_1 \cdot \sin\left(s(q)_1\right) - CM6 \cdot K(q)_3 \cdot \sin\left(s(q)_3\right) \\ C4 \cdot K(q)_2 \cdot \cos\left(s(q)_2\right) + C8 \cdot K(q)_1 \cdot \cos\left(s(q)_1\right) + CM6 \cdot K(q)_3 \cdot \cos\left(s(q)_3\right) \end{pmatrix}$$

Extension

$\mathrm{EE}(q) := \sqrt{\left(\mathrm{E}(q)_1\right)^2 + \left(\mathrm{E}(q)_2\right)^2} - 2$ $\qquad q := 217 \cdot \mathrm{deg}, 219 \cdot \mathrm{deg} .. 286 \cdot \mathrm{deg}$





Kinetic Analysis

In this section of the analysis, virtual work equations are written for the normal and maximum loading conditions. From these equations, the torques on the worm gear shaft and worm shaft are determined.

Virtual Work - Torque on Worm Gear

$$\delta W = -F_{leg}\cdot\delta Y_F - F_{CM2}\cdot\delta Y_{CM2} - F_{CM3}\cdot\delta Y_{CM3} - F_{CM4}\cdot\delta Y_{CM4} - F_{CM5}\cdot\delta Y_{CM5} - F_{CM6}\cdot\delta Y_{CM6} + C\cdot\delta q = 0$$

$$\delta Y_F = Kf(q)_2\cdot\delta q$$

$$\delta Y_{CM2} = Km2(q)_2\cdot\delta q$$

$$\delta Y_{CM3} = Km3(q)_2\cdot\delta q$$

$$\delta Y_{CM4} = Km4(q)_2\cdot\delta q$$

$$\delta Y_{CM5} = Km5(q)_2\cdot\delta q$$

$$\delta Y_{CM6} = Km6(q)_2\cdot\delta q$$

$$F_{leg}\cdot Kf(q)_2\cdot\delta q + F_{CM2}Km2(q)_2\cdot\delta q + F_{CM3}Km3(q)_2\cdot\delta q + F_{CM4}Km4(q)_2\cdot\delta q + F_{CM5}Km5(q)_2\cdot\delta q + F_{CM6}Km6(q)_2\cdot\delta q = C\cdot\delta q$$

Normal Loading

$$\boxed{C_{gear1}(q) := F_{total1}\cdot Kf(q)_2 + F_{CM2}\cdot Km2(q)_2 + F_{CM3}\cdot Km3(q)_2 + F_{CM4}\cdot Km4(q)_2 + F_{CM5}\cdot Km5(q)_2 + F_{CM6}\cdot Km6(q)_2}$$

(in*lb) Torque loading on gear shaft

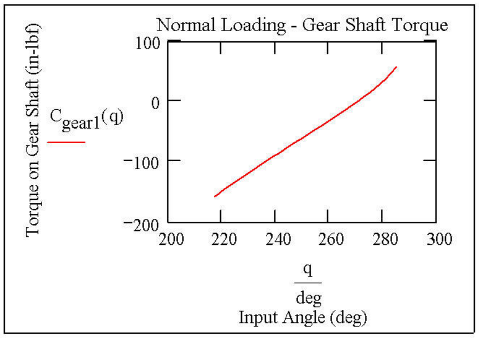
Maximum Loading

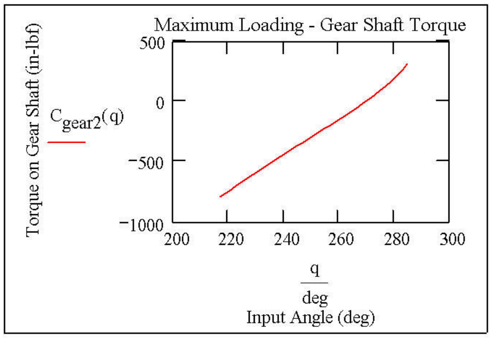
$$\boxed{C_{gear2}(q) := F_{total2}\cdot Kf(q)_2 + F_{CM2}\cdot Km2(q)_2 + F_{CM3}\cdot Km3(q)_2 + F_{CM4}\cdot Km4(q)_2 + F_{CM5}\cdot Km5(q)_2 + F_{CM6}\cdot Km6(q)_2}$$

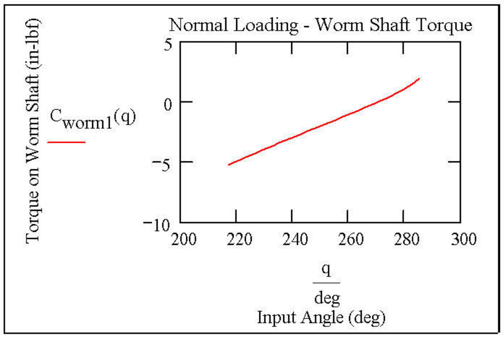
(in*lb) Torque loading on gear shaft

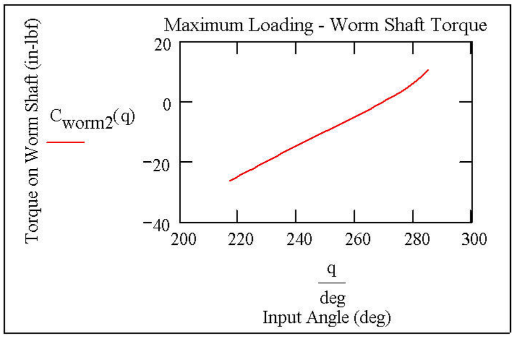
Torque Loadings

Normal	*Maximum*		
$q_{lowered} := qmax$			
$q_{raised} := qmin$			
$C_{gear1}(q_{lowered}) = 64.854$	$C_{gear2}(q_{lowered}) = 351.097$	(in*lb)	
$C_{gear1}(q_{raised}) = -158.507$	$C_{gear2}(q_{raised}) = -795.525$	(in*lb)	Maximum torque loading on gear shaft.
$N_g := 30$			Number of teeth on worm gear
$N_w := 1$			Number of teeth on worm
$m_G := \frac{N_w}{N_g}$			Gear ratio
$C_{worm1}(q) := m_G\cdot C_{gear1}(q)$	$C_{worm2}(q) := m_G\cdot C_{gear2}(q)$	(in*lb)	
$C_{worm1}(q_{lowered}) = 2.162$	$C_{worm2}(q_{lowered}) = 11.703$	(in*lb)	
$C_{worm1}(q_{raised}) = -5.284$	$C_{worm2}(q_{raised}) = -26.517$	(in*lb)	Maximum torque loading on worm shaft









User Interface Requirements

$\Delta q := qmax - qmin$ $\qquad \frac{\Delta q}{deg} = 69.106$

$\xi q := \frac{\Delta q}{2 \cdot \pi}$ $\qquad \xi q = 0.192$

$\xi N_g := \xi q \cdot N_g$ $\qquad \boxed{\xi N_g = 5.759}$ (Number of turns needed for full elevation)

Stress Analysis

In the section of the analysis, the torque loads determined from the Kinetic Analysis are used to determine the torsional shear stresses and corresponding safety factors for the worm gear shaft, worm shaft, and worm gear hub system components.

Gear Shaft Stress Analysis

$d1 := 0.4375$	(in)	Gear Shaft Diameter
$r1 := 0.5 \cdot d1$	(in)	Gear Shaft Radius
$J1 := \frac{\pi \cdot d1^4}{32}$	(in^4)	Polar Moment of Inertia
$K_{ts1} := 1.0$		Stress Concentration Factor (keyway)
Normal Loading	*Maximum Loading*	
$\tau1 := K_{ts1} \cdot \frac{\left\lvert C_{gear1}\left(q_{raised}\right)\right\rvert \cdot r1}{J1}$	$\tau2 := K_{ts1} \cdot \frac{\left\lvert C_{gear2}\left(q_{raised}\right)\right\rvert \cdot r1}{J1}$	Shear Stress on Gear Shaft (psi)
$\tau1 = 9.64 \times 10^3$	$\tau2 = 4.838 \times 10^4$	
$Sy_{1045} := 77 \cdot 10^3$		Yield strength of gear shaft material (psi)
$N1 := \frac{Sy_{1045}}{\tau1}$	$N2 := \frac{Sy_{1045}}{\tau2}$	Gear shaft safety factor
$N1 = 7.987$	$N2 = 1.591$	

Worm Shaft Stress Analysis

$d2 := 0.250$	(in)	Worm Shaft Diameter
$r2 := 0.5 \cdot d2$	(in)	Worm Shaft Radius
$d3 := 0.0938$	(in)	Worm Shaft Hole Diameter
$J2 := \frac{\pi \cdot d2^4}{32}$	(in^4)	Polar Moment of Inertia

$$K_{ts2} := 3.9215 - 24.435 \cdot \left(\frac{d3}{d2}\right) + 234.06 \cdot \left(\frac{d3}{d2}\right)^2 - 1200.5 \cdot \left(\frac{d3}{d2}\right)^3 + 3059.5 \cdot \left(\frac{d3}{d2}\right)^4 - 3042.4 \cdot \left(\frac{d3}{d2}\right)^5$$

$K_{ts2} = 2.304$		Stress Concentration Factor (drilled hole)
Normal Loading	*Maximum Loading*	
$\tau3 := K_{ts2} \cdot \frac{\left\lvert C_{worm1}\left(q_{raised}\right)\right\rvert \cdot r2}{J2}$	$\tau4 := K_{ts2} \cdot \frac{\left\lvert C_{worm2}\left(q_{raised}\right)\right\rvert \cdot r2}{J2}$	Shear stress on worm shaft (psi)
$\tau3 = 3.968 \times 10^3$	$\tau4 = 1.992 \times 10^4$	
$N3 := \frac{Sy_{1045}}{\tau3}$	$N4 := \frac{Sy_{1045}}{\tau4}$	Worm shaft safety factor
$N3 = 19.403$	$N4 = 3.866$	

Gear Stress Analysis

$d4 := 0.75$	Gear Hub Diameter (in)
$r4 := 0.5 \cdot d4$	Gear Hub Radius (in)
$J3 := \frac{\pi \cdot \left(d4^4 - d1^4\right)}{32}$	Polar Moment of Inertia (in^4)
$K_{ts3} := 1.0$	Stress Concentration Factor (keyway)
$Sy_{bronze} := 47 \cdot 10^3$	Yield strength of gear material (psi)

Normal Loading	*Maximum Loading*	
$\tau5 := K_{ts3} \cdot \frac{\left\lvert C_{gear1}\left(q_{raised}\right)\right\rvert \cdot r4}{J3}$	$\tau6 := K_{ts3} \cdot \frac{\left\lvert C_{gear2}\left(q_{raised}\right)\right\rvert \cdot r4}{J3}$	Shear Stress on Gear Hub (psi)
$\tau5 = 2.164 \times 10^3$	$\tau6 = 1.086 \times 10^4$	
$N5 := \frac{Sy_{bronze}}{\tau5}$	$N6 := \frac{Sy_{bronze}}{\tau6}$	Gear Hub Safety Factor
$N5 = 21.718$	$N6 = 4.327$	

Finding the Extended Length of Link 4 and the Length of Link 5

In this section of the analysis, the length of link 5 and the extended length of link 4 are determined. These lengths were needed for the creation of the sixbar linkage in Chapter 7.

$B := 3.558762097$

$C := 6.656315354$

$C5 := 2.9$

$C6 := 4.9$

Given

$$C6^2 = C5^2 + B^2 + 2 \cdot C5 \cdot B \cdot 0.1645907141$$

$$C6^2 = C5^2 + C^2 - C5 \cdot C \cdot 1.485711063$$

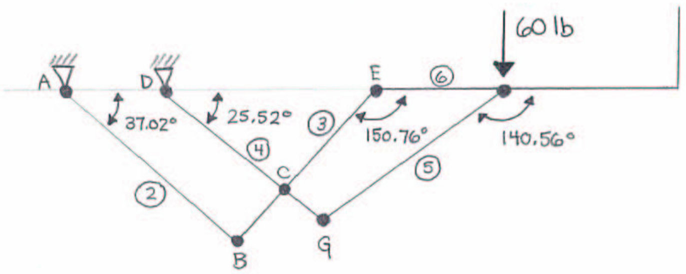
$$\begin{pmatrix} C5 \\ C6 \end{pmatrix} := \mathrm{Find}(C5, C6)$$

$C5 = 2.861$ Extended length of link 4 (inches)

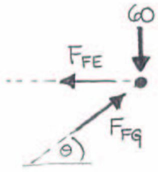
$C6 = 4.919$ Length of link 5 (inches)

APPENDIX B – PRELIMINARY LINKAGE STRESS CALCULATIONS

For the linkage part of the design, preliminary stress calculations were performed on the linkage members to determine whether the safety factors against failure were low enough to require additional analysis. The calculated safety factors concluded the links were non-critical components and did not need additional analysis.



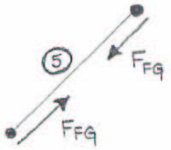
F



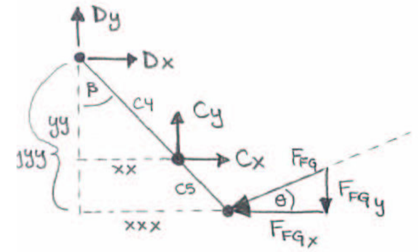
$\theta = 39.436°$

$F_{FG} \cdot \sin\theta = 60 \rightarrow F_{FG} = 94.456 \text{ lb} \rightarrow$

$F_{FE} = F_{FG} \cdot \cos\theta \rightarrow F_{FE} = 72.952 \text{ lb}$



LINK 4



$\theta = 39.436°$

$F_{FG_x} = F_{FG} \cdot \cos\theta = 72.952 \text{ lb}$

$F_{FG_y} = F_{FG} \cdot \sin\theta = 60$

$\beta = 64.477°$

$C_4 = 4.392 \text{ in}$

$C_5 = 2.861 \text{ in}$

$xx = C_4 \cdot \sin\beta = 3.964 \text{ in}$

$xxx = (C_4 + C_5) \cdot \sin\beta = 6.545 \text{ in}$

$\circlearrowleft + \ \Sigma M_D = C_y(xx) - F_{FG_y}(xxx) = 0 \rightarrow C_y = F_{FG_y}\left(\frac{xxx}{xx}\right) = 99.083 \text{ lb}$

$yy = C_4 \cdot \cos\beta = 1.892 \text{ in}$

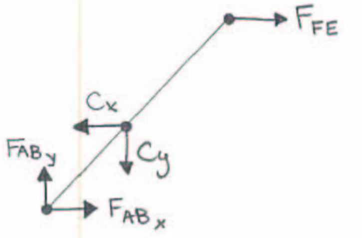
$yyy = (C_4 + C_5) \cdot \cos\beta = 3.125 \text{ in}$

$\circlearrowleft + \ \Sigma M_D = C_x(yy) - F_{FG_x}(yyy) = 0 \rightarrow C_x = F_{FG_x}\left(\frac{ppp}{pp}\right) = 120.471 \text{ lb}$

$\Sigma F_x = 0 = D_x + C_x - F_{FG_x} \rightarrow D_x = F_{FG_x} - C_x = -47.519 \text{ lb}$

$\Sigma F_y = 0 = D_y + C_y - F_{FG_y} \rightarrow D_y = F_{FG_y} - C_y = -39.083 \text{ lb}$

LINK 3



$\Sigma F_x = 0 = F_{FE} + F_{AB_x} - C_x$

$\rightarrow F_{AB_x} = C_x - F_{FE} = 47.519 \text{ lb}$

$\Sigma F_y = 0 = F_{AB_y} - C_y$

$\rightarrow F_{AB_y} = C_y = 99.083 \text{ lb}$

STRESSES

LINK 5: COMPRESSION

$\rightarrow A_{xc} = 0.125 \text{ in}^2$

$\rightarrow \sigma_x = \frac{F}{A} = \frac{F_{FG}}{A_{xc}} = \frac{94.456 \text{ lb}}{0.125 \text{ in}^2} = 756 \text{ psi}$

$\rightarrow S_y = 45000 \text{ psi}$

$\rightarrow N = \frac{S_y}{\sigma_x} = \frac{45000 \text{ psi}}{756 \text{ psi}} = \boxed{98.8}$

LINK 3: BENDING MOMENT

$\rightarrow M_{max} = 63.249 \text{ lb} (3 \text{ in}) = 189.75 \text{ in-lb}$

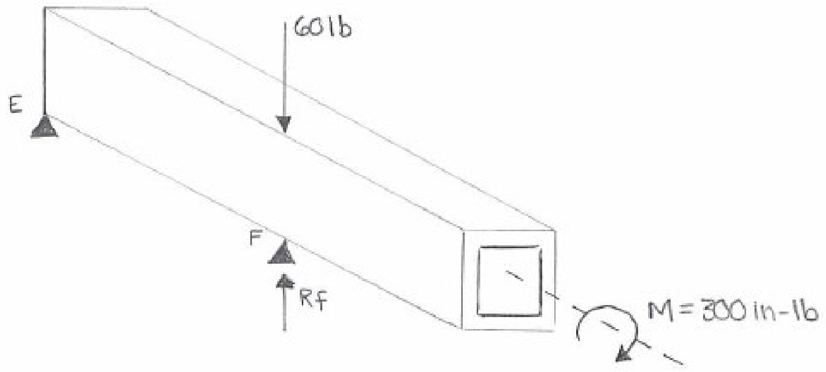
$\rightarrow c = \frac{1}{2}(0.750 \text{ in}) = 0.375 \text{ in}$

$\rightarrow I = 0.00875 \text{ in}^4$

$\rightarrow \sigma = \frac{M_{max}(c)}{I} = \frac{189.75 \text{ in-lb} (0.375 \text{ in})}{0.00875 \text{ in}^4} = 8132.14 \text{ psi}$

$\rightarrow N = \frac{S_y}{\sigma} = \frac{45000 \text{ psi}}{8132.14 \text{ psi}} = \boxed{5.53}$

LINK 6: TORSION



T= 300 in-lb

$Q_{\text{hollow square}} = 2t(a-t)^2$

→ t= 0.125 in

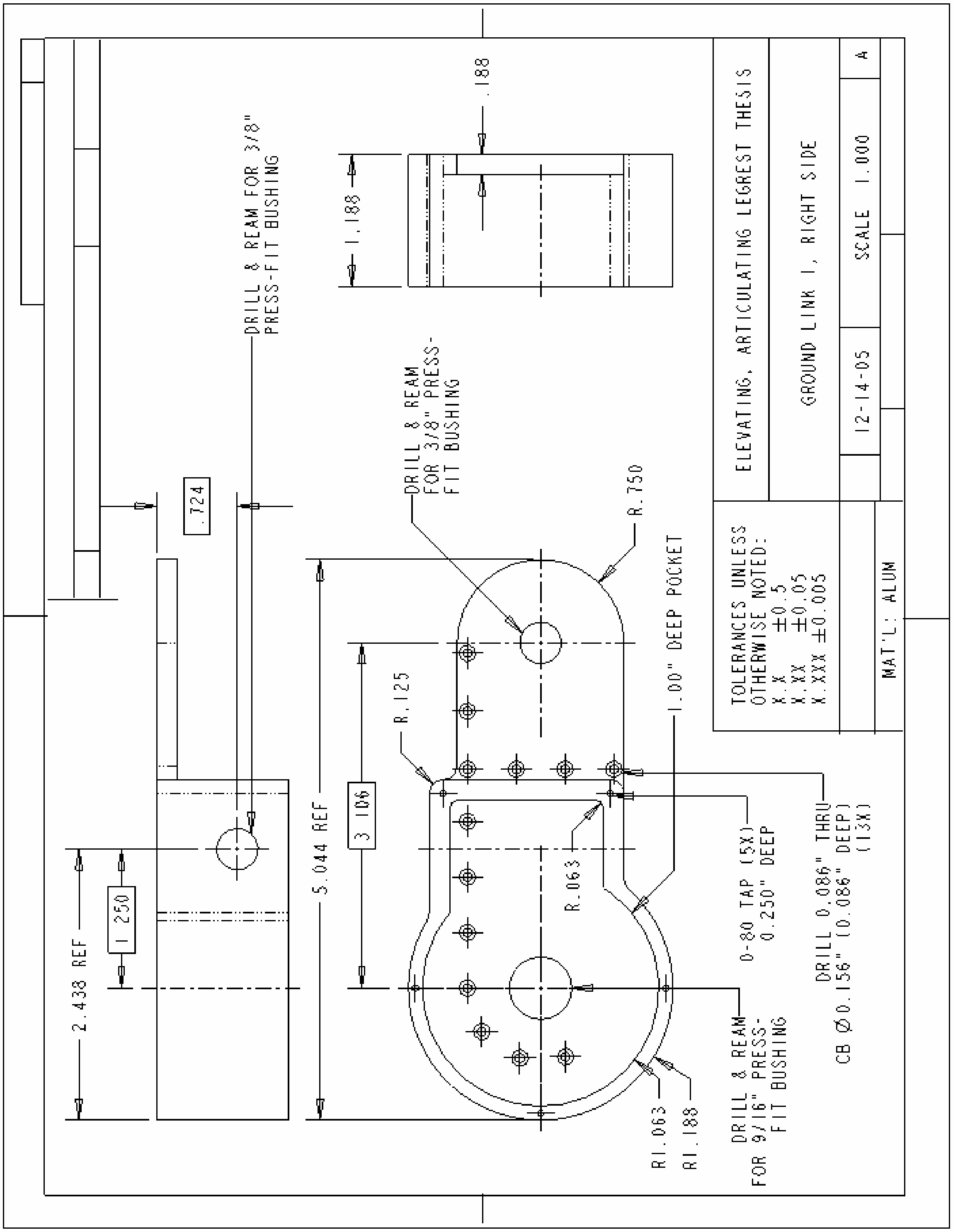
→ a= 1.00 in

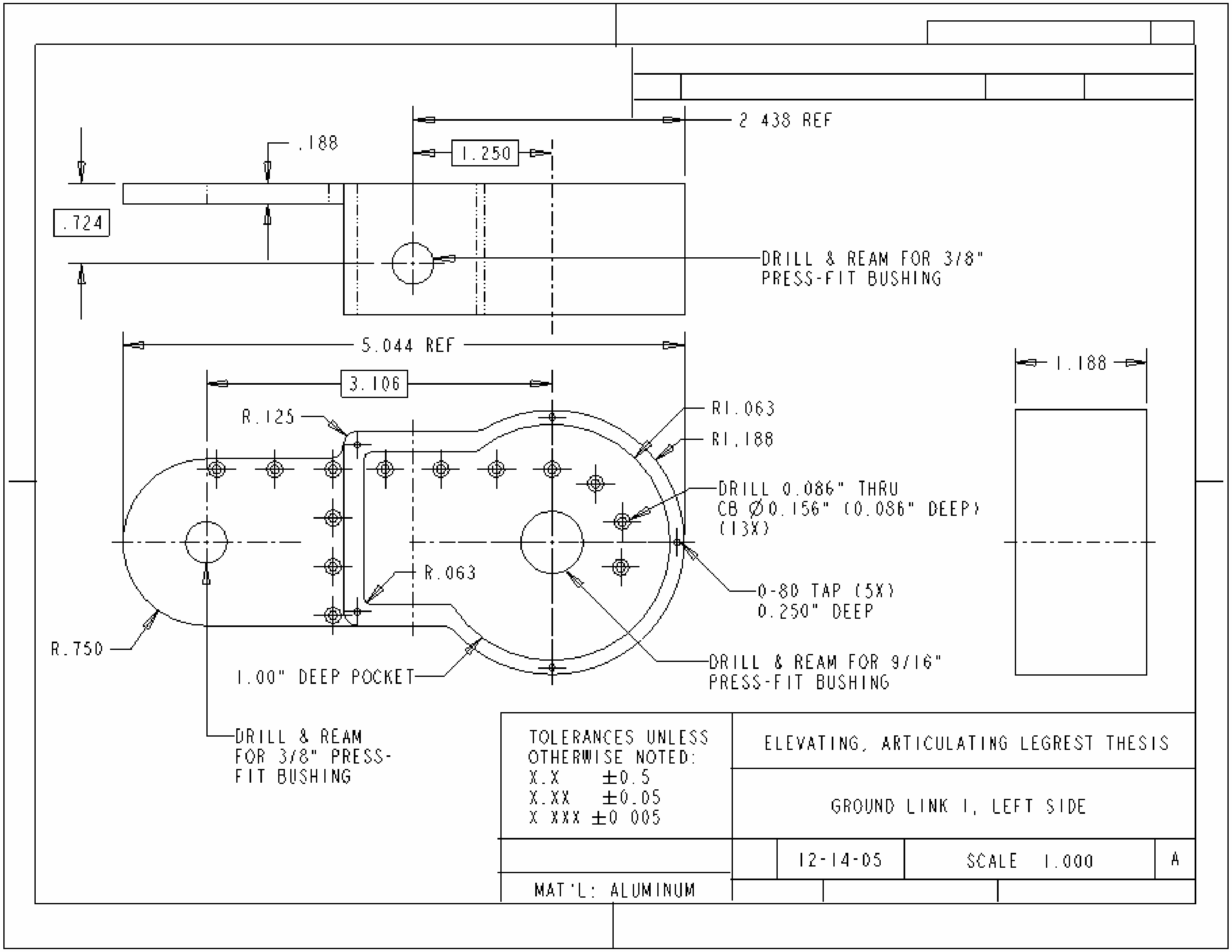
→ $Q = 0.191\ in^3$

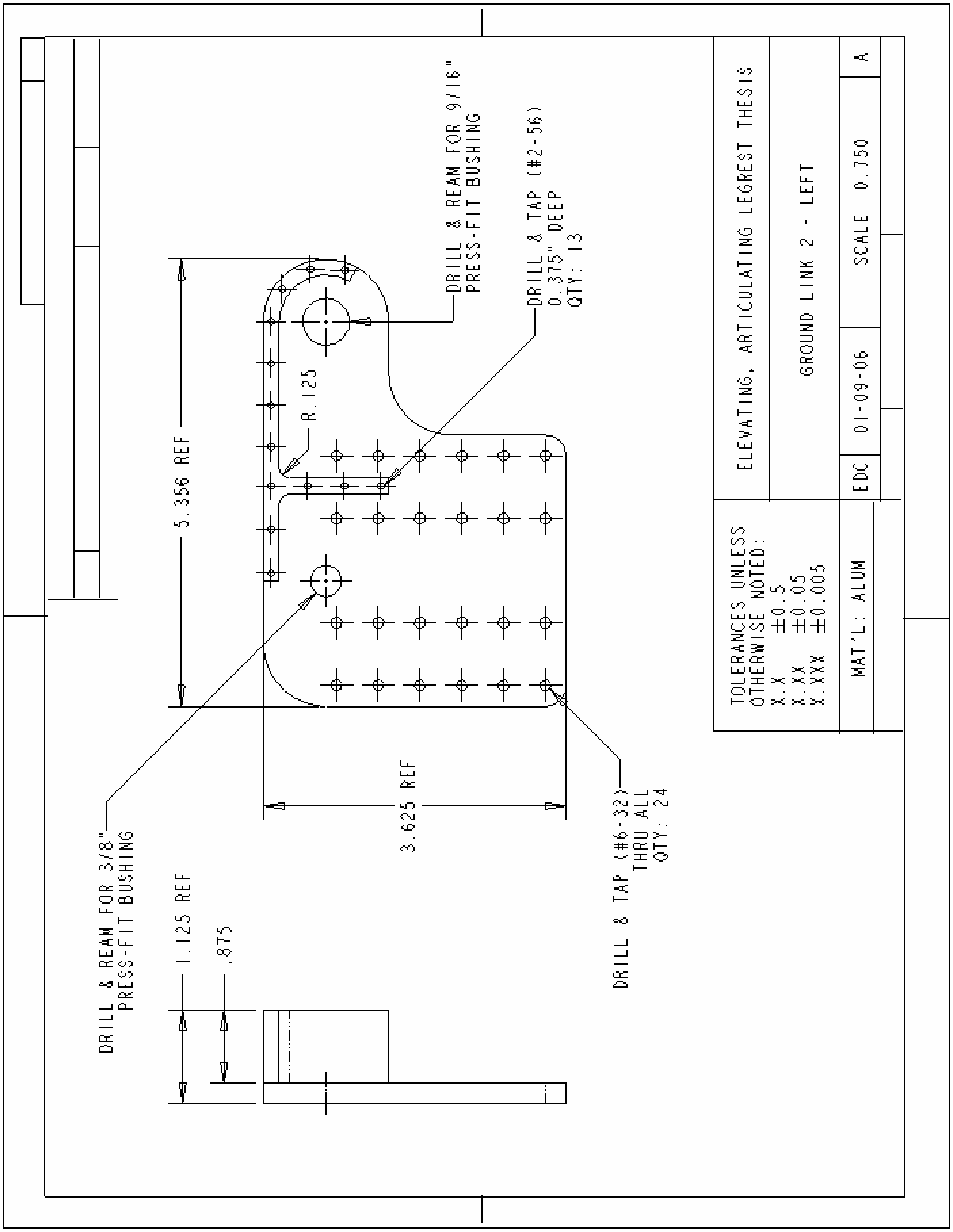
$$\tau_{max} = \frac{T}{Q} = \frac{300\ in\text{-}lb}{0.191\ in^3} = \boxed{1567.35\ psi}$$

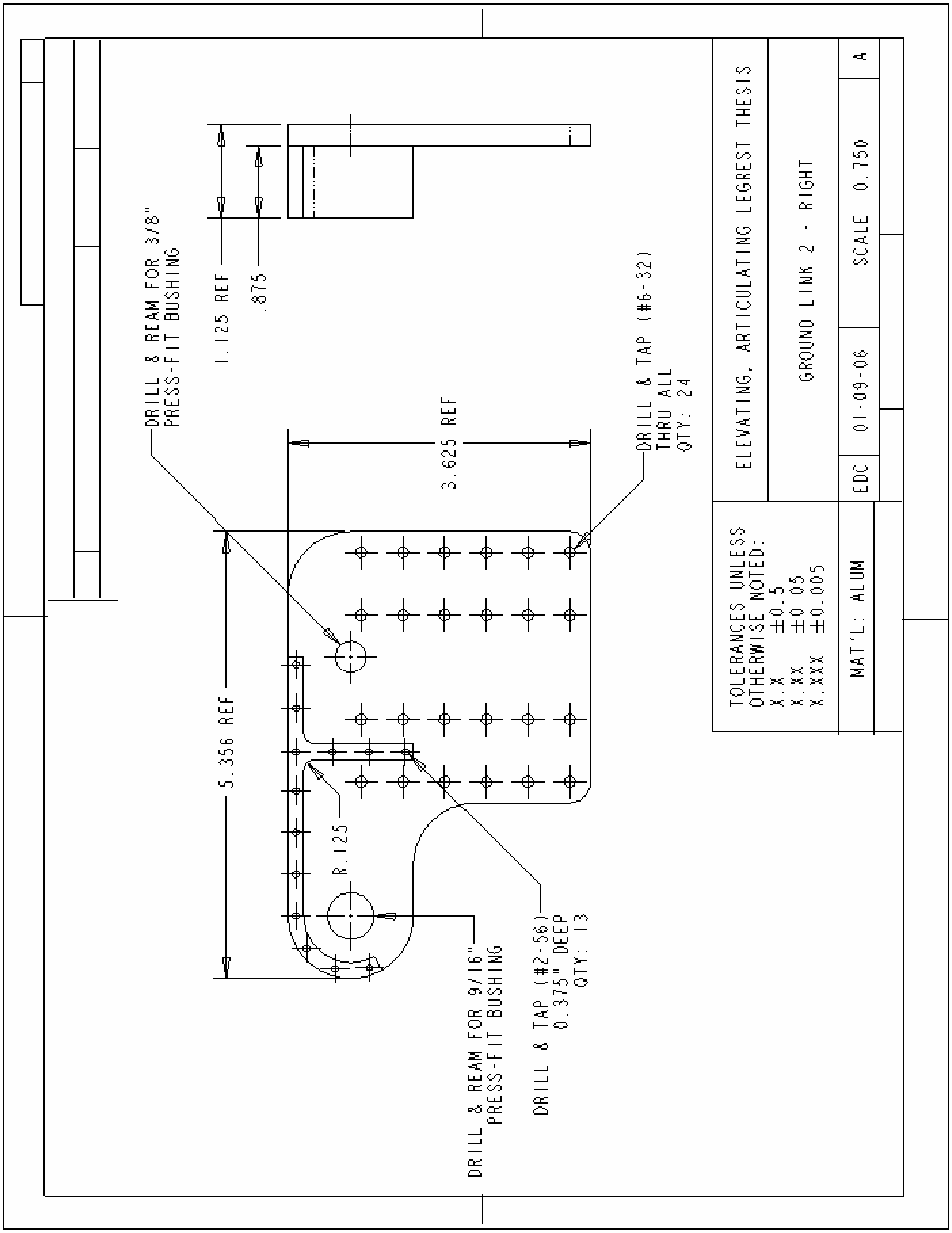
$$N = \frac{S_y}{\tau_{max}} = \frac{45000\ psi}{1567.35\ psi} = \boxed{28.71}$$

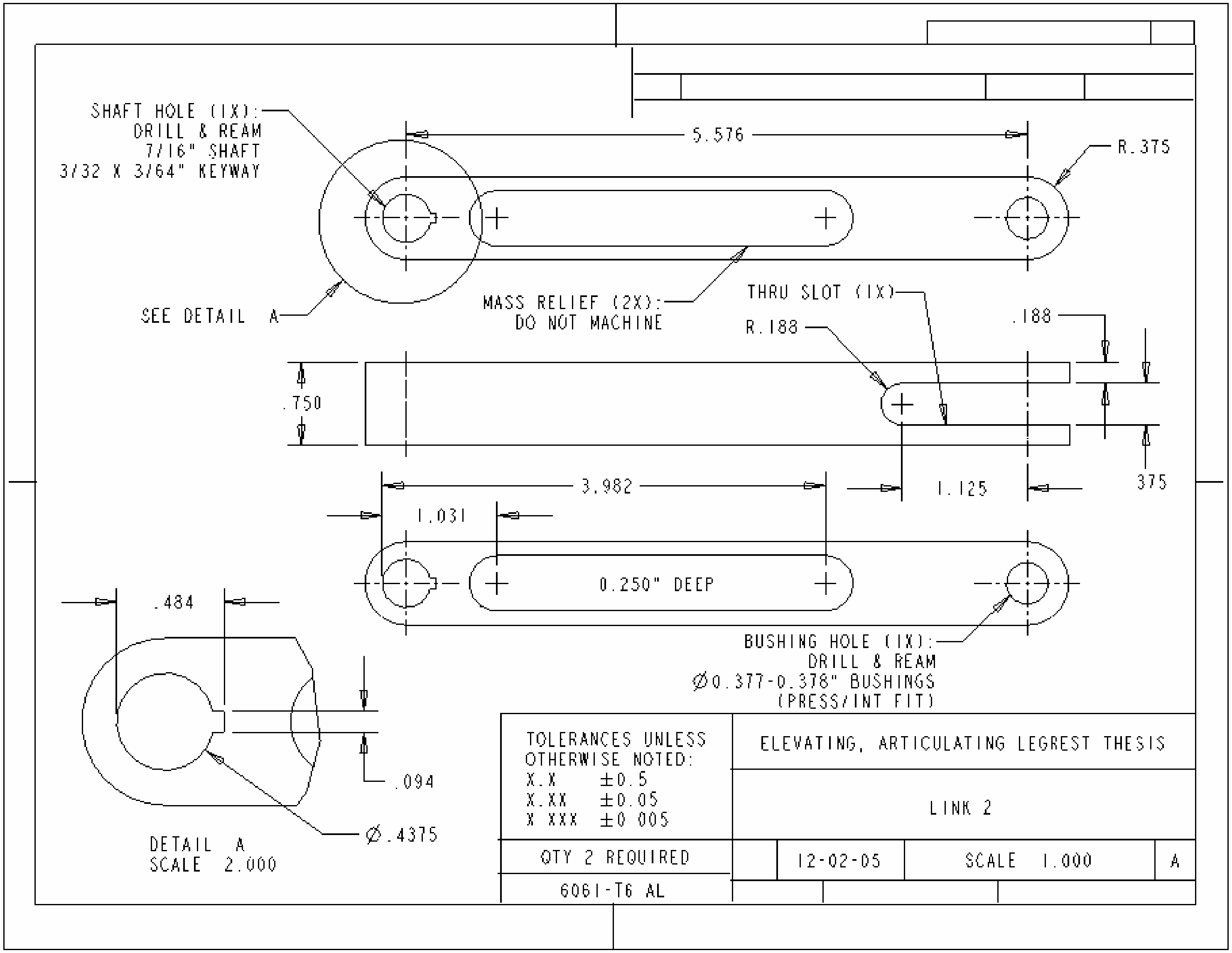
APPENDIX C – PRO/ENGINEER DRAWINGS

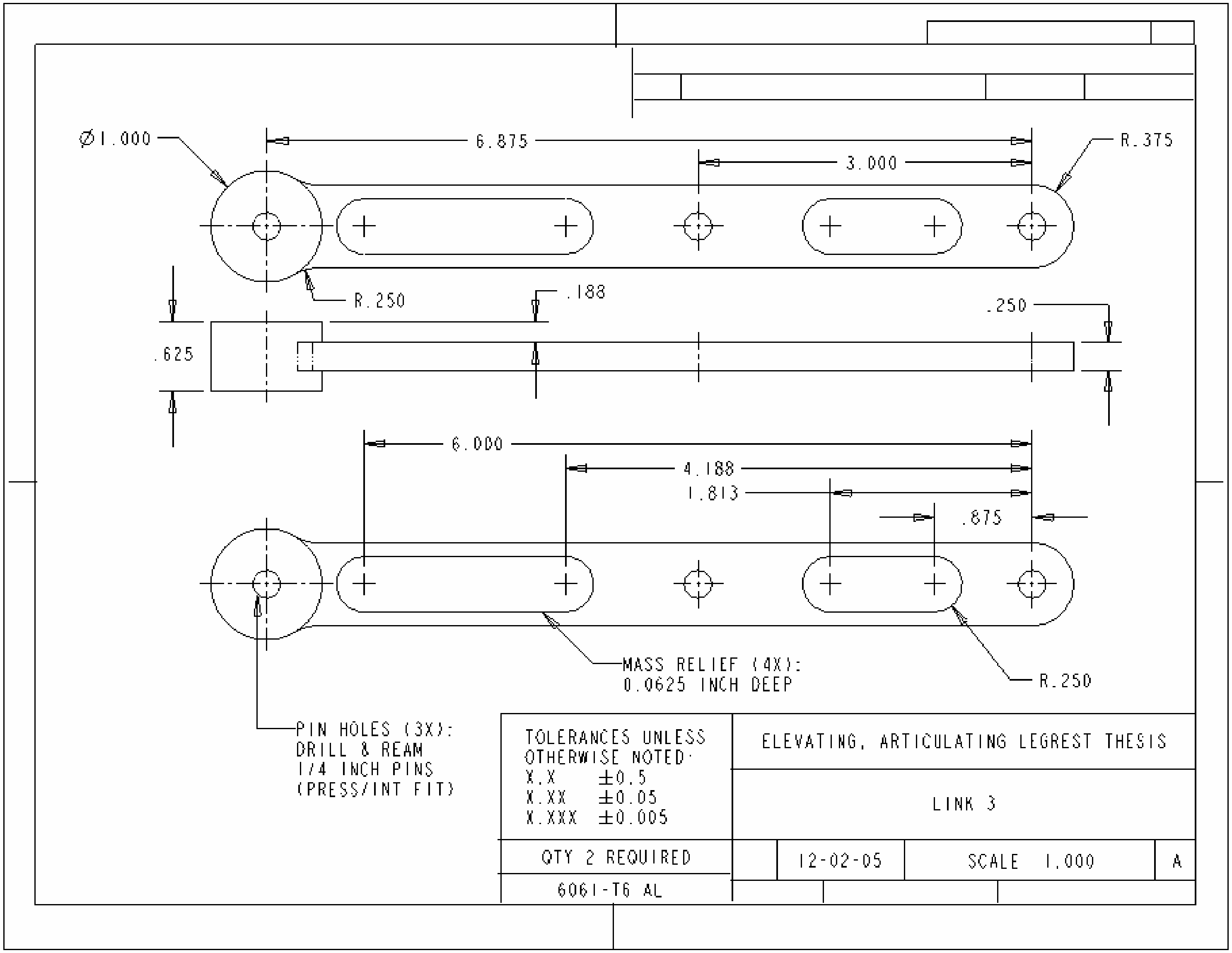


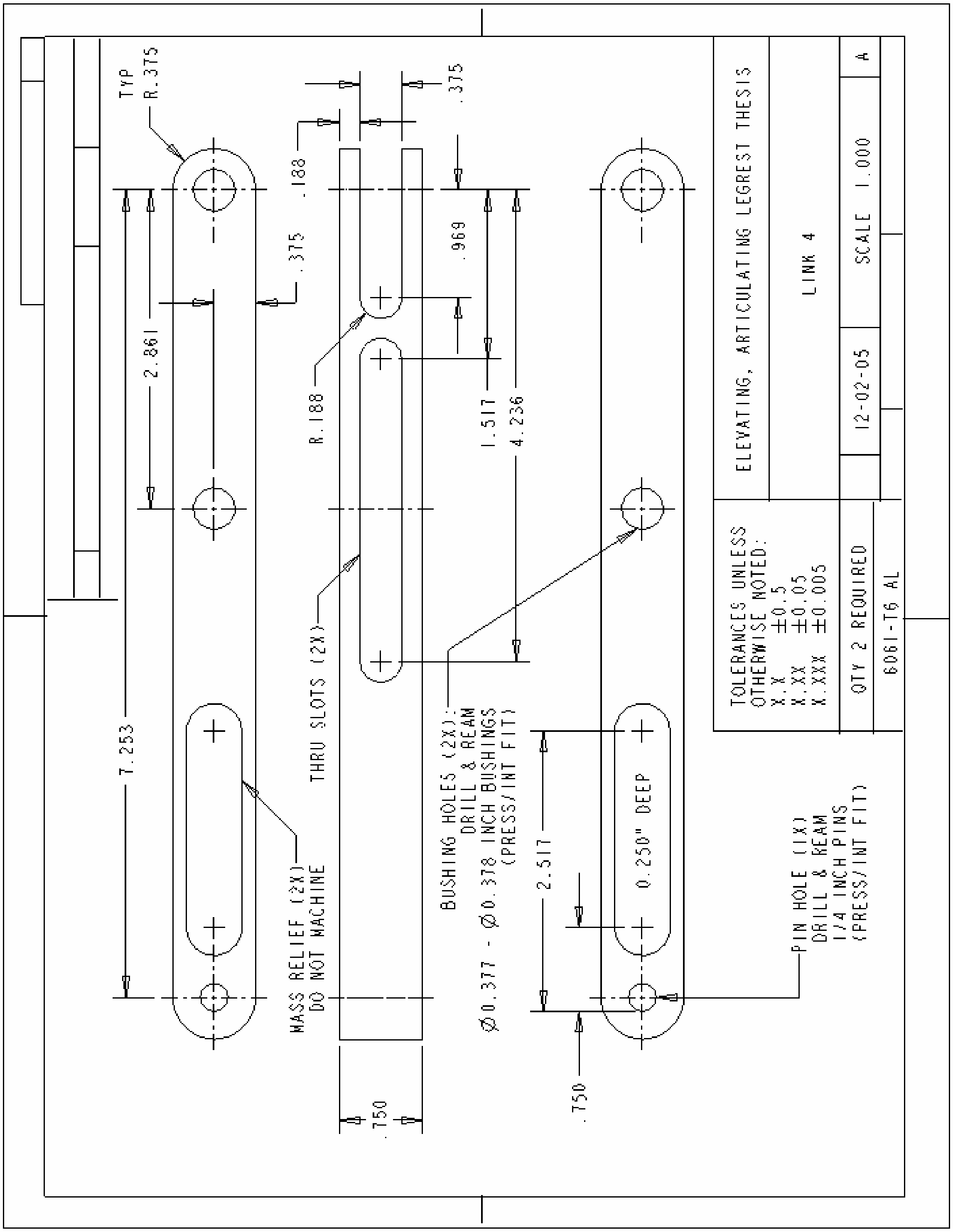

2 438 REF
1.250
.188
.724
DRILL & REAM FOR 3/8" PRESS-FIT BUSHING
5.044 REF
3.106
1.188
R.125
R1.063
R1.188
DRILL 0.086" THRU CB Ø0.156" (0.086" DEEP) (13X)
R.063
0-80 TAP (5X) 0.250" DEEP
R.750
1.00" DEEP POCKET
DRILL & REAM FOR 9/16" PRESS-FIT BUSHING
DRILL & REAM FOR 3/8" PRESS-FIT BUSHING
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X XXX ±0 005
ELEVATING, ARTICULATING LEGREST THESIS
GROUND LINK 1, LEFT SIDE
12-14-05
SCALE 1.000
A
MAT'L: ALUMINUM

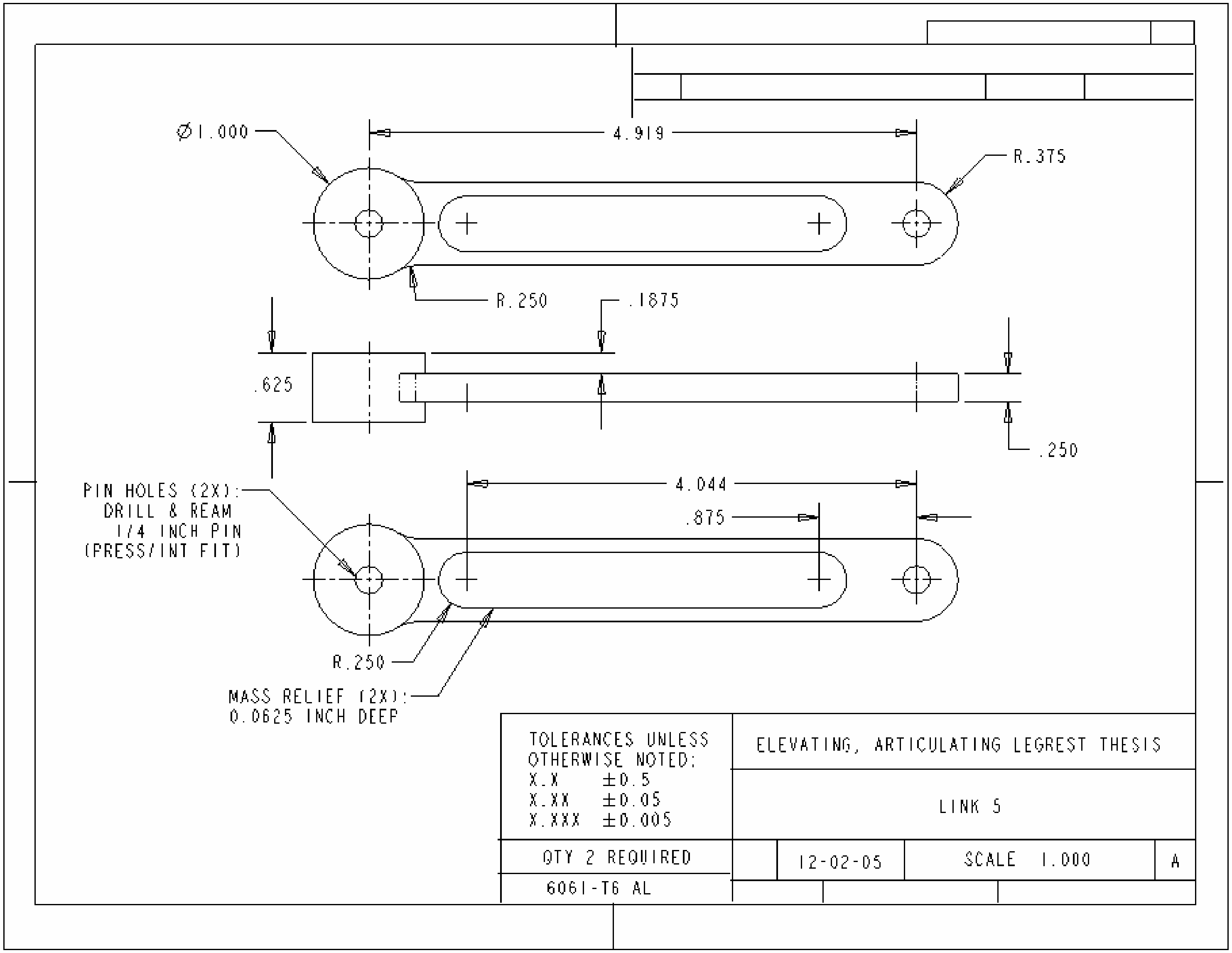

DRILL & REAM FOR 9/16"
PRESS-FIT BUSHING
DRILL & TAP (#2-56)
0.375" DEEP
QTY: 13
R.125
5.356 REF
3.625 REF
DRILL & TAP (#6-32)
THRU ALL
QTY: 24
DRILL & REAM FOR 3/8"
PRESS-FIT BUSHING
1.125 REF
.875
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
ELEVATING, ARTICULATING LEGREST THESIS
GROUND LINK 2 - LEFT
EDC
01-09-06
SCALE 0.750
A

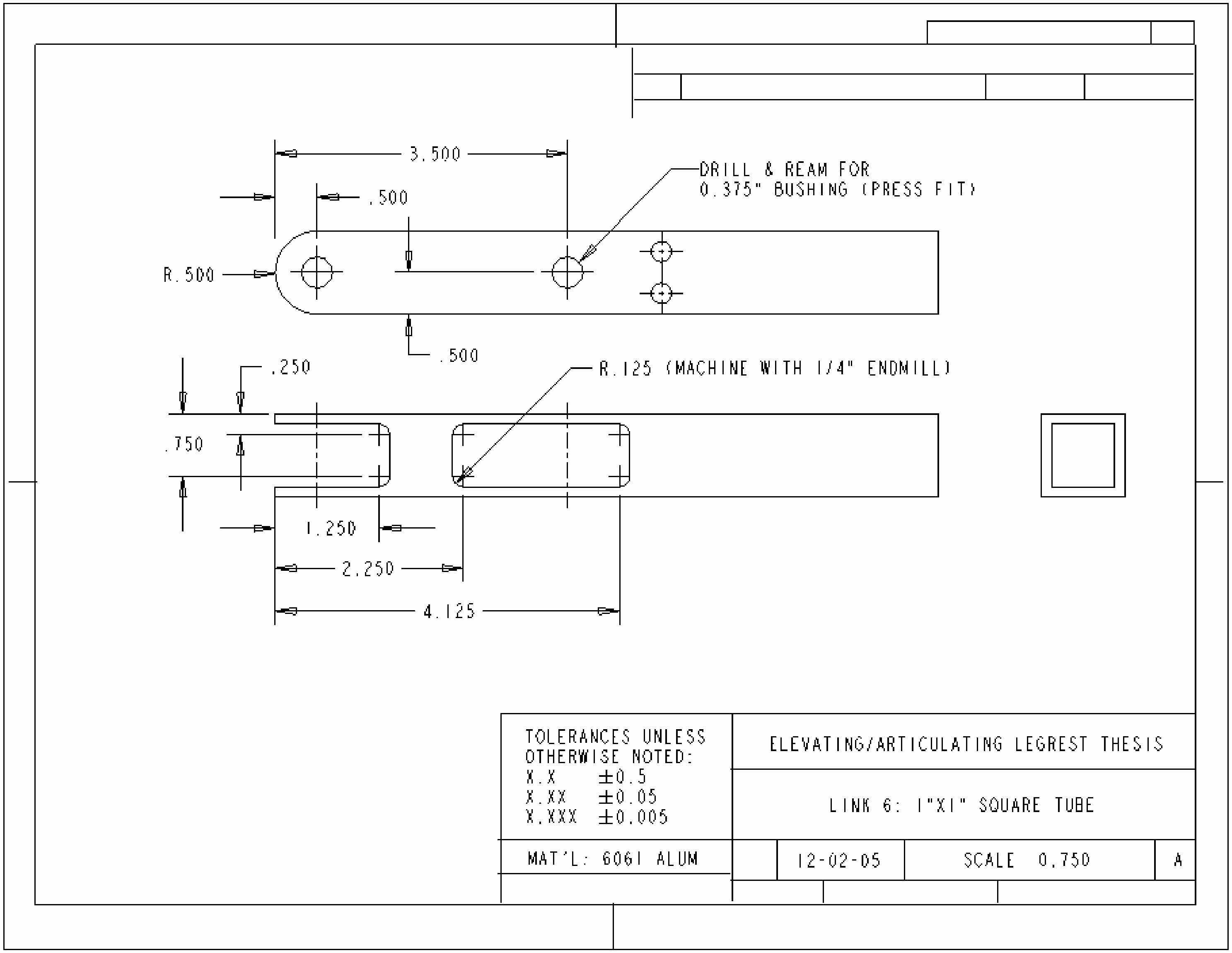

DRILL & REAM FOR 3/8"
PRESS-FIT BUSHING
1.125 REF
.875
3.625 REF
DRILL & TAP (#6-32)
THRU ALL
QTY: 24
5.356 REF
R.125
DRILL & REAM FOR 9/16"
PRESS-FIT BUSHING
DRILL & TAP (#2-56)
0.375" DEEP
QTY: 13
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
ELEVATING, ARTICULATING LEGREST THESIS
GROUND LINK 2 - RIGHT
EDC
01-09-06
SCALE 0.750
A

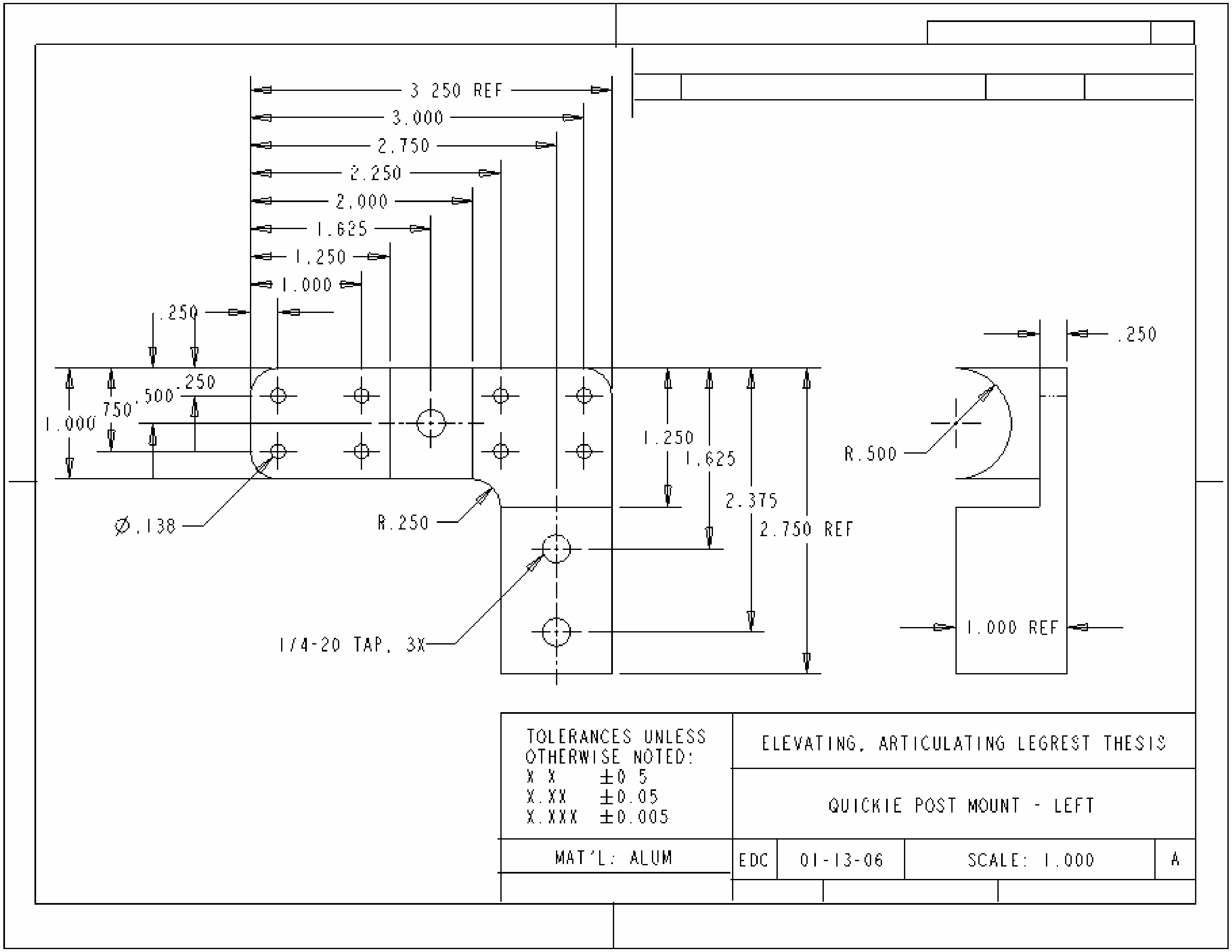

SHAFT HOLE (1X):
DRILL & REAM
7/16" SHAFT
3/32 X 3/64" KEYWAY
5.576
R.375
SEE DETAIL A
MASS RELIEF (2X):
DO NOT MACHINE
THRU SLOT (1X)
R.188
.188
.750
375
3.982
1.125
1.031
0.250" DEEP
.484
BUSHING HOLE (1X):
DRILL & REAM
Ø0.377-0.378" BUSHINGS
(PRESS/INT FIT)
.094
Ø.4375
DETAIL A
SCALE 2.000
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
ELEVATING, ARTICULATING LEGREST THESIS
LINK 2
QTY 2 REQUIRED
12-02-05
SCALE 1.000
A
6061-T6 AL

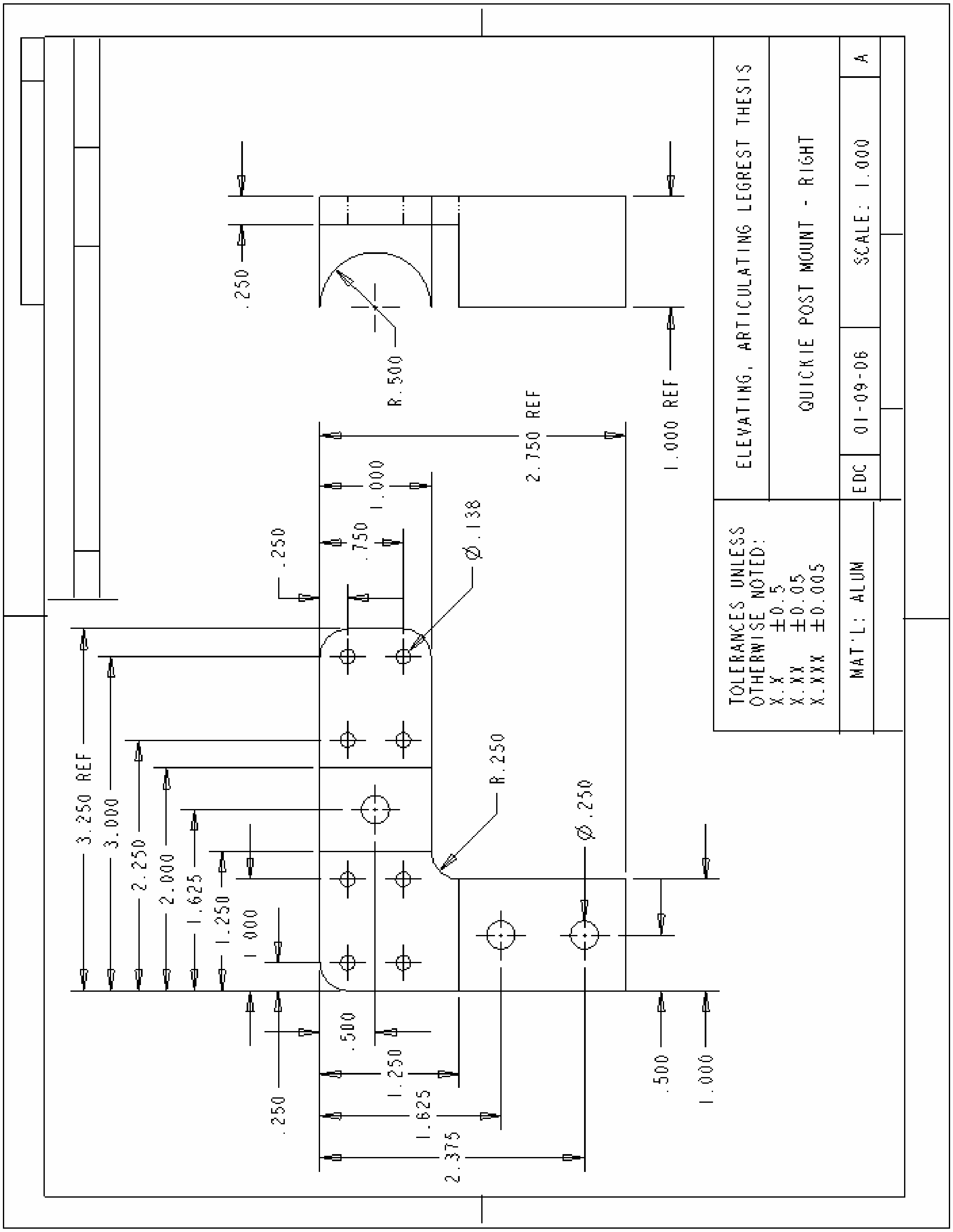

∅1.000
6.875
3.000
R.375
R.250
.188
.250
.625
6.000
4.188
1.813
.875
MASS RELIEF (4X):
0.0625 INCH DEEP
R.250
PIN HOLES (3X):
DRILL & REAM
1/4 INCH PINS
(PRESS/INT FIT)
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
ELEVATING, ARTICULATING LEGREST THESIS
LINK 3
QTY 2 REQUIRED
6061-T6 AL
12-02-05
SCALE 1.000
A

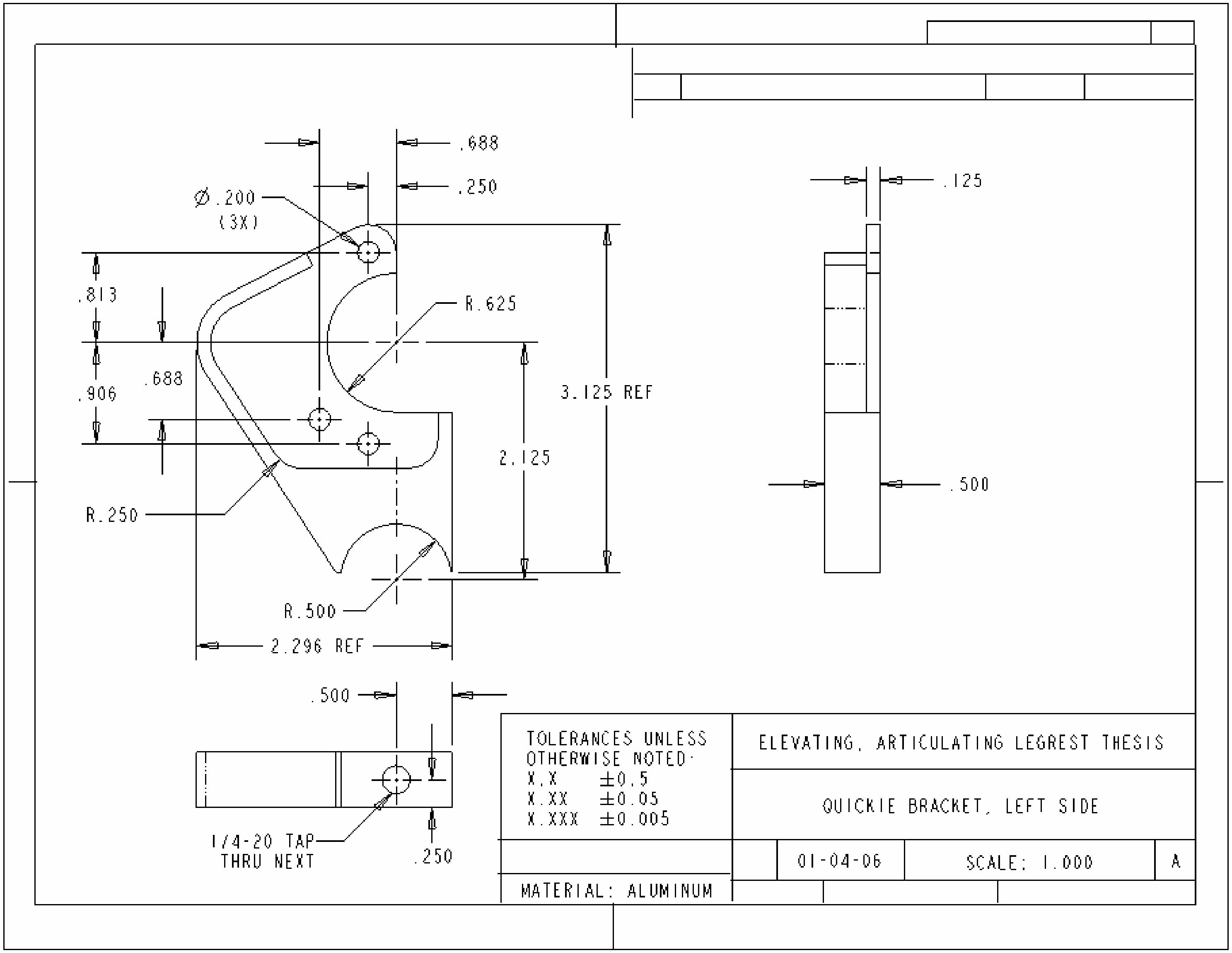

TYP
R.375
.375
.188
.375
7.253
2.861
.969
1.517
4.236
R.188
THRU SLOTS (2X)
MASS RELIEF (2X)
DO NOT MACHINE
BUSHING HOLES (2X):
DRILL & REAM
Ø0.377 - Ø0.378 INCH BUSHINGS
(PRESS/INT FIT)
2.517
0.250" DEEP
.750
.750
PIN HOLE (1X)
DRILL & REAM
1/4 INCH PINS
(PRESS/INT FIT)
ELEVATING, ARTICULATING LEGREST THESIS
LINK 4
12-02-05
SCALE 1.000
A
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
QTY 2 REQUIRED
6061-T6 AL

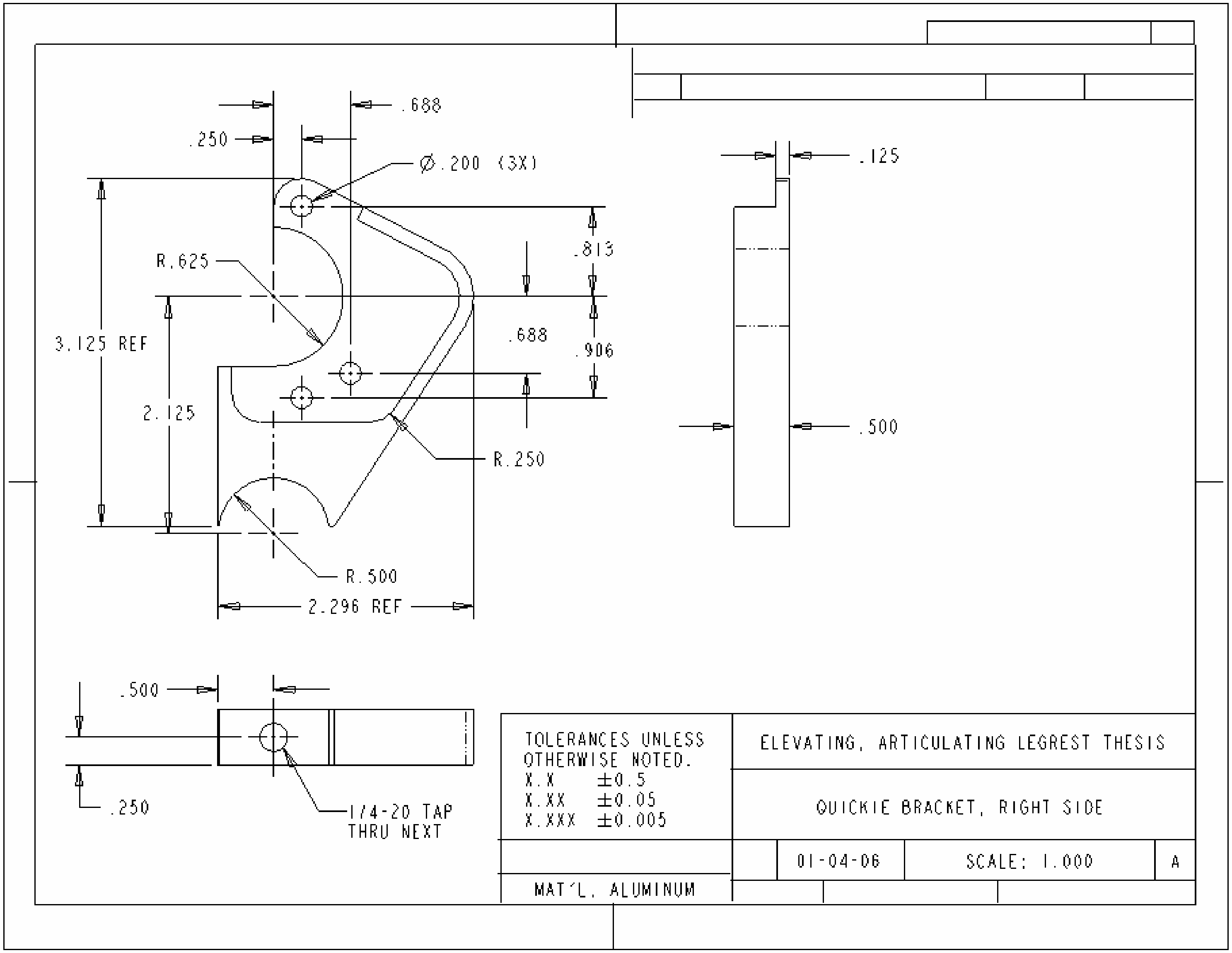

Ø1.000
4.919
R.375
R.250
.1875
.625
.250
PIN HOLES (2X):
DRILL & REAM
1/4 INCH PIN
(PRESS/INT FIT)
4.044
.875
R.250
MASS RELIEF (2X):
0.0625 INCH DEEP
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
ELEVATING, ARTICULATING LEGREST THESIS
LINK 5
QTY 2 REQUIRED
6061-T6 AL
12-02-05
SCALE 1.000
A

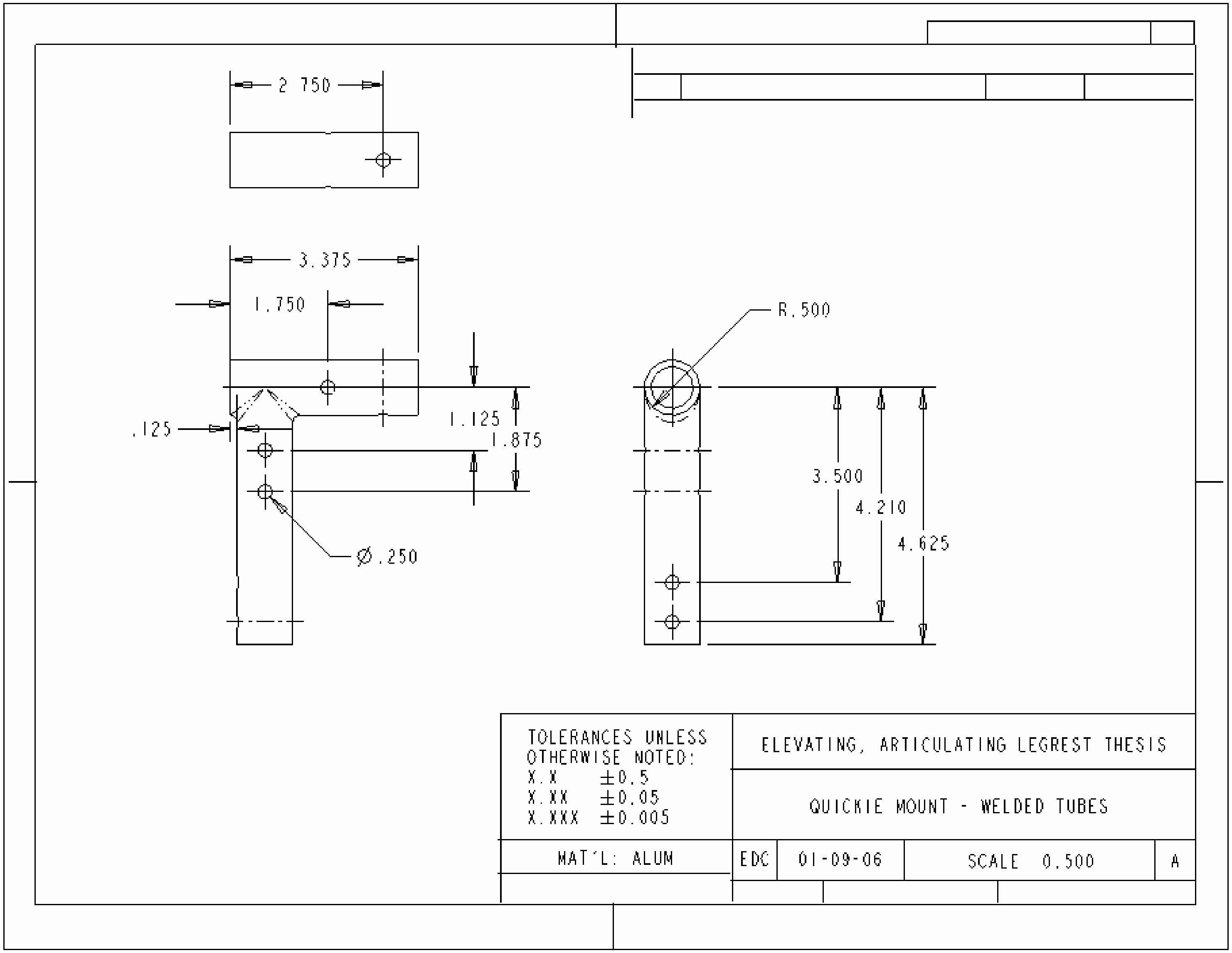

3.500
.500
DRILL & REAM FOR
0.375" BUSHING (PRESS FIT)
R.500
.500
.250
R.125 (MACHINE WITH 1/4" ENDMILL)
.750
1.250
2.250
4.125
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: 6061 ALUM
ELEVATING/ARTICULATING LEGREST THESIS
LINK 6: 1"X1" SQUARE TUBE
12-02-05
SCALE 0.750
A

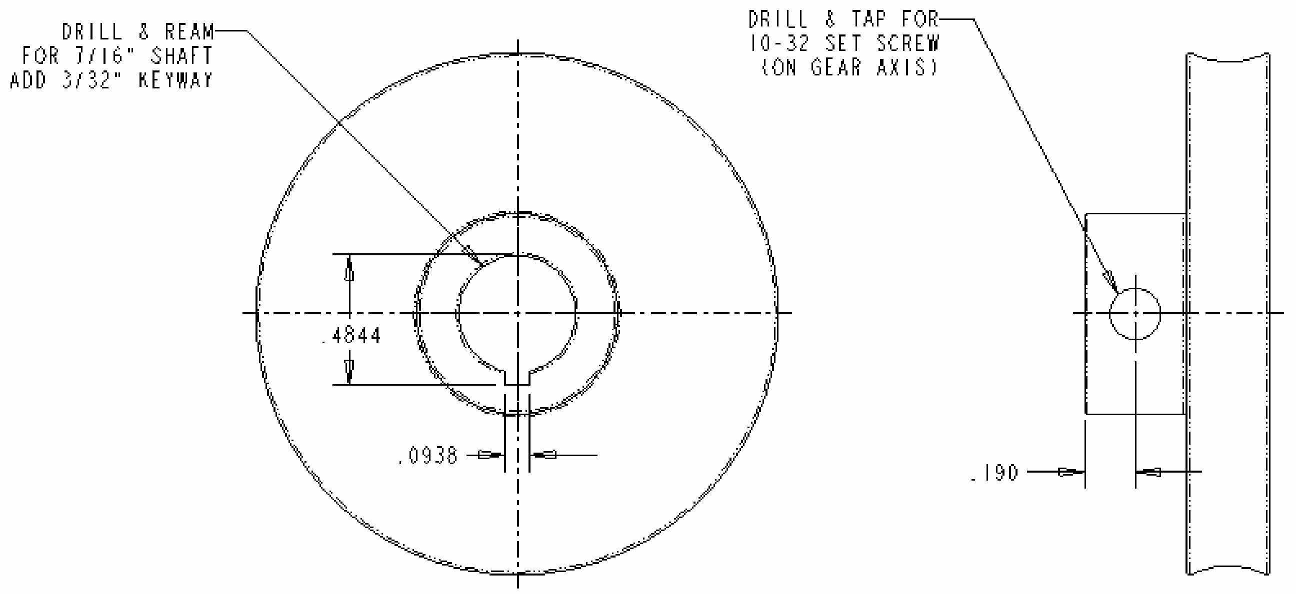

3 250 REF
3.000
2.750
2.250
2.000
1.625
1.250
1.000
.250
.250
.500
.750
1.000
Ø.138
R.250
1/4-20 TAP, 3X
1.250
1.625
2.375
2.750 REF
R.500
.250
1.000 REF
TOLERANCES UNLESS OTHERWISE NOTED:
X X ±0 5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
ELEVATING, ARTICULATING LEGREST THESIS
QUICKIE POST MOUNT - LEFT
EDC
01-13-06
SCALE: 1.000
A


ELEVATING, ARTICULATING LEGREST THESIS
QUICKIE POST MOUNT - RIGHT
EDC
01-09-06
SCALE: 1.000
A
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
.250
R.500
1.000 REF
2.750 REF
1.000
.750
.250
Ø.138
R.250
Ø.250
3.250 REF
3.000
2.250
2.000
1.625
1.250
1.000
.250
.500
1.250
1.625
2.375
.500
1.000


.688
.250
∅.200
(3X)
.125
R.625
.813
.906
.688
3.125 REF
2.125
.500
R.250
R.500
2.296 REF
.500
1/4-20 TAP
THRU NEXT
.250
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MATERIAL: ALUMINUM
ELEVATING, ARTICULATING LEGREST THESIS
QUICKIE BRACKET, LEFT SIDE
01-04-06
SCALE: 1.000
A


.688
.250
Ø.200 (3X)
R.625
3.125 REF
2.125
.813
.688
.906
R.250
R.500
2.296 REF
.125
.500
.500
.250
1/4-20 TAP
THRU NEXT
TOLERANCES UNLESS
OTHERWISE NOTED.
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L. ALUMINUM
ELEVATING, ARTICULATING LEGREST THESIS
QUICKIE BRACKET, RIGHT SIDE
01-04-06
SCALE: 1.000
A


2 750
3.375
1.750
.125
1.125
1.875
Ø.250
R.500
3.500
4.210
4.625
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
ELEVATING, ARTICULATING LEGREST THESIS
QUICKIE MOUNT - WELDED TUBES
EDC
01-09-06
SCALE 0.500
A



NOTES:
1) WITH GEAR ORIENTED AS SHOWN
(WITH KEYWAY IN THE DOWN POSITION)
MACHINE ONE GEAR WITH SET SCREW
TAP ON THE RIGHT AND ONE GEAR WITH
SET SCREW TAP ON THE LEFT
2) GEAR SHAFT NOT MACHINED YET.
MAY WANT TO WAIT ON REAMING THE
GEAR BORE UNTIL EXACT SHAFT DIAMETER
IS KNOWN.

TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005

ELEVATING, ARTICULATING LEGREST THESIS

WORM GEAR MODIFICATION

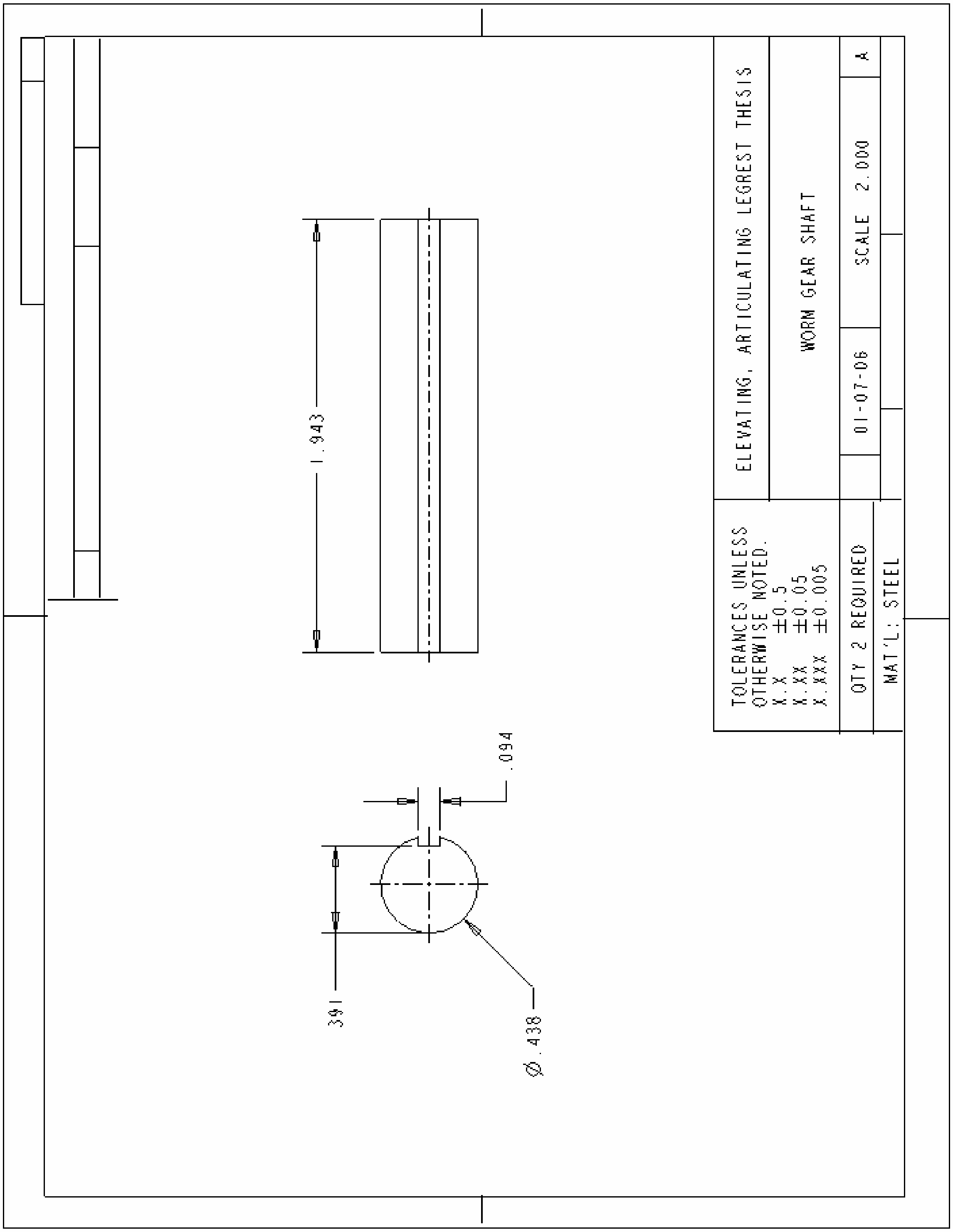
QTY 2 REQUIRED

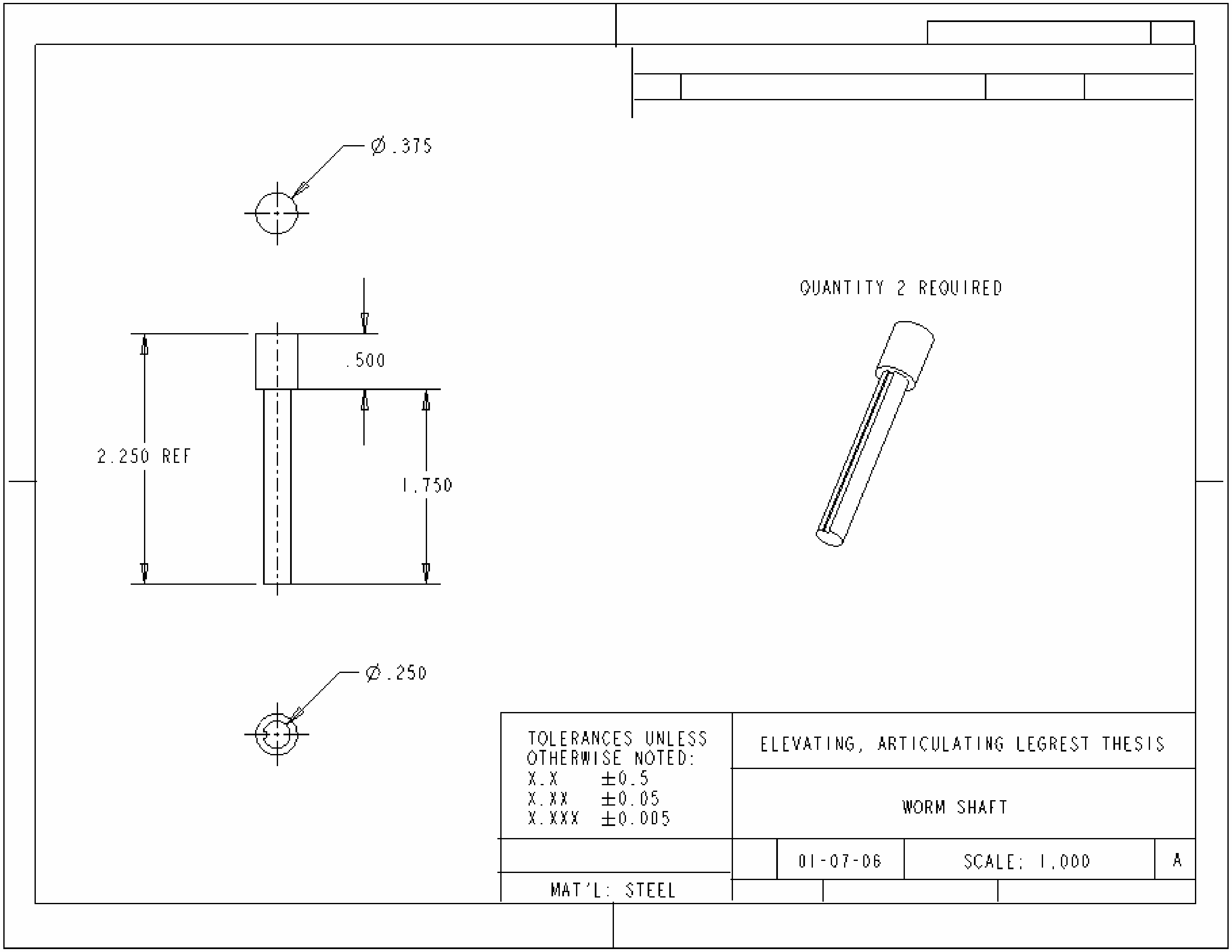
01-07-06

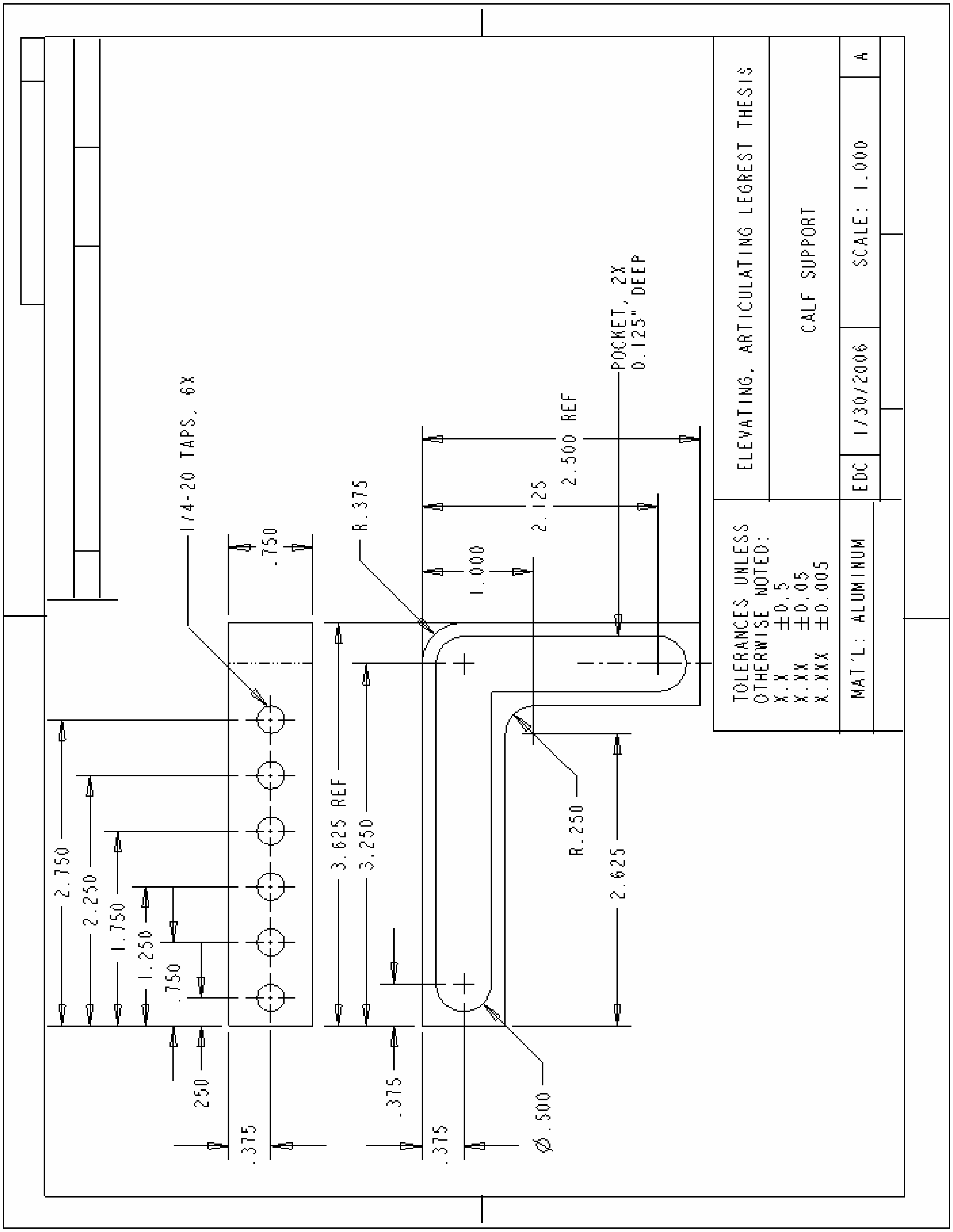
SCALE 2.000

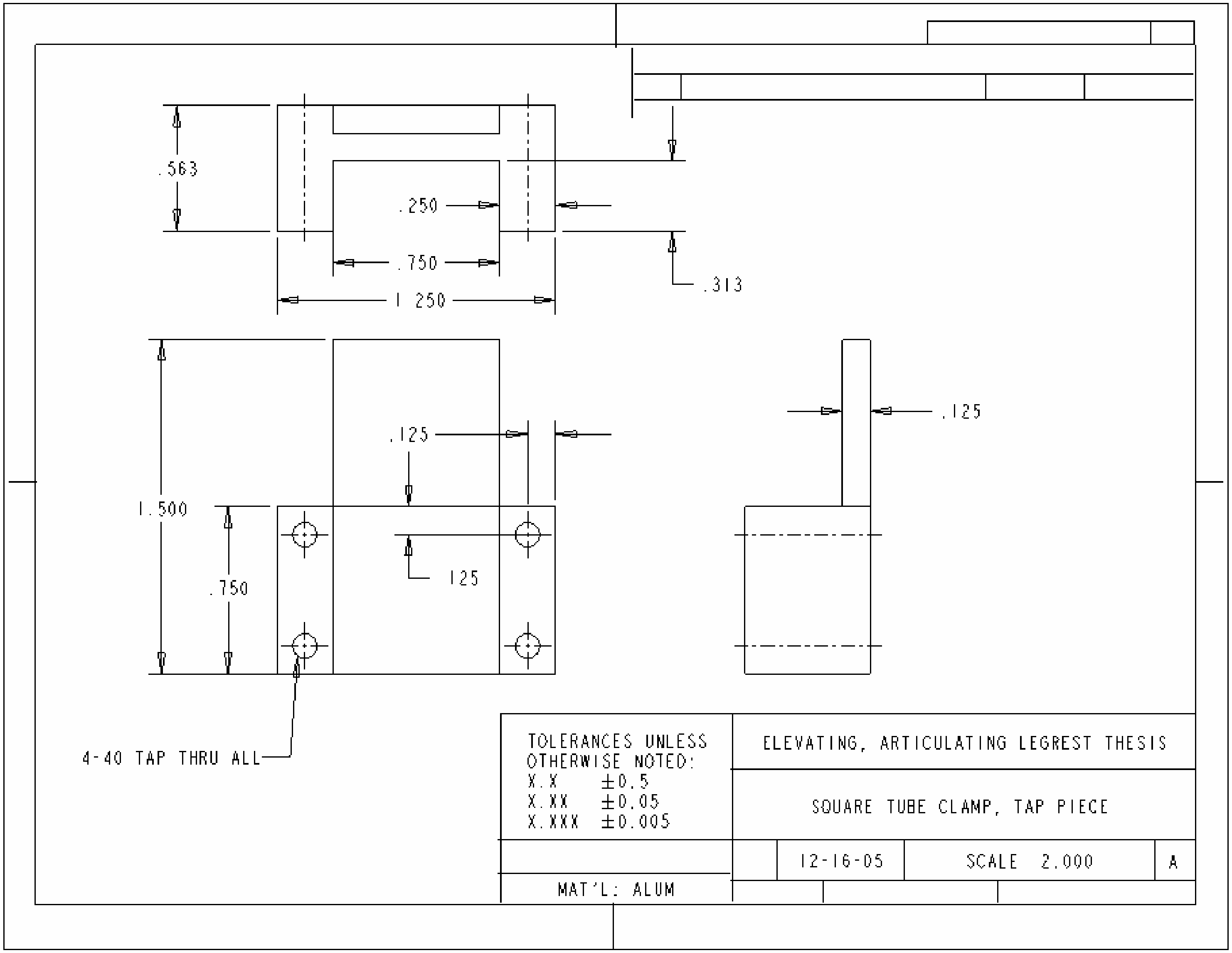
A

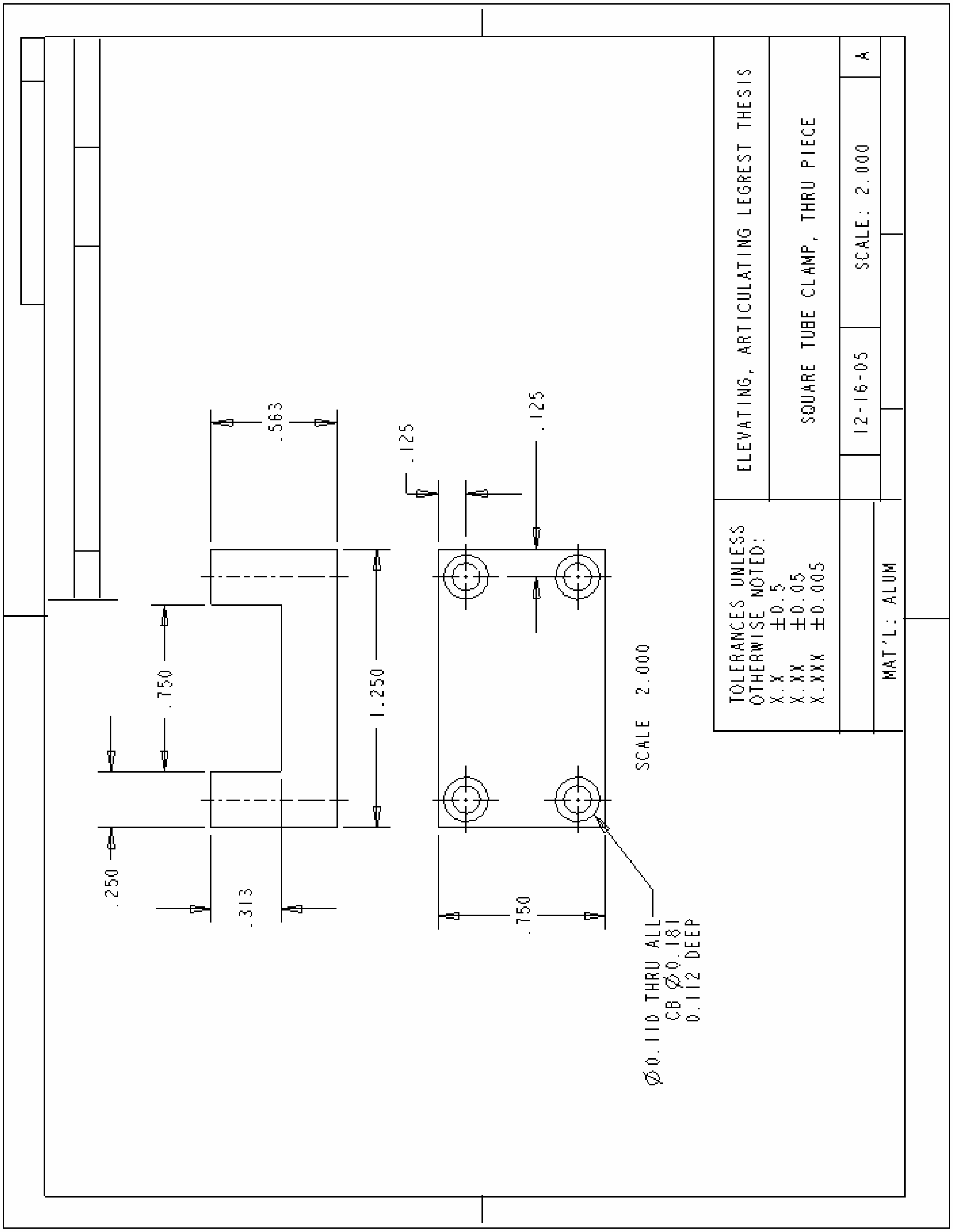
MAT'L: BRONZE

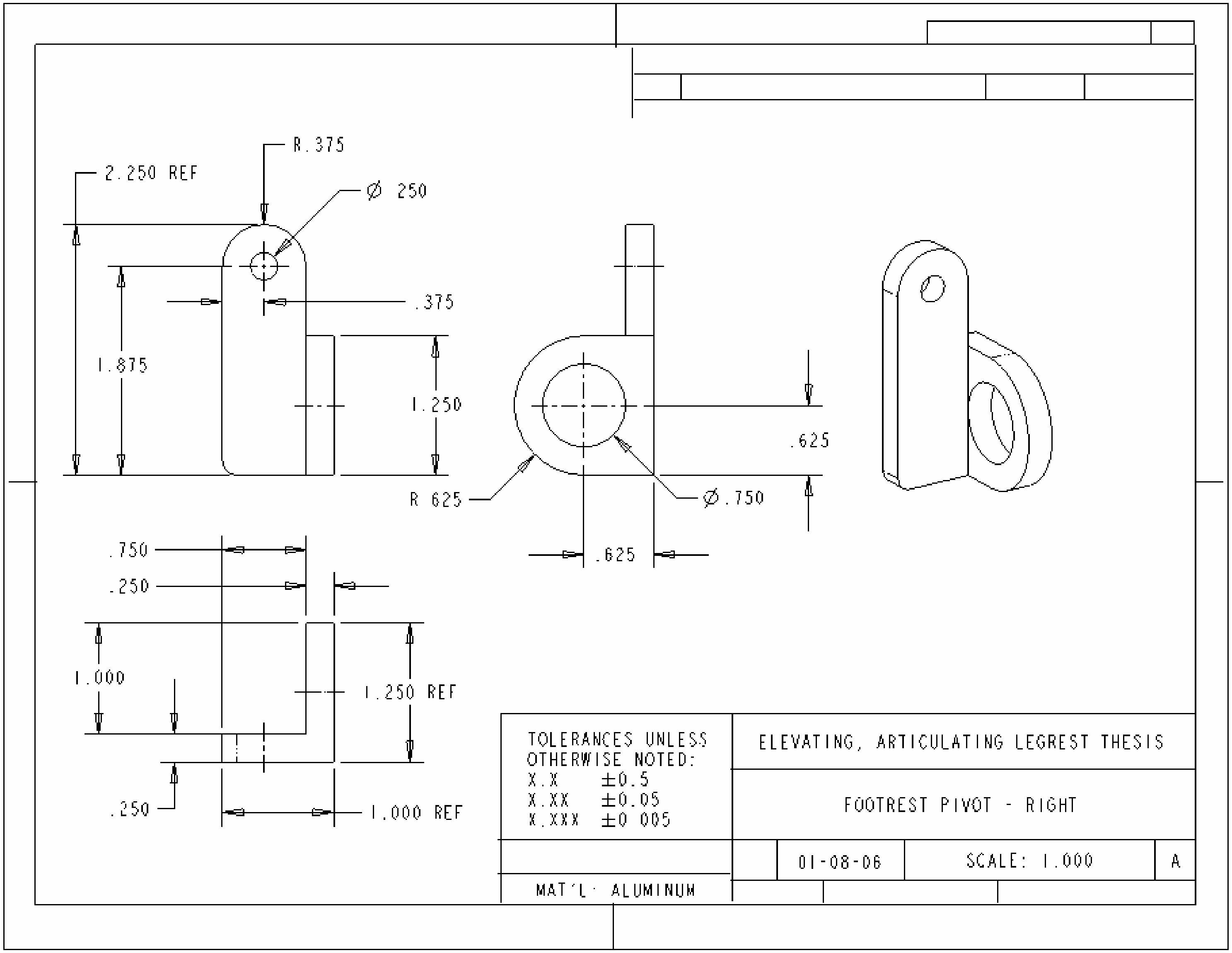

ELEVATING, ARTICULATING LEGREST THESIS
WORM GEAR SHAFT
01-07-06
SCALE 2.000
A
TOLERANCES UNLESS OTHERWISE NOTED.
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
QTY 2 REQUIRED
MAT'L: STEEL
1.943
.094
.391
Ø.438

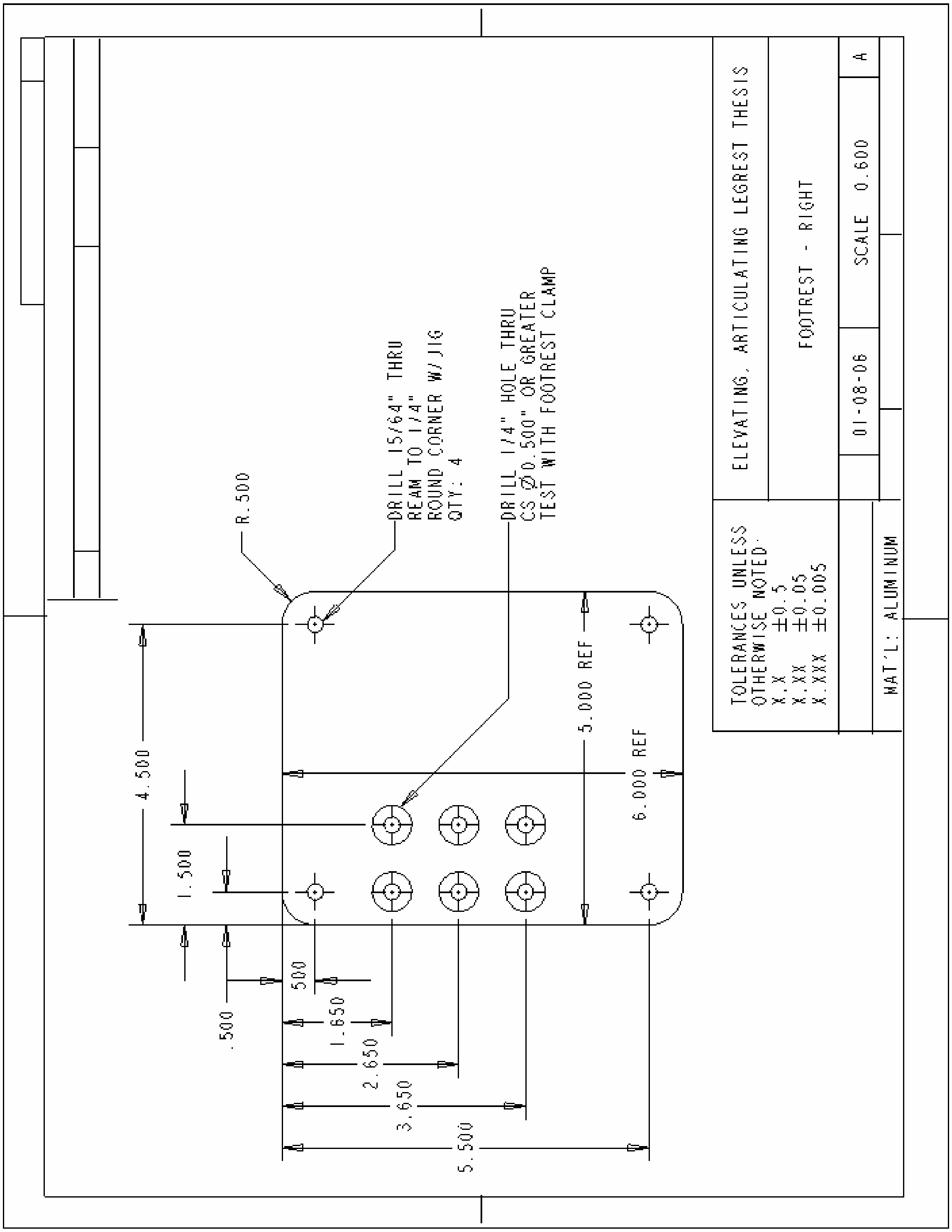

Ø.375
.500
2.250 REF
1.750
Ø.250
QUANTITY 2 REQUIRED
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: STEEL
ELEVATING, ARTICULATING LEGREST THESIS
WORM SHAFT
01-07-06
SCALE: 1.000
A

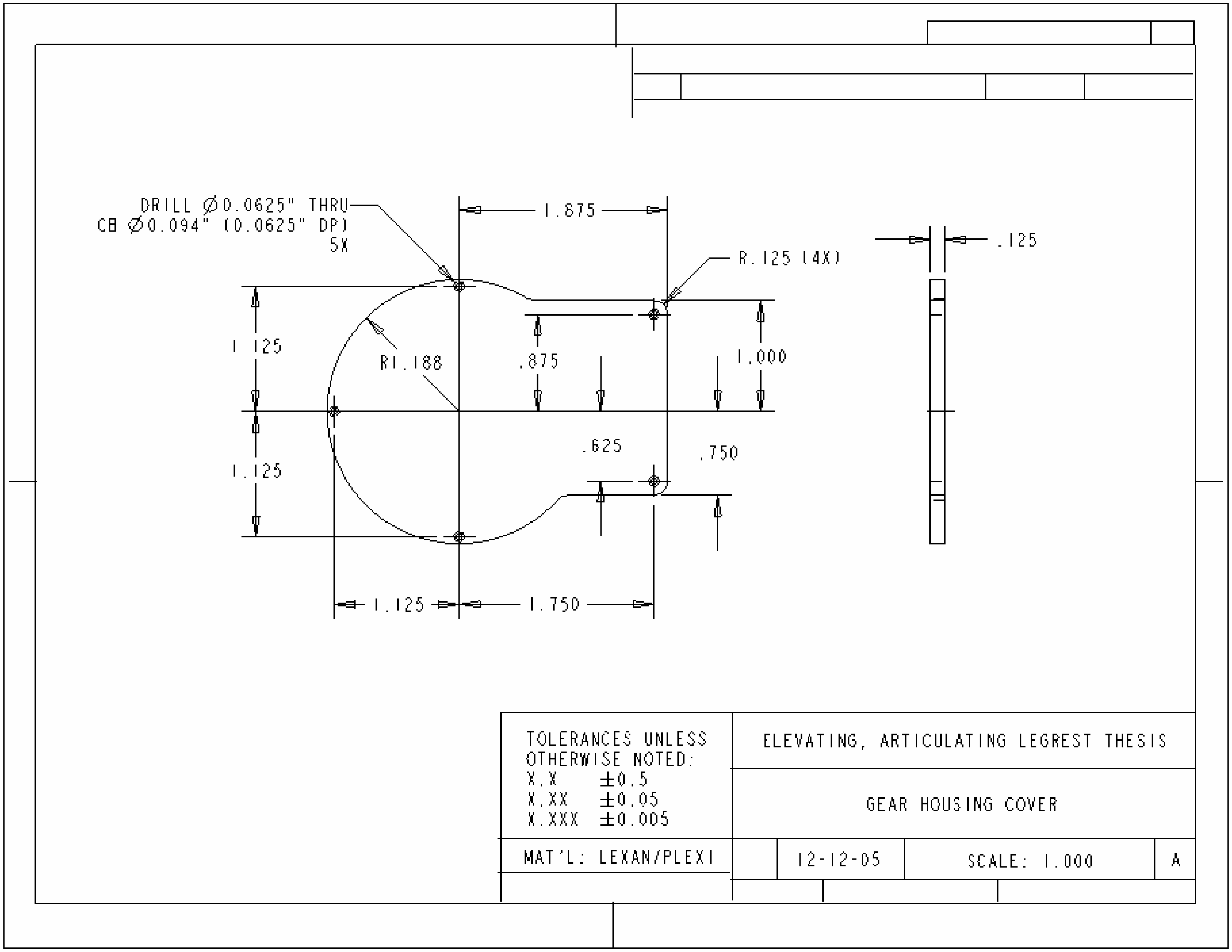

ELEVATING, ARTICULATING LEGREST THESIS
CALF SUPPORT
EDC
1/30/2006
SCALE: 1.000
A
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUMINUM
1/4-20 TAPS, 6X
.750
R.375
1.000
2.125
2.500 REF
POCKET, 2X
0.125" DEEP
R.250
2.625
3.625 REF
3.250
2.750
2.250
1.750
1.250
.750
.250
.375
.375
.375
.375
Ø.500


.563
.250
.750
1.250
.313
.125
1.500
.750
.125
.125
4-40 TAP THRU ALL
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
ELEVATING, ARTICULATING LEGREST THESIS
SQUARE TUBE CLAMP, TAP PIECE
12-16-05
SCALE 2.000
A


ELEVATING, ARTICULATING LEGREST THESIS
SQUARE TUBE CLAMP, THRU PIECE
12-16-05
SCALE: 2.000
A
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUM
SCALE 2.000
.563
.125
.125
.750
1.250
.250
.313
.750
Ø0.110 THRU ALL
CB Ø0.181
0.112 DEEP


R.375
2.250 REF
Ø 250
.375
1.875
1.250
R 625
.625
Ø.750
.625
.750
.250
1.000
1.250 REF
.250
1.000 REF
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0 005
MAT'L· ALUMINUM
ELEVATING, ARTICULATING LEGREST THESIS
FOOTREST PIVOT - RIGHT
01-08-06
SCALE: 1.000
A


R.500
DRILL 15/64" THRU
REAM TO 1/4"
ROUND CORNER W/JIG
QTY: 4
DRILL 1/4" HOLE THRU
CS ∅0.500" OR GREATER
TEST WITH FOOTREST CLAMP
4.500
1.500
.500
.500
1.650
2.650
3.650
5.500
5.000 REF
6.000 REF
ELEVATING, ARTICULATING LEGREST THESIS
FOOTREST - RIGHT
01-08-06
SCALE 0.600
A
TOLERANCES UNLESS
OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: ALUMINUM


DRILL Ø0.0625" THRU
CB Ø0.094" (0.0625" DP)
5X
1.875
R.125 (4X)
.125
1.125
1.125
R1.188
.875
1.000
.625
.750
1.125
1.750
TOLERANCES UNLESS OTHERWISE NOTED:
X.X ±0.5
X.XX ±0.05
X.XXX ±0.005
MAT'L: LEXAN/PLEXI
ELEVATING, ARTICULATING LEGREST THESIS
GEAR HOUSING COVER
12-12-05
SCALE: 1.000
A

APPENDIX D – BILL OF MATERIALS (BOM)

BILL OF MATERIALS

Vendor	Quantity	Model/Part #	Item Description	Item Price	Total Price
McMaster-Carr	1	9125A079	2-56 SHCS (Pack of 100)	$9.38	$9.38
McMaster-Carr	1	98535A125	(3/32"x3/32") 12" Key	$1.50	$1.50
McMaster-Carr	1	90145A540	3/4" (1/4") Pins (Pack of 20)	$5.62	$5.62
McMaster-Carr	1	90145A544	1-1/4" (1/4") Pins (Pack of 20)	$8.22	$8.22
McMaster-Carr	30	6338K411	1/4" Bronze Bushings	$0.49	$14.70
McMaster-Carr	6	6338K462	7/16" Bronze Bushings	$0.68	$4.08
Eastern Bearings, Inc.	2	G1043	Bronze Worm Gear, Ng=30	$28.90	$57.80
Eastern Bearings, Inc.	2	LVHB-1	Unhardened Steel Worm	$14.80	$29.60
McMaster-Carr	1	92196A054	#0-80 SHCS (Pack of 100)	$4.91	$4.91
McMaster-Carr	1	92196A115	#4-40 SHCS (Pack of 100)	$5.40	$5.40
McMaster-Carr	1	6546K213	1"x1" Aluminum Square Tube	$13.21	$13.21
McMaster-Carr	1	88875K523	3/4"x3/4" Aluminum Square Tube	$6.76	$6.76
McMaster-Carr	1	3151A109	7/16" Keyway Broach Bushing	$9.44	$9.44
Monroe	2	61663	Safety Pocket Handwheel	$48.36	$96.72
McMaster-Carr	1	91255A148	#6-32 Screws (Pack of 100)	$10.31	$10.31
McMaster-Carr	1	91255A547	1/4"-20 Screws (Pack of 10)	$6.30	$6.30
McMaster-Carr	1	91255A544	1/4"-20 Screws (Pack of 25)	$11.63	$11.63
McMaster-Carr	1	91255A546	1/4"-20 Screws (Pack of 10)	$6.60	$6.60
McMaster-Carr	1	98535A120	1/16"x1/16" Key	$0.96	$0.96
McMaster-Carr	1	3153A12	1/16" Keyway Broach	$40.93	$40.93
McMaster-Carr	1	3151A109	1/4" Keyway Broach Bushing	$9.44	$9.44
McMaster-Carr	1	91255A548	1/4"-20 Screws	$7.20	$7.20
McMaster-Carr	1	97763A265	1/4"-20 Screws	$6.92	$6.92
TOTAL					$367.63

Worm Gear Information:

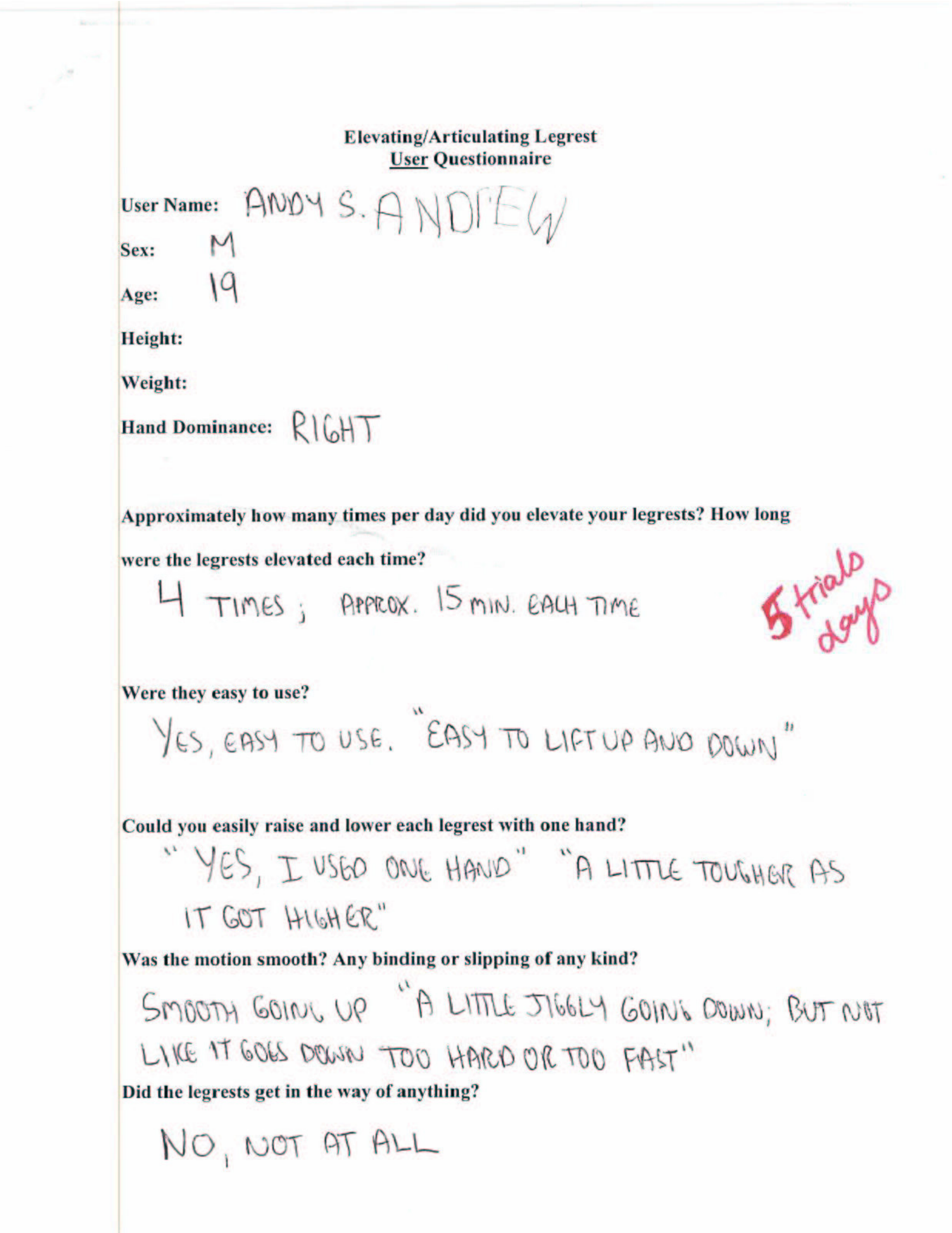
Diametral pitch:	16
Number of teeth:	30
Pitch diameter:	1.250”
Bore diameter:	0.3125”
Hub diameter:	0.750”
Hub projection:	0.380”
Face width:	0.313”
Material:	Bronze
Style B	
Single thread	

Worm Information:

Diametral pitch:	16
Number of teeth:	1
Pitch diameter:	0.625”
Face:	1.00”
Bore diameter:	0.250”
Hub diameter:	0.440”
Hub projection:	0.250”
Material:	Unhardened steel

APPENDIX E – MHS QUESTIONNAIRES

Andy



Elevating/Articulating Legrest
User Questionnaire

User Name: ANDY S. ANDREW

Sex: M

Age: 19

Height:

Weight:

Hand Dominance: RIGHT

Approximately how many times per day did you elevate your legrests? How long were the legrests elevated each time?

4 TIMES; APPROX. 15 MIN. EACH TIME

5 trials days

Were they easy to use?

YES, EASY TO USE. "EASY TO LIFT UP AND DOWN"

Could you easily raise and lower each legrest with one hand?

"YES, I USED ONE HAND" "A LITTLE TOUGHER AS IT GOT HIGHER"

Was the motion smooth? Any binding or slipping of any kind?

SMOOTH GOING UP "A LITTLE JIGGLY GOING DOWN; BUT NOT LIKE IT GOES DOWN TOO HARD OR TOO FAST"

Did the legrests get in the way of anything?

NO, NOT AT ALL

Did any clothes get caught in the legrests?

NO

How was the angle of the legrests in the down position?

FINE - IT COULD GET EVEN LOWER THAN THE OTHER [ORIGINAL] LEGREST

When you elevated the legrests, were your legs able to be straight?

YES; KNEE STAYED STRAIGHT; ONE ON OTHER LEGREST (ORIGINAL] IS BENT

Did you have any pain or discomfort using the legrests?

NO

Were you easily able to transfer into and out of your wheelchair with the legrests in place?

NO; NO DIFFICULTY.

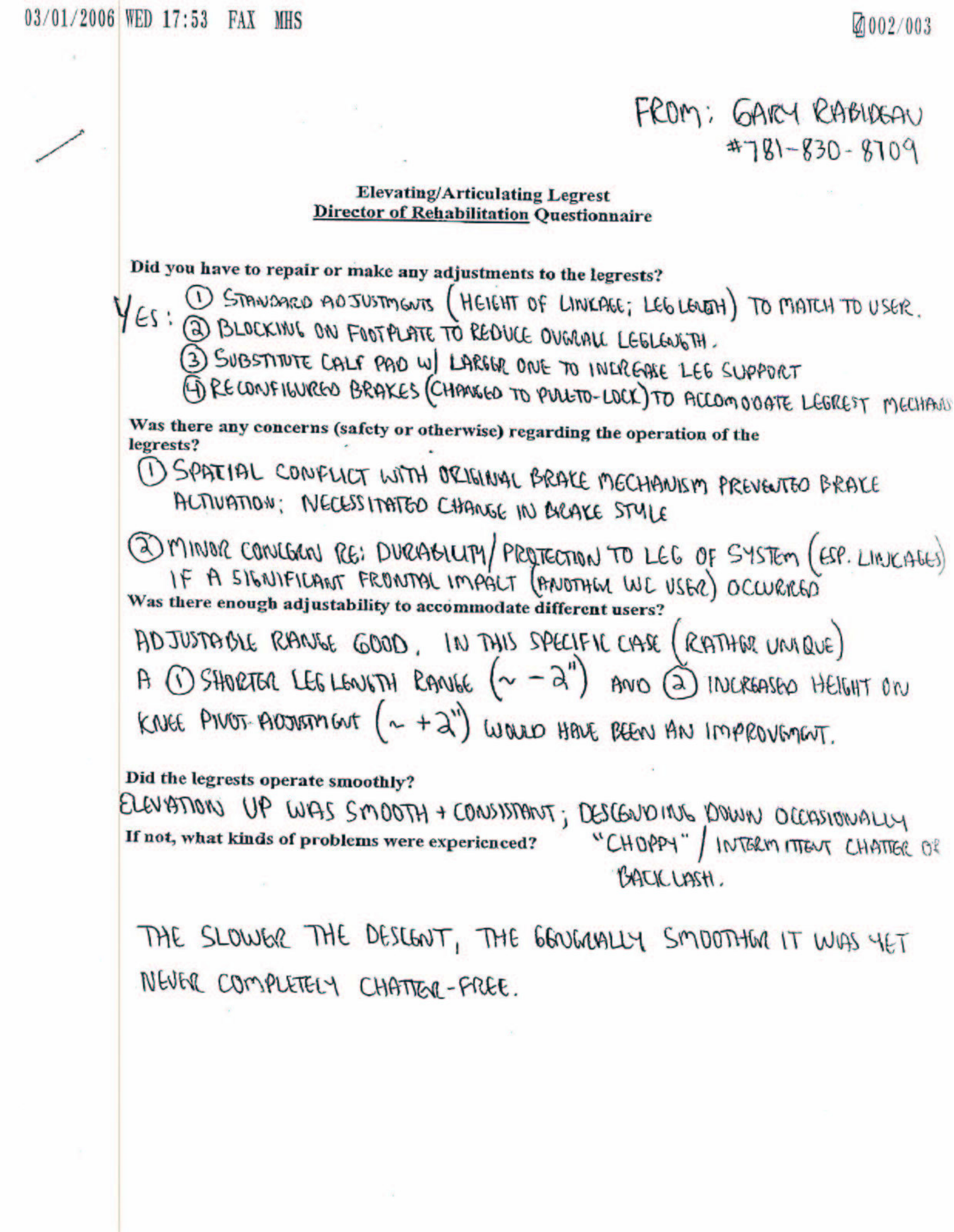
Any general comments?

I WISH IT SWUNG OUTWARD; SOME NURSES HAD DIFFICULTY WITH TRANSFERS (SOME HAD TO CHANGE HOW THEY DID IT.

I LIKE THE WAY IT LOOKS.

IT'S EASY TO LIFT UP AND DOWN.

Gary Rabideau – Director of Rehabilitation Engineering



03/01/2006 WED 17:53 FAX MHS ☑002/003

FROM: GARY RABIDEAU
#781-830-8709

Elevating/Articulating Legrest
Director of Rehabilitation Questionnaire

Did you have to repair or make any adjustments to the legrests?

YES: ① STANDARD ADJUSTMENTS (HEIGHT OF LINKAGE; LEG LENGTH) TO MATCH TO USER.
② BLOCKING ON FOOTPLATE TO REDUCE OVERALL LEGLENGTH.
③ SUBSTITUTE CALF PAD W/ LARGER ONE TO INCREASE LEG SUPPORT
④ RECONFIGURED BRAKES (CHANGED TO PULL-TO-LOCK) TO ACCOMODATE LEGREST MECHAN

Was there any concerns (safety or otherwise) regarding the operation of the legrests?

① SPATIAL CONFLICT WITH ORIGINAL BRAKE MECHANISM PREVENTED BRAKE ACTUATION; NECESSITATED CHANGE IN BRAKE STYLE

② MINOR CONCERN RE: DURABILITY/PROTECTION TO LEG OF SYSTEM (ESP. LINKAGES) IF A SIGNIFICANT FRONTAL IMPACT (ANOTHER WC USER) OCCURRED

Was there enough adjustability to accommodate different users?

ADJUSTABLE RANGE GOOD. IN THIS SPECIFIC CASE (RATHER UNIQUE) A ① SHORTER LEG LENGTH RANGE (~ -2") AND ② INCREASED HEIGHT ON KNEE PIVOT ADJUSTMENT (~ +2") WOULD HAVE BEEN AN IMPROVEMENT.

Did the legrests operate smoothly?

ELEVATION UP WAS SMOOTH + CONSISTANT; DESCENDING DOWN OCCASIONALLY

If not, what kinds of problems were experienced?

"CHOPPY" / INTERMITTENT CHATTER OR BACKLASH.

THE SLOWER THE DESCENT, THE GENERALLY SMOOTHER IT WAS YET NEVER COMPLETELY CHATTER-FREE.

Do you have any recommendations for improving the design?

① INCORPORATE LARGER CALF PAD PER REVISION

② RECONFIGURE SWING-INWARD-TO-REMOVE BACK TO CONVENTIONAL SWING AWAY OR LIFT UP/OFF MECHANISM. THIS WILL FACILITATE TRANSFERS AND POSITIONING WHEN REMOVAL OF LEGRESTS ARE INDICATED.

③ REDUCE POTENTIAL SPACE/ACCESS CONFLICTS WITH HAND BRAKE/WHEEL LOCK MECHANISMS

How does this design compare to other elevating and/or articulating designs you've dealt with?

SOME EXCELLENT IMPROVEMENTS OVER COMMERCIAL DESIGNS, INCLUDING:

① INDEPENDENT ELEVATION BY USER BIG ADVANTAGE

② FUNCTIONAL ARTICULATION ACCOMMODATES TRUE LEG EXTENSION WHILE ELEVATING

③ KNEE AXIS ADJUSTMENT VERY USEFUL - IMPORTANT FOR EFFECTIVE ELEVATION (②+③ DECREASES RISK OF STRESS OR CONTRAINDICATED POSITIONING OF THE LEG)

What is your overall evaluation of the design?

A VERY GOOD DESIGN - CREATIVE, FUNCTIONAL AND POTENTIALLY VERY BENEFICIAL TO THE USER. IMPROVEMENTS OVER COMMERCIAL DESIGNS AS NOTED ABOVE.

ONE SIGNIFICANT IMPEDIMENT TO MARKET APPLICATION WOULD BE SWING INWARD FEATURE - THIS NEEDS REVISION AS DESCRIBED ABOVE.

Any general comments?

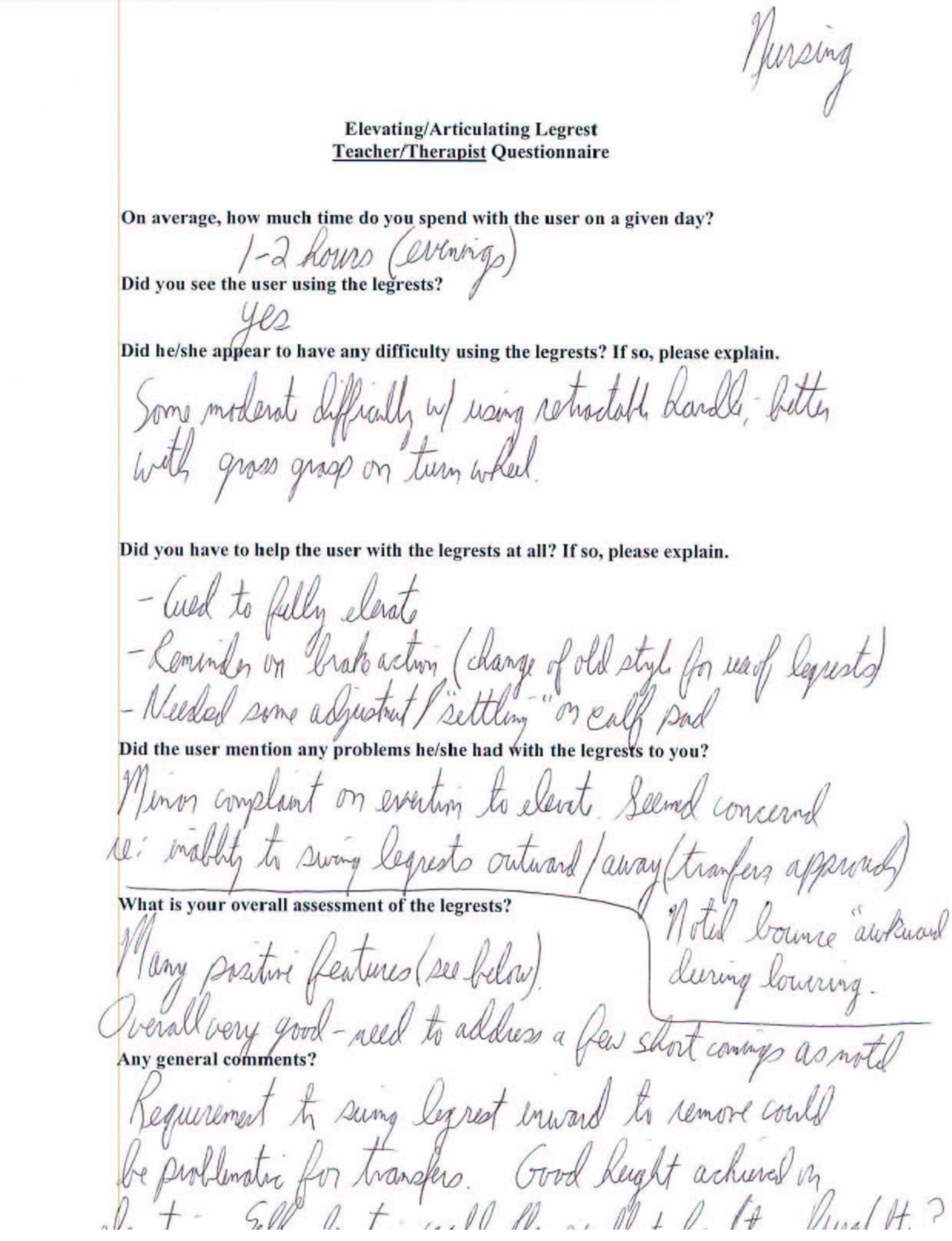
① VERY WELL DONE !

② THOUGHTFUL DESIGN - USER FRIENDLY IN MANY RESPECTS

③ FABRICATION VERY WELL EXECUTED - A GOOD WORKING MODEL FOR TRIALS.

④ WOULD LOVE TO SEE FEEDBACK INCORPORATED INTO NEW VERSION (MUCH MARKET POTENTIAL HERE)

Nursing



Nursing

Elevating/Articulating Legrest
Teacher/Therapist Questionnaire

On average, how much time do you spend with the user on a given day?

1-2 hours (evenings)

Did you see the user using the legrests?

yes

Did he/she appear to have any difficulty using the legrests? If so, please explain.

Some moderate difficulty w/ using retractable handle; better with gross grasp on turn wheel.

Did you have to help the user with the legrests at all? If so, please explain.

- Cued to fully elevate
- Reminder on brake action (change of old style for use of legrests)
- Needed some adjustment / "settling" on calf pad

Did the user mention any problems he/she had with the legrests to you?

Minor complaint on exertion to elevate. Seemed concerned re: inability to swing legrests outward / away (transfers approach)

What is your overall assessment of the legrests?

Many positive features (see below).

Noted bounce "awkward" during lowering.

Overall very good - need to address a few short comings as noted

Any general comments?

Requirement to swing legrest inward to remove could be problematic for transfers. Good height achieved on