MQP HXA-1601

# Transfer Device Design for an Eight Year Old Student

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# Abstract

The goal of this project was to facilitate the transfer of an eight-year-old student with cerebral palsy from her wheelchair to an existing standing assist device by designing an attachment for the standing device. The transfer to and from the standing device used to require two aides, which was demanding in the school environment. A four-bar slider mechanism, driven by a linear actuator, was designed to rotate a frame from a position over her wheelchair to the standing device. The client is suspended from the crossbar of this frame in a quick to don and stable harness. Additionally, the transfer mechanism has a small footprint outside of the initial device, which was important for use in a public school. The mechanism facilitates the client's transfer by a single aide more quickly and with less physical exertion.

# Authorship

This report represents the cumulative work of Lindsey Andrews, Jonathan Rheaume and Yingzhe Zhao. All members of the team contributed to the completion of the project and the accompanying report.

# Acknowledgements

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- Sally Goodhile, PT and the Roosevelt Elementary School – *Project Sponsors*
- Professor Allen Hoffman and Professor Holly Ault – *Co-Advisors*
- James Loiselle - *Manufacturing Labs Senior Instructor and Technician*
- Alex Lemmon and Brian Peterson - *Manufacturing Assistance*

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# 1. Introduction

The purpose of this project is to create a device that will allow the client to be transferred from her wheelchair into a standing device. The client is an eight-year old girl named Felicity who has cerebral palsy, a condition that affects a person's ability to control their muscular activity. This client is not able to stand on her own, therefore she must spend most of her time in a wheelchair. Though she is nonverbal, she is able to bring life to those around her with a simple, yet beautiful, smile.

Students from Worcester Polytechnic Institute (WPI) worked with this client two years ago to design a device that would allow her to be supported in a vertical position to simulate standing. With a series of boards and straps, this device is able to hold her in a vertical position with little muscular effort. The standing device was highly successful and was used two to three times a week for about 20 to 30 minutes at a time. Felicity's time in the standing device is very meaningful physiologically as well as psychologically. Physiologically, this device allows Felicity to put dynamic loads on her legs, increasing bone density, and improves the functionality of her organ systems, such as her cardiovascular and digestive systems. Psychologically, standing is proven to improve confidence and promote a feeling of equality among peers.

The problem this project has set out to solve is the simplification of the transfer process to and from the standing device from the wheelchair to maximize the amount of time Felicity is able to spend in her standing device. Currently, this process is time consuming and physically straining for the people assisting in the transfer. Two people are needed for this process. One assistant must lift and carry the client to the standing device, then hold her in place as the second assistant secures the straps in place. As the client grows, this transfer will continue to become more difficult and time consuming.

For our client to spend more time in the standing device, a change in the transfer process must occur. The goal of this project will become a reality using mechanical design experience and clinical research.

# 2. Background

Prior to design, it is crucial to understand the client's conditions and the functions that will be required for the design due to these conditions. Detailed background research was conducted on Cerebral Palsy, its causes, symptoms and treatments, available products on the market and the needs assessment for the design. Our client, Felicity, is an eight-year-old student from Worcester public school systems; due to her condition, she is nonverbal and has only control of her arm movement, requiring total assistance.

## 2.1 Cerebral Palsy

Cerebral Palsy (CP) is a group of neurological disorders characterized by neurological impairments resulting from abnormal development of or damage to the brain either before birth or during the first years of life [1]. As a result of the brain damage, a child's muscle control, muscle coordination, muscle tone, reflex, posture and balance can be affected. It can also impact a child's fine motor skills, gross motor skills, and oral motor functioning.

### 2.1.1 CP Causes

The brain damage that causes Cerebral Palsy could be a result of cell death, ineffective cell migration, non-functional or inappropriate connections between brain cells or poor myelination of developing nerve cell fibers during the prenatal period. Trauma, infections, events in the birthing process that starve oxygen to the brain, genetic and environmental effects are all factors that may affect brain development and lead to CP in an infant before, during, or after birth [2].

### 2.1.2 CP Symptoms

There are four kinds of CP: spastic, athetoid, ataxic, and mixed CP. The spastic form of CP involves a severe paralysis of voluntary movements and is the most common type of CP. Athetoid CP is characterized by abnormal and involuntary movement and inability to control muscle tone. Ataxtic CP is diagnosed by poor coordination, muscle weakness, unsteady gait, and difficulty performing rapid or fine movements. The final condition is defined by the occurrence of two or more of these conditions and the individual is diagnosed with mixed CP [1].

The cerebral damage which causes spastic cerebral palsy primarily affects the neurons and connections of the cerebral cortex, either of one cerebral hemisphere (contralateral to paralysis) called infantile hemiplegia, or of both hemispheres called diplegia. Spasticity refers to the increased tone or tension in a muscle. There are two commands in muscle control for muscles to move smoothly and easily while maintaining strength. The tense command goes to the spinal cord via nerves from the muscle itself, while, on the other hand, the command to be flexible comes from nerves in the brain to the spinal cord. In a person with CP, damage to the brain has occurred. The damage tends to be around muscle control nerves, especially for arm and leg movements.

### 2.1.3 Treatments

Due to the fact that CP is a condition caused by permanent brain damage, most treatments serve to alleviate chronic CP symptoms rather than cure the underlying condition. Treatment for CP also depends on the severity and type of CP. Long-term treatments include physical and other therapies, drugs, and sometimes surgery. All treatments require proper assessment of the patient's specific condition.

Medications that provide positive effects for CP include muscle relaxants and sedatives. People with CP suffer from improper muscle control. Therefore, muscle relaxants are therapeutic because they are able to reduce muscle tension and help relieve muscle pain and discomfort. For example, Baclofen and Tizanidine are commonly used drugs for muscle spasms. People with CP sometimes perform involuntary movements, therefore, sedatives, which cause drowsiness, calmness and dull senses, are often considered for CP treatment. Diazepam is the most common type of sedative [3].

Orthopedic surgery can be effective for individuals with mild CP conditions. Muscle and tendon lengthening can relieve tightness and reduce painful contractures. This lengthening allows for a greater range of motion and increases the patient's' motor skills. Tendon transfer and tendonomy involve cutting and replacement of tendons, to increase muscle function as well as reduce pain and walking problems. Osteotomy is used to realign joints for better posture and mobility. It involves repositioning bones at angles more conducive to healthy alignments and is commonly used to correct hip dislocations. In severe cases of spasticity, when splints and casts are not enough, arthrodesis may be used to permanently fuse bones together. Fusing the bones in the ankle and foot can make it easier for a child with CP to walk [4].

Therapeutic treatments of CP often involve the use of assistive devices. Wheelchairs are the most commonly used and most beneficial device during daily life. After wheelchairs, standing devices are considered the second most beneficial to children with special needs [5]. Standing has been shown to improve quality of life in several ways. Psychologically, being at eye level with peers increases a person's confidence and sense of equality [6]. Standing also has physiological benefits. Exposing bone to the dynamic loading caused by standing helps increase bone density and muscle mass. It can also improve cardiopulmonary function, bladder function, and reduce the chance of pressure ulcers [6].

## 2.2 Needs Assessment

### 2.2.1 Felicity

The client for which this device is being designed is an eight year old girl named Felicity. Felicity has a severe form of spastic Cerebral Palsy. Her muscles are in constant contracture due to incorrect signaling from her brain. The contraction in her arms and legs cause her to exhibit constant flexion in her knees, elbows, and ankles. This reduces flexibility in her joints and inhibits weight bearing capabilities of her muscles. She is therefore unable to stand on her own so she spends most of her day in a wheelchair. Felicity has some arm and hand function but lacks precise control. She is able to wave her arms around to express herself but not able to write or pick up objects.

Felicity is also a non-verbal case of Cerebral Palsy. She is unable to communicate through spoken words, however, she can communicate in various ways. Her facial expressions are bright and animated so they are an effective way of communicating how she is feeling. Her physical therapist has used a switch system to communicate a "yes" or "no" response, which she has enough control in her arms to use. Felicity was recently provided new technology called the MyTobii, which is a gaze tracker designed to help her communicate as well. Currently, this device is not used regularly as both the school staff and Felicity must learn how to use it effectively.

Felicity's body segment lengths and circumferences, and joint flexion were recorded. Understanding the client's physical limitations and dimensions is vital for the success of the transfer device. Felicity's limbs are very thin--having a small circumference. These small circumferential values can be explained by her lack of weight bearing capabilities (Table 1). Due to the fact that her muscles rarely experience significant load, her muscle content is very minimal. The angles of flexure in Felicity's legs are recorded in Table 2. This table shows the angles in her knees and hips when she is in her most extended, or straightened position, and her relaxed position. These measurements were taken from the previous MQP report with the assumption that these angles have not changed in the past two years. Supplemental value of Felicity's limb lengths and circumferences were taken upon the team's first meeting with her. As can be seen by these values, Felicity is not able to achieve a fully straightened position in her knees. She is able to straighten, with some force, her knees to a slightly straighter position and her hips to a fully straightened position. It is important to understand that the device must account for this flexion and not cause injury or discomfort due to it.

*Table 1 Felicity's Body Measurements*

| Body Segment Lengths (inches) | | Segment Circumferences (inches) | |
|---|---|---|---|
| Heel to Hip* | 21 | Thigh | 9.5 |
| Feet to Knee | 13 | Knee | 9 |
| Knee to Hip | 10.5 | Calf | 8.5 |
| Hip to Shoulder | 13 | Chest | 28 |
| Shoulder to Head | 6 | Waist | 25 |
| Wrist to Shoulder | 13 | Hips | 21 |
| Shoulder to Elbow | 7 | Upper Arm | 6 |
| Elbow to Wrist | 6 | Lower Arm | 5 |
| *This measurement was taken at Felicity's straightest knee position | | | |

*Table 2 Felicity's Angles of Flexure Taken [7]*

| | Resting Angles of Flexure | | Maximum Angles of Flexure | |
|---|---|---|---|---|
| | Hip | Knee | Hip | Knee |
| Right Leg | 15° | 35°-25° | 0° | 20° |
| Left Leg | 15° | 45°-35° | 0° | Not Taken |

### 2.2.2 Current Devices

Two years ago, a group of student from WPI completed a design project for Felicity. Their design task was to create a device which would allow Felicity to stand in a supported vertical position. While standing devices are common on the market, Felicity and her physical therapist felt they did not fully meet their needs. The devices previously available did not account for Felicity's joint flexion, making them uncomfortable and not fully functional.

The Standing Device consists of three supportive particle boards at the feet, shins, and thigh and lower torso (Figure 1). The kneeboard and the front board are padded with exercise mats to create a water resistant cushion for Felicity's comfort. Strap supports along the kneeboard and front board safely secure Felicity in the device.

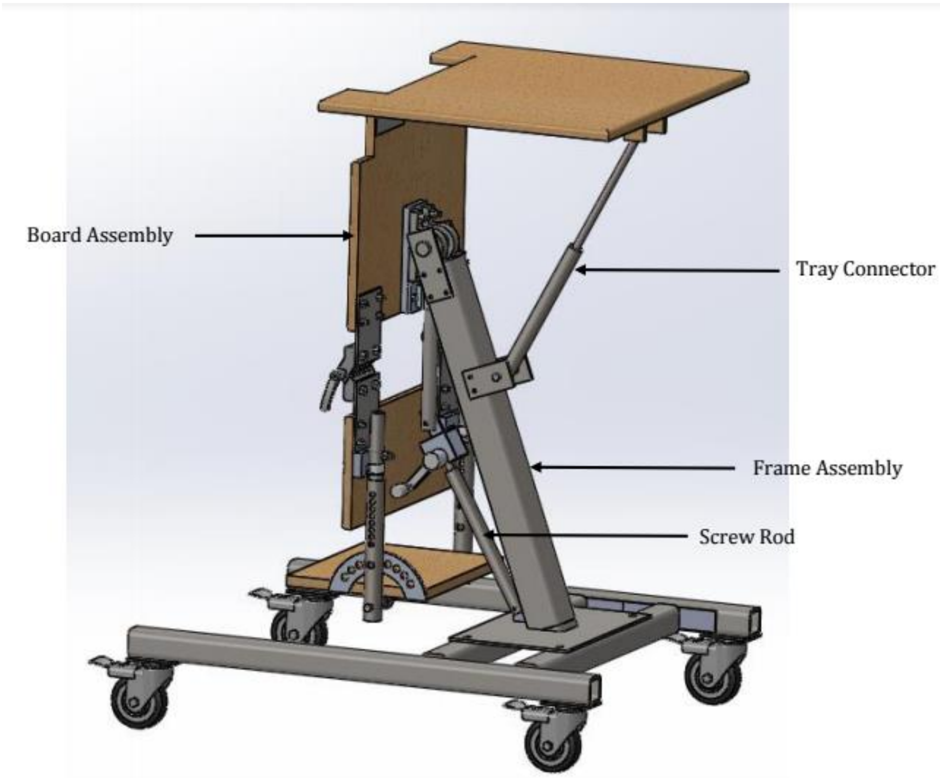



*Figure 1 Full Standing Device Assembly [7]*

The kneeboard and front board are connected by two hinges which can be locked at any angle. This design compensates for Felicity's knee flexion. The kneeboard has two metal telescoping tubes on each side which extend down to the footboard. These telescoping tubes can be extended or shortened by engaging and disengaging the pin from the incremental slots along the length of the tube (Figure 2). This was a design component to allow for Felicity's growth.

The telescope tubes are then connected to the footboard by another pin in slot system. This pin in slot system is allows for only angular adjustment, consisting of an aluminum arc with several holes along the perimeter. This provides compensation for her ankle flexion.

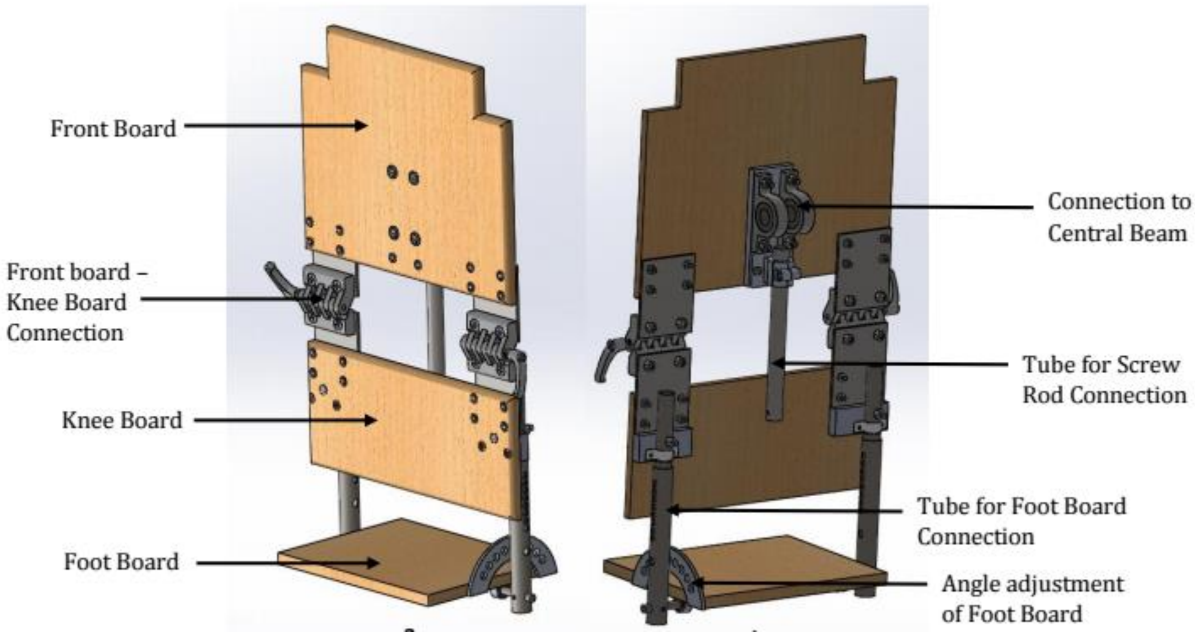



*Figure 2 Front Board, Kneeboard, Footboard Assembly [7]*

At the top of the front board, a tray is connected by a hinge. On the end of the tray, farthest from the front board, another telescope tube acts as a support. Adjustments can be made with the telescope tube to modify the angle of the tray in relation to the front board. The other end of the telescope tube is secured to the main frame with a pin joint. This whole system is connected to the main frame at the front board. This frame supports the whole system and allows for transportation with a lockable wheel at each corner.

### 2.2.3 Technology Available to Felicity

Felicity has various devices available to her at her school. She has a device that helps her communicate called MyTobii, which is still being introduced to her and the staff. Created by Tobii Dynavox, it is a tablet-like device that allows individuals with communication disabilities (conditions such as cerebral palsy, autism, or ALS) to interact through eye gaze. It allows for control through touch, switch, or retinal tracking. The user is provided with several options for how he or she wishes to communicate. The user may be provided with a set of images to select from to choose to communicate her needs or thoughts. Additionally, a keyboard can be displayed on the touch screen. The user can look at each individual letter and spell the words that he or she would like to communicate, and then the software will read out those words. Lastly, the system can save common phrases and allow the user to choose among those as necessary [8].

## 2.2.4 Device Requirements

The new transfer device must assist the physical therapist or teacher with Felicity's transfer from her wheelchair to the standing device. The transfer is currently done by two caregivers who must work together to lift and correctly place and fasten Felicity into the standing device. One of the problems with this method is that it requires too many resources, such as time and personnel, to complete the transfer. The school staff cannot take away valuable class time to help one student without being a detriment to other students.

The physical therapist expressed a strong desire for certain requirements to be met. The transfer device must be space-efficient due to the school's lack of storage and the significant size of the current device. It is also important for the transfer device to interface with the current standing device to simplify the transfer process. The transfer device must eliminate the need for an individual to "dead lift" Felicity out of her wheelchair into the standing device. The device must also be functional for many years. Therefore, it must compensate for Felicity's growth.

## 2.2.5 Roosevelt Elementary School

Roosevelt Elementary School is located at 1006 Grafton Street in Worcester, MA as part of the Worcester public school system. There are about 650 students from grades pre-K to 6th studying at Roosevelt. The Worcester Public School system focuses on the TEAM (together everyone achieves more) approach, which has resulted in the development of programs to meet the special needs of students and guarantee them the Least Restrictive Environment. The current facility at Roosevelt opened in 2000, and covers an area of 121,000 square feet. The hallways are approximately 6 feet wide and would allow easy turns for a 30 inch wide standing device. All floors in the building have access to elevators, which can fit two normal size wheelchairs. The school has a designated room for special needs education and storing assistive devices.

## 2.3 Available Products

Felicity's transfer from her wheelchair to her standing device, and vice versa, is a time consuming process that requires the assistance of at least one additional aide. Our device must be designed to reduce the time and resources the transfer takes. There are currently devices on the market designed for transfer processes. Though they may not be traditionally used for a patient transfer such as Felicity's, their mechanisms offer insight into the various ways a transfer can be carried out. Both the kinematic and dynamic analysis of available designs need to be understood and an open mind needs to be kept to the advantages and disadvantages of the devices studied.

### 2.3.1 EasyStand

The EasyStand Magician is a sit-to-stand device designed to accommodate individuals ranging from 3' to 4' 6'' tall that weigh up to 100 lbs (Figure 3) [7]. Both the back angle and seat depth are adjustable using pin slots to allow for various body types. A pelvic guide on the left and right side of the seat provides additional hip support. Two independent kneepads are attached to the front of the frame to provide additional leg stability and accommodate for knee contraction. There are also two independent footplates which can be adjusted in three directions: plantar/dorsi, toe-in/toe-out, and forward/aft. The device has an optional head support accessory in order to compensate for the user's diminished neck strength.


*Figure 3 EasyStand [7]*

The device uses a hydraulic system to raise and lower the seat to an inclined position. The hydraulic system can be operated by pressing a lever on the base of the unit and gently lifting the handles located on the back of the seat. The seat is supported by a four bar linkage system that causes the seat to rotate from the horizontal position to the vertical position as the hydraulic system raises the seat up. During the transfer, the hydraulic system provides a lift to move link a to a' position in the sketch in Figure 4. The four-bar linkage is a rocker-rocker

Grashof mechanism. The motion range is limited by a stop on link c in Figure 4. The driver link is lockable at any time allowing any angled position [7]. The operation of this device only requires one person.

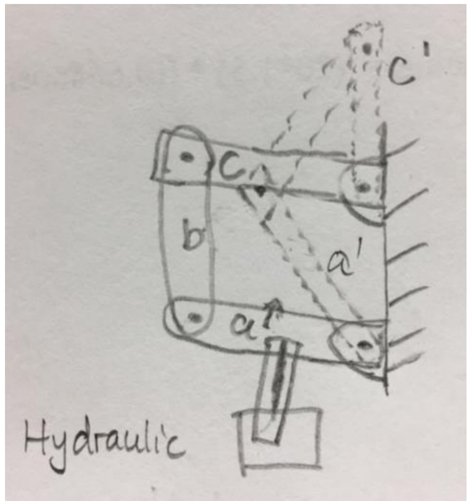



*Figure 4 Sketch of Linkage used in EasyStand*

According to Felicity's physical therapist, this device did not work effectively for the client because it did not provide enough head support. Moreover, the client did not respond well to the sit-to-stand motion due to the flexion in her knees. The device did not provide the support needed and she did not enjoy the experience overall [7].

The four bar linkage system is seen to be effective, and easy to operate, which could be utilized during future designs. The team needs to take account of user's comfort during the transfer process. Due to Felicity's lack of stability in her legs and neck, it is essential to provide neck, legs, and trunk support during transfer in order for the transfer to be safe and comfortable.

### 2.3.2 Invacare Get-U-Up

The Invacare Get-U-Up is designed for partially weight-bearing patients to raise them from a sitting to standing position or vice versa (Figure 5). A two point sling is placed around the lower back and buttocks of the patient and attaches to the lift arm (A), which has several points available for adjustment. The patient places their feet on the footplate, which keeps them off the ground and allows the entire device to roll even when the patient is standing on it. Braces at the shins (D) keep the patient's lower body in place when the lift arm is raised. The patient is then assisted in raising their torso up and over their knees in a natural standing motion by the raising of the lift arms. To raise the lift arms, a hydraulic jack (C) is operated by an aide. The hydraulic piston is connected at a pin joint located between the sling and mast (B) on the lift arm and creates rotation about the fixed mast. This rotation is transferred to the motion of the patient's upper body, lifting them up and over their knees to a standing position [9]. The arrangement of the jack, mast and lift arm prevent binding in the jack. The primary force exerted on the jack is the downward weight of the patient, which is aligned with the axial direction of the jack. Forces parallel to the floor, which would cause binding in the hydraulic, are primarily transferred to the joint on the mast. Being a single fixed bar, the mast is suited to this form of stress. The simplest breakdown of forces, focusing on the primary role each part of the assembly accomplishes, are also shown in Figure 5 as well.

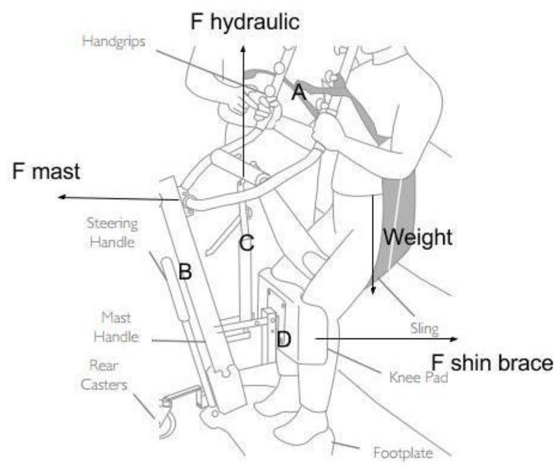



*Figure 5 Invacare Get-U-Up Force Flow Analysis*

Although Felicity is non-weight-bearing, the Get-U-Up is of interest for its ability to move the patient from a sitting to standing position with a two-point sling; this is opposed to the seated position maintained in a four-point sling such as that on many Hoyer brand lifts (Section 2.3.3). The position of the lifting mechanism in front of the patient prevents the linear transfer of a patient from the sitting position to a supine standing position. Additionally, the two-point sling only provides support from the posterior of the patient and would fail to provide any assistance as the patient moves to the supine position.

### 2.3.3 Hoyer Lift (HML400)

Hoyer Lift HML400 utilizes a sling to provide lift for the user. The lift consists of three major parts: the base, the link arm and the lift arm (Figure 6). The base is a U-shaped stable structure, with a wheel attached at each corner. The link arm is attached to the middle bar on the base assembly. User could use the control bar near the connection on the link arm to lock and unlock all four wheels. To adjust height, user could utilize the four bar linkage that is about a third of the way up the link arm [10]. The center of mass must remain inside the base to prevent entire device from tipping. The device used two hinges to secure safety of lift for the connection between lift arm and hooks. The hinge on the lift arm is set up horizontally with only one degree of freedom to lock and unlock user's facing position. The other hinge that is placed on the hooks is a swivel with only one degree of freedom. It can only provide a rotation which helps change direction of the patient.

*Figure 6 Hoyer HML400 [10]*

The Hoyer Lift has a Standard Operating Procedure (SOP) for bed-and-chair transfer. The user is placed in the sling in seated position, and the corners of the sling are picked up by the hooks on the lifting arm [10]. Then the chair can be removed and user's weight is solely supported by the lifting arm. The system is rolled by the four wheels on the main frame to the bed. The link arm is slowly dropped to bed level and the sling is detached from the hooks, completing the transfer.

## 2.3.4 Jolly Jumper

Jolly Jumper is a simple lifting device designed for children who weigh less than 30 pounds (Figure 7). An adjustable harness is used to hold the user's body vertically. There are four cords attached to the harness, and linked to a single cable. The cable then is attached to a door frame or separate system [11]. The four cord system distributes the user's body weight, so there is less tension on each cord.

*Figure 7 Jolly Jumper*

The Jolly Jumper system is limited due to its potentially low user weight capacity. Though it has four chords on the harness to distribute pressure, all four strings are connected to a single cable. This cable must be approved for use with the full weight of the patient. While the Jolly Jumper itself is designed for infants under thirty-five pounds, the design could easily be constructed with more adequate material to support Felicity's size and weight.

### 2.3.5 Chair with Lift Mechanism

The chair with lift mechanism is a seat with a linkage system facilitated lifting mechanism which helps bring an individual from seated to a partially standing position. The linkage consists of four bars (Figure 8) [12]. Link 1 runs parallel to the bottom surface of the seat and acts as the connection between the seat and the linkage system. At one end of Link 1, a pin joint effectively attaches the system to the ground or in this case the body of the chair's frame. At the other end of Link 1, another pin joint connects Link 1 to Link 2. The second joint on link 2 is a pneumatic cylinder connecting to the final bar in the linkage (link 3). The second joint in link 3 is a pin joint which connects back to the grounded chair frame. Ground is the virtual fourth link in the linkage.

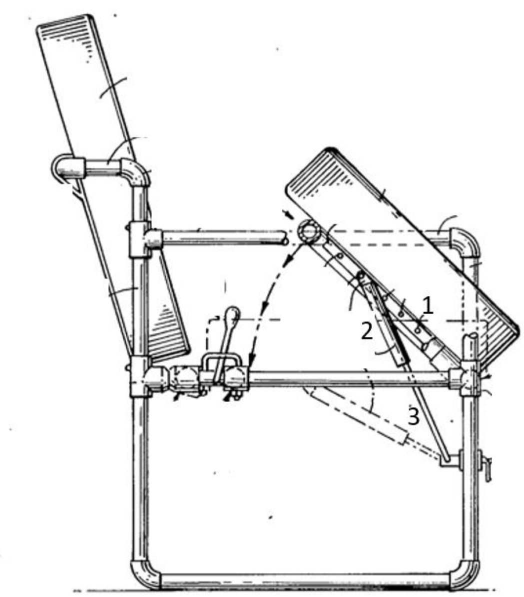



*Figure 8 Chair with Assistive Mechanism [12]*

The component that supplies the upward force needed to lift the seat of the chair is the slider component between links 2 and 3. The pneumatic cylinder fully extends when released from a hook towards the back of the chair. This motion occurs due to the expansion of air in the chamber of the cylinder. The extension causes an upward force at the top of link 2. The result of the force on the joint between links 1 and 2 is rotation of link 1 around its connection to ground.

When the seat is in its locked position, a hook is inserted into the pin joint between links 1 and 2. This hook counters the upward force caused by the pneumatic cylinder between links 2 and 3, ensuring that the seat stays horizontal. In order for the system to be in equilibrium when it is locked, the hook must exert a force on link 2 equal and opposite to the force being exerted on link 2 by the pneumatic cylinder. The mechanical advantage of this system could be controlled by changing the lengths of the input arm (link 3) and the output arm (link 1).

This system could be useful in our design as a way to lift Felicity out of the seated position. The transfer process would have to include a lateral transfer from the wheelchair to a seat with this device. The device could then be released to push Felicity into an almost standing position. In order for this system to be useful for this application, supports would have to be added to stabilize Felicity's extremities as she is lifted. This is due to the fact that she is non-weight bearing and cannot stand on her own as the chair pushes her to a standing position.

### 2.3.6 Patient Transfer Mechanism

The Patient Transfer Mechanism is used to transfer a patient from supine to prone and vice versa while on the operating table (Figure 9) [13]. The mechanism consists of a rectangular board supported by a pin joints 428 (1) and 428 (2). This pin joint is lockable when the board is not being rotated. The pin joints are connected to the main support frame label 102. The main support frame consists of square metal tubing.

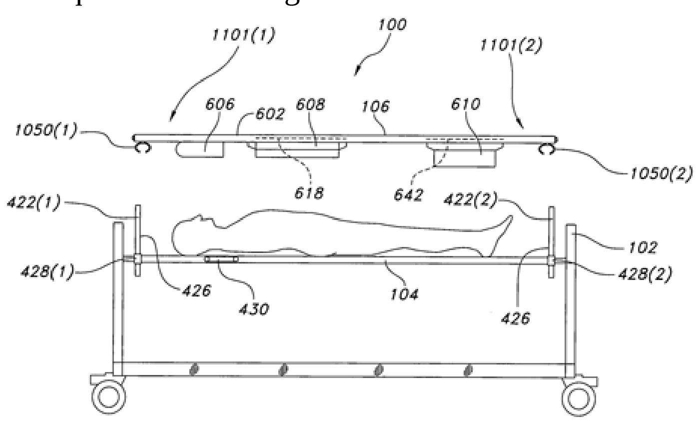



*Figure 9 Patient Transfer Mechanism [12]*

The patient would be in the supine position on the board. Another board, component 100, with knee (610), trunk (608), and head (606) supports is laid on top of the patient and locked into place at clasps 1050(1) and 1050(2). The pin joints, 428(1) and 428 (2), are unlocked and the board is then free to rotate with the patient secured between them. The patient would be rotated about pins 428(1) and 428(2) 180 degrees, board 106 is removed with the patient now in the prone position.

The rotation mechanism in this device could be useful in our future designs. The rotation may be needed during the transfer because Felicity must transfer from the supine support of her wheelchair to the prone support of her stander. This transfer would require a lateral transfer from the wheelchair to the board. This design could be modified from a horizontal rotation to an angled or vertical rotation by flipping the whole system on its end. This design has the advantage of already including leg, trunk, and head support which is required with Felicity. The design would have to be modified for Felicity's flexion, however, as she cannot straighten her legs fully as required by the design.

### 2.3.7 Romedic TurnTable Patient Turner

The Romedic Turntable Patient Turner has a relatively simple mechanism. It is made of two combined disks (Figure 10). The bottom disk has an anti-skid pad which keeps the device secured on the floor while it is being used. The top disk is a turnable plate that interfaces with the bottom disk and provides a place where the patient can place their feet [14]. While applying a force on the top disk, a rotation with the same direction is created. To use this device, the patient puts their feet on the top disk, which allows the rotational movement without having to pick up their feet.

*Figure 10 Romedic Turntable [14]*

This device has a significant limitation as well. It does not provide any lift holding user in place, which means while using this device, the body weight of user needs to be supported elsewhere. Thus this Patient Turner has typically been used for change in place between two seating positions. The team did not obtain any insight from this device for lifting mechanisms, but the device did give the team a way of turning the user's facing position.

### 2.3.8 Hydraulic Jack

Many of the commercial products developed specifically as patient lifts utilize a hydraulic jack to provide the force necessary to raise and lower the lift arm. This integral mechanism takes advantage of the incompressible property of liquids to transfer the force exerted on a lever arm by a user to the head of the jack (Figure 11).

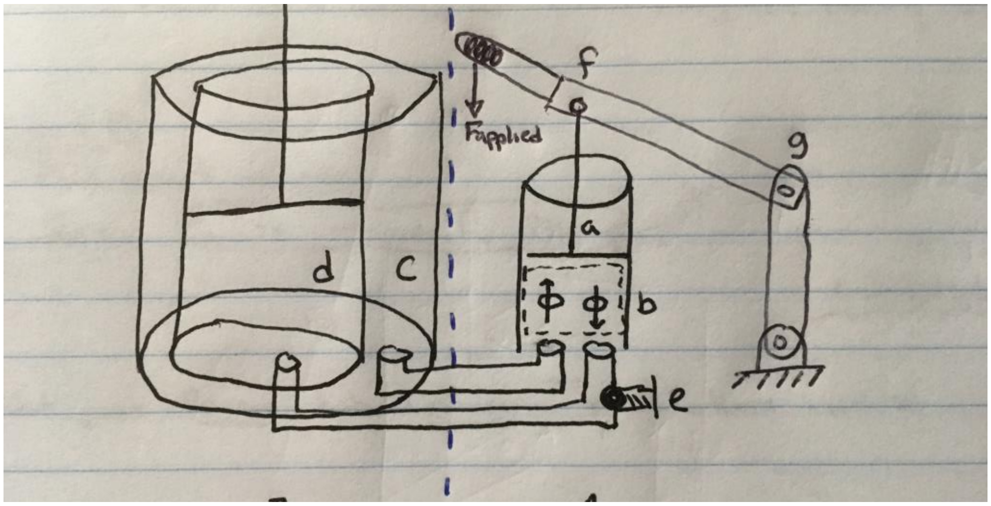


*Figure 11 Hydraulic Jack Sketches*

The first primary system in a hydraulic jack is the piston assembly (1). This mechanism consists of a four-bar linkage consisting of three pin joints and a slider, which is the piston (a). At the base of cylinder containing the piston is a ball valve (b) that allows the movement of liquid from the reservoir (c) into the chamber containing the jack head (d). This constitutes the jack assembly (2). Movement of the lever arm up and down drives the piston, which creates suction from the reservoir on the upstroke, pulling liquid into the piston chamber, and then drives it into the jack chamber on the downstroke. The pressure of the liquid and its incompressible nature in the jack chamber drive the jack head up. To lower the jack head, a screw (e) is loosened, which allows a metal ball previously providing blockage between the jack chamber and the reservoir to be pushed out of the way by the pressure of the liquid and for the liquid to travel back into the reservoir [15].

The mechanical advantage of a hydraulic jack is the result of several simple systems in series. The first advantage comes from the application of a lever to provide the force on the piston during the downstroke. This is equal to the distance from the point of application of force on the lever to the pin joint (f) over the length of the linkage f-g. The mechanical advantage of the hydraulic system is equal to the area of the circular face of the jack chamber divided by the area of the piston face. These two values are multiplied to express the total mechanical advantage the simple mechanisms in series, which is the hydraulic jack as a whole.

Another factor to note with the hydraulic jack is that the greater the difference in areas of the cylinder faces, the less height the jack is raised for each stroke of the piston. Therefore, the needs of the mechanical advantage for the output force at the jack head must be balanced with the consideration of how much pumping of the lever arm is desired to operate the lift. Additionally, the hydraulic jack provides very good support in the axial direction, but is susceptible to binding when moments act upon it. This factor is primarily controlled by the geometry of the forces loading the jack. The great mechanical advantage and compactness of design for a hydraulic mechanism make it an attractive option for providing manual assistance in the lifting effort of a transfer device.

# 3. Goal Statement

The goal of this project is to design and manufacture a transfer device for an eight-year old student with Cerebral Palsy named Felicity. This device must be operable by one person and facilitate the transfer between Felicity's wheelchair and her standing device. The device must be safe, easy to use, and complete the transfer quickly and efficiently. The device should not interfere with her standing device and must account for Felicity's future growth projection. The device should provide as much comfort and support as possible for Felicity during the transfer.

# 4. Design Specifications

## 4.1 Functionality

- Must only require one aide to complete the transfer **ESSENTIAL**
    - Due to limited number of teachers available at the school, our device must not require more than one person to perform the transfer.
- Must support user's neck, legs, and trunk during transfer **ESSENTIAL**
    - Felicity lacks stability in her legs and neck due to her condition. In order for the transfer to be safe and comfortable for her, the device must support these extremities.
- Must lift patient from supine and prone position **ESSENTIAL**
    - The device will have to lift Felicity from her wheelchair when the transfer is to the standing device or from the standing device if the transfer is to her wheelchair
- Must release patient into supine and prone position **ESSENTIAL**
    - The device must have the capability of placing Felicity in her wheelchair and the standing device
- Must accommodate user's growth for at least three years **ESSENTIAL**
    - Felicity is now eight years old now and continues to grow, and the device is designed for use when she is at Roosevelt School for at least three more years.
- Should require less than three minutes to complete the transfer process **IMPORTANT**
    - Due to the classes at Roosevelt elementary school are normally an hour, the teacher in the classroom only has less than 3 minutes to complete the transfer.
- Should have a simple operating procedure **IMPORTANT**
    - The device is used designed to be used in school, and a few people might act as caregivers and operate this device. Therefore, it is important to have a simple operating procedure and not require caregiver to lift.
- Should have a connection to the standing device frame **IMPORTANT**
    - A connection between the standing device would make the transfer safer, less complicated and save storage space
- Must have wheels for transportation **IMPORTANT**
    - The device will be used in various rooms
- Transportation wheels must be lockable **IMPORTANT**
    - During storage, the wheel should be locked for convenience. During use, wheels may need to be locked for safety and stability
- Should connect to the frame of Felicity's wheelchair **OPTIONAL**
    - This connection will provide a more stable transfer

## 4.2 Dimensions

- The width of the device must be less than 30" **ESSENTIAL**

- ADA standards require a 32” minimum for the width of a door opening. In order for the device to be easily maneuverable through doorways with the minimum width the design spec has a 2’’ clearance. [7]

- The height of the device must be less than 78” **ESSENTIAL**
  - The doorways in Roosevelt Elementary School are 80” high.
- The length of the device must be less than 50” **ESSENTIAL**
  - ADA standards for elevators require a minimum length of 51” from the back wall to front wall (inside the elevator). A less than 50” long device will ensure that device will fit in all ADA approved elevators. [7]

## 4.3 Safety

- The device must be able to safely support 176 lbs **ESSENTIAL**
  - Felicity is currently eight years old. Our device is aiming to remain useful for a few years. The estimated weight of a 12-year-old girl is 88 lbs. A safety factor of 2 results in a design load of 176 lbs.
- Felicity must be stable and supported during transfer **ESSENTIAL**
  - The means by which Felicity is supported must prevent her from flipping, dropping, or falling in any manner
- The device must be stable while completing the transfer. **ESSENTIAL**
  - The device must be locked in position while the patient is being transferred into the device
- No sharp edges can be exposed. **ESSENTIAL**
- Weight lifted by the assistant using this device must not exceed 50 lbs **IMPORTANT**
  - OSHA regulation states that an assistant cannot support more than 50lbs on their own.

## 4.4 Manufacturability and Cost

- Total cost for this design should be less than $750 **ESSENTIAL**
  - Each mechanical engineering student at WPI has a $250 budget for their Major Qualifying Project (MQP). The Felicity MQP team consists three members so the team has a total budget of $750.
- All design components should be able to be manufactured using machinery on WPI campus. **IMPORTANT**
- Must be able to be manufactured within 4 weeks. **IMPORTANT**

## 4.5 Maintenance

- The device must minimize the maintenance throughout its lifecycle **ESSENTIAL**
  - The school does not have easy access to qualified individuals to perform maintenance on this device, so the device must ideally require no maintenance

except for cleaning during its intended use for 3 years.

- All components of the device must be easily accessible to clean. **IMPORTANT**

## 4.6 Materials

- Materials used must not cause injury to users **ESSENTIAL**
  - No sharp edges
  - Nontoxic
  - Non-allergenic
- Materials must be washable and water resistant **IMPORTANT**
  - User is incontinent therefore messes may need to be cleaned easily

# 5. Preliminary Design Process

Three preliminary designs were created for first-round design analysis. The transfer device needs be compact and make the transfer process as simple and streamlined as possible. A decision matrix, which contains the most important aspects of design specifications with respective weighting factors, was used to assist in determining the final design (Appendix A). The three preliminary design concepts are Hydraulic Lift with Swing, Double Crankshaft Sling and Swing Arm.

## 5.1 Preliminary Concepts

### 5.1.1 Hydraulic Lift with Swing

This hydraulic lift is very similar to a Hoyer Lift. The system is comprised of a three sided rectangular frame with the fourth side open for the wheelchair to slide inside (Figure 12a). The base frame is 48 inches by 30 inches. A vertical beam is connected to the second beam of the based frame, opposite to the opening. This vertical beam is connected by a pivot to a horizontal lifting arm. This lifting arm has a hook at its end which is used to connect the patient harness to the arm by a cord. The hook is connected to the lifting arm by a ball joint to allow for full rotational freedom. A hydraulic piston is used to actuate rotation about the pin joint at the top of the vertical beam (Figure 12b). This rotation causes the lifting arm to rotate up and down, bringing the patient harness with it.

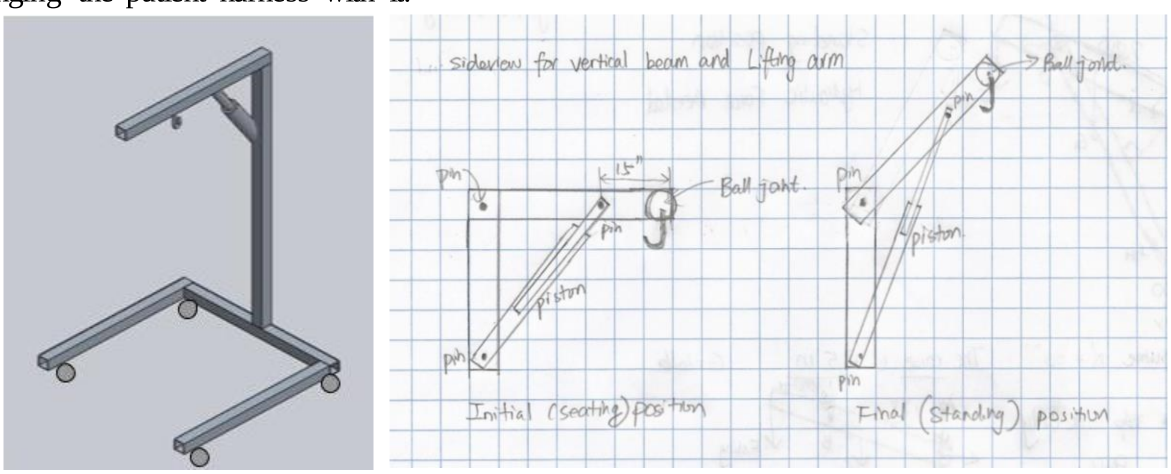



*Figure 12 a. Dimensions and Isometric Sketch for Hydraulic Lift (Left) b. Side View of Lifting Mechanism for Preliminary Design 1(Right)*

The lifting arm would be horizontal as the patient is loaded into the sling from the wheelchair. The arm would then lift up as the piston extends and the whole device would be rolled over to the standing device. The joint between the harness cords and the horizontal arm would allow for free rotation so the patient can be turned around 180 degrees to face the open edge of the frame rather than the edge connected to the vertical beam. This allows the patient to face the standing device as the lift is rolled over the standing device. The arm would then be lowered slightly as the patient is strapped into the standing device.

The difference between this design and the Hoyer Lift is the customized base width to fit over both the standing device and the wheelchair. While this concept offers an easy, quick transfer, a drawback to this concept is its large footprint of 48 inches by 30 inches.

### 5.1.2 Double Crankshaft Sling

This preliminary design uses crankshafts to lift the patient (Figure 13). The main frame of this system is designed to allow for two 30 inch, parallel beams to sit 24 inches apart at 60 inches above the ground. A crankshaft would be mounted 20 inches apart on each of the overhead beams. These crankshafts would be used to hoist four cords that attach to a harness up and down. The purpose of having two separately actuated crankshafts is so the patient can be tilted forwards and backwards as well as lifted up and down. The four cords also allow for stability and resistance against the user flipping in the harness.

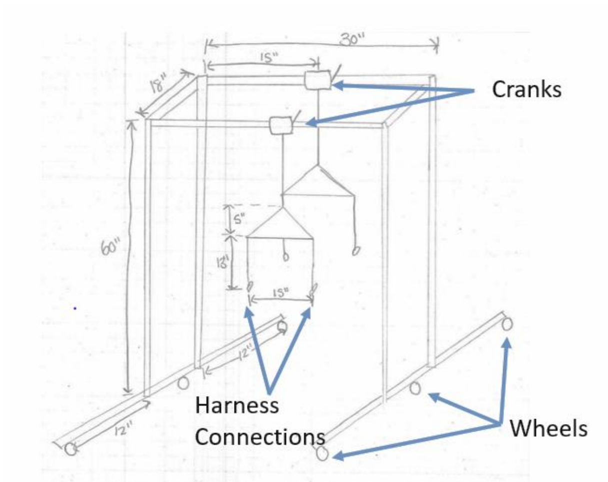



*Figure 13 Dimensions and Isometric Sketch for Double Crankshaft Sling*

The harness is full torso harness with neck support (Figure 14). This design was chosen because of its full coverage along the front and back side of the user. This allows the patient to be tilted forward in the harness without the concern of the harness becoming unstable and flipping.

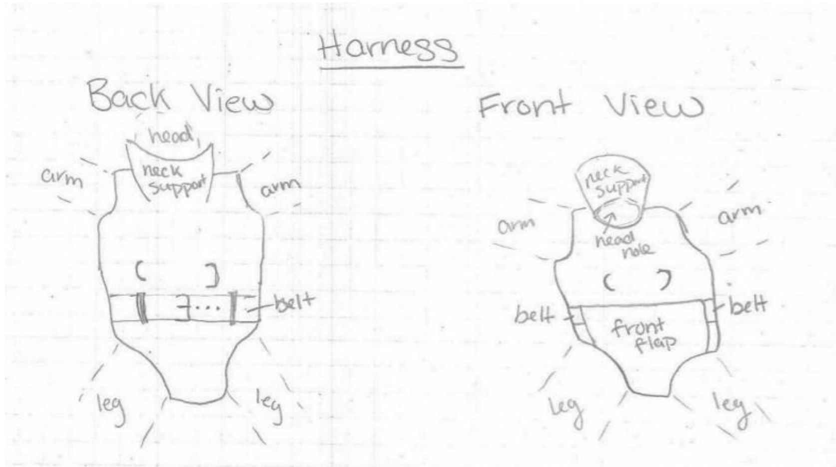


*Figure 14 Sketch of Harness Type for Double Crankshaft Sling*

### 5.1.3 Swing Arm

This mechanism consists of a U-shaped arm fixed to the base of the standing device. The patient is transferred to the wheelchair from standing device and vise versa in a process that uses the rotational motion of the arm to translate the patient both vertically and horizontally while supported by a harness. The arm is mounted left and right of the footboard end of the base. The arm is controlled by a handle operated by an aide. The handle uses the properties of leverage and a gear train to create a mechanical advantage. The harness is attached to the horizontal beam in the U-shape of the arm by two cords 20 inches apart, which is slightly wider than Felicity's shoulder width to provide extra room for movement and comfort. The rotation of the harness allows for the patient to be rotated towards the prone position and still be supported while strapped into the standing device fully. Another major attribute of the design is that the arm can continue its rotation towards the front of the device to be stored lower than the tray and still within the footprint of the original standing device.

A zero order prototype, built of Legos, is completed in preliminary design stage (Figure 15). The primary flaw of this design is the complexity involved in designing a gear train to create the mechanical advantage for the handle.


*Figure 15 Swing Arm Zero Order Prototype*

The center of mass of the Swing Arm is outside of the base of the standing device when lifting the patient out of the wheelchair, which means it may tip when the patient's weight is lifted from the wheelchair. To combat this, extensions from the base of the standing device lock onto the front of the wheelchair to create one large rigid base for the center of mass to lie within.

## 5.2 Final Design Selection

### 5.2.1 Decision Rubric and Decision Matrix

The team developed a detailed decision rubric to choose a final design (Table 3). The four main design attributes are functionality, dimensions, safety and manufacturability according to the design specifications. The design weighing factors are determined by the importance of each design attribute.

*Table 3 Preliminary Design Decision Rubric*

| Design Attributes | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Functionality | Weight-bearing capability | cannot hold 88 lbs | can hold only 88 lbs | factor of safety 1.5 = 132lbs | factor of safety 1.75= 154lbs | factor safety of 2=176 lbs |
| | Neck Support | neck can move and range of motion is greater than 90 degrees | | neck can move but range of motion is 30-90 degrees | | neck is fully supported (0-30 degree range of motion) |
| | Torso Support | no torso support (greater than 90 degree range of motion) | | torso is partially supported (20-90 degree range of motion) | | torso is fully supported (0-20 degree range of motion) |
| | Leg Support | legs may move freely | | partial leg support | | legs are immobilized |
| | Transportability | more than 40 lbs | 40 lbs | 30 lbs | 20 lbs | 10 lbs |
| | Force to Operate | more than 40 lbs | 30-40 lbs | 20-30 lbs | 10-20 lbs | Below 10 lbs |
| | Number of Aides Needed | >2 | | 2 | | 1 |
| | Time for Transport | >11min. | 8 < time < 11min. | 5 < time < 8min. | 3 < time < 5min. | less than 3 min. |
| Dimensions | Width | >32" | 32" | 31" | 30" | 29" |
| | Height | >78" | 78" | 75" | 72" | 70" |
| | Length | >48" | 45" | 43" | 40" | 36" |
| Safety | Tipping Susceptibility | patient is suspended outside of the base | | patient is suspended at the edge of the base | | patient is only suspended within the the base |
| | Sharp Edges | more than 6 danger points | less than six danger points | less than four danger points | less than two or in non-accessible areas | 0 sharp edges |
| | Weight supported by Aide | >50 lbs | 40-50 lbs | 30-40 lbs | 20-30 lbs | less than 20 lbs |
| | Aide's Body Rotation | >30 degrees | 30 degrees | 20 degrees | 10 degrees | 0 |
| | Aide's Lifting Distance | more than 2' | 1.5'-2' | 1'-1.5' | 0.5'-1' | less than 0.5' |
| | Joint/Hinge Safety | more than 3 uncovered hinges | 3 uncovered hinges | 2 uncovered hinges | 1 uncovered hinge | no uncovered hinges |
| Manufacturability | Number of Complex Parts | >4 | 4 | 3 | 2 | 1 |
| | Estimated Cost | more than $750 | $600-750 | $500-600 | $350-500 | less than $350 |

Through the decision rubric, the team was able to determine scores for each of the design attributes in the decision matrix (Table 4). The decision matrix displays a clear winner, the Crankshaft design, amongst the second iterations of preliminary designs. This is largely due to its highest score in Functionality, which weighted the most in the decision matrix and scoring almost 0.5 points greater than the runner-up. Although the Hydraulic sling yielded a perfect score in safety, its low weight bearing capacity and low dimension score placed it last among the three designs. One of the greatest advantages for the Arm Swing design is that it is attached to the existing devices, which resulted in a perfect score in dimension. As the team moves to final design selection, these numerical scores will be considered alongside discussion of observations and anecdotal reasoning to make the choice.

*Table 4 Design Matrix*

| Design Attributes | | Percentage | Crank Shaft | Hydraulic Sling | Arm Swing |
|---|---|---|---|---|---|
| Functionality | Weight-bearing capability | 12% | 5 | 2 | 3 |
| | Leg Support | 4% | 1 | 1 | 1 |
| | Force to operate | 12% | 4 | 3 | 3 |
| | Time for Transport | 12% | 3 | 3 | 4 |
| | **Total** | **40%** | **1.48** | **1** | **1.24** |
| Dimensions | Width | 10% | 4 | 4 | 5 |
| | Length | 10% | 3 | 1 | 5 |
| | **Total** | **20%** | **0.70** | **0.50** | **1.00** |
| Safety | Aide's Body Rotation | 9% | 5 | 5 | 4 |
| | Stability of Locking Mechanism | 12% | 5 | 5 | 4 |
| | Joint/Hinge Safety | 9% | 4 | 5 | 4 |
| | **Total** | **30%** | **1.41** | **1.50** | **1.20** |
| Manufacturability | Number of Complex Parts | 4% | 5 | 4 | 3 |
| | Estimated Cost | 6% | 4 | 3 | 4 |
| | **Total** | **10%** | **0.44** | **0.34** | **0.36** |
| **Weighted Score** | | **100%** | **4.03** | **3.34** | **3.80** |

## 5.2.2 Discussion with School Staff

Before making a final design selection for the transfer device, the team met with the physical therapist, Sally Goodhile. Her discussion proved very enlightening because from her perspective, the most important attribute of the standing device was size and storage capability. She explained again that there is very little room for storage at Roosevelt Elementary School and was impressed by the concept of the Swing Arm being capable of stowing on the standing device.

Another question that Mrs. Goodhile was able to provide an opinion on was Felicity's comfort in using a harness. She stated that Felicity has used a Hoyer lift before and should be reasonably comfortable using a harness. Ms. Goodhile also proposed the possibility of using a harness that buckles around the torso and not the legs as it would be easier and quicker to put this type of harness on while Felicity is sitting.

### 5.2.3 Final Decision

The result of the full analysis with the use of the design matrix and additional discussion with Sally Goodhile was the selection of the Swing Arm concept for the final product. Its score on the design matrix was not significantly lower than the Crank Shaft design and the primary reason for any difference was the weight-bearing capability and complexity of parts. However, these limitations will drive the material choice and method of construction and all concerns will be met. Ultimately, the efficient motion and storage meet the conceptual requirements that drove design selection and the team pursued the innovative approach of the swing arm.

# 6. Final Design

The previous chapter discussed how the team chose the Swing Arm concept among three preliminary designs. After the decision, the team focused on coming up with the details to achieve a fully viable design. This chapter explains the details of final design and final design components.

## 6.1 Details of Final Design

The final design focuses on the motion of a U-shaped arm, fixed to the base of the standing device (Figure 16). The motion of the U-shaped arm is created by a four-bar linkage driven by a linear actuator. The linear actuator consists of a block travelling along a screw driven by an electric motor. The coupler link is connected to this block and the U-shaped arm by pin joints. This connection translates the linear motion of the block to the rotation of the U-shaped arm about the pin at its base. To prevent the device from tipping, two stabilizing rods with wheels are mounted to the base of the standing device. A harness is used as the interface to transfer Felicity between the standing device and the wheelchair. The harness is attached to the top arm of the U-shaped frame through two eyebolts.

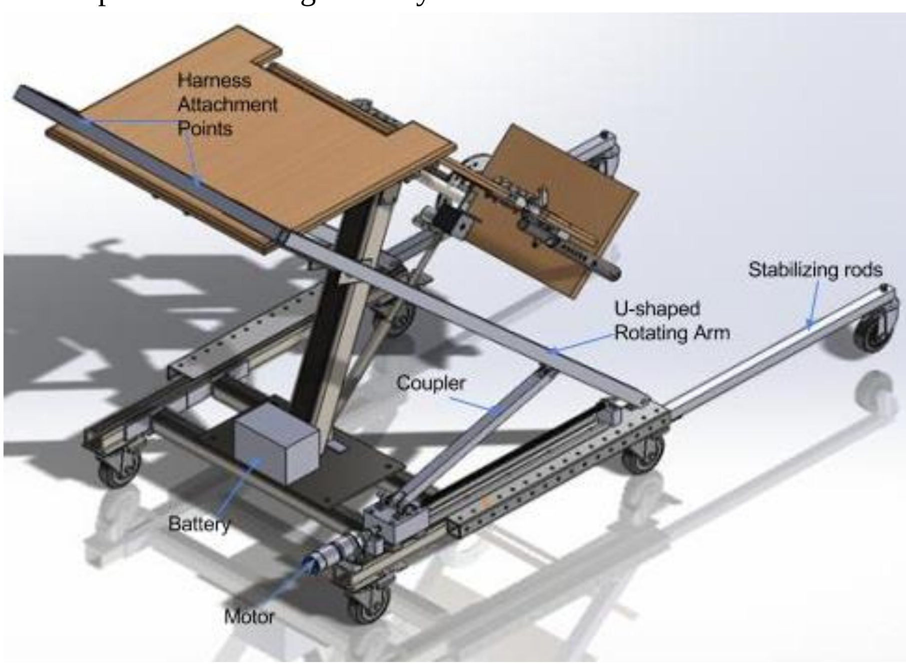



*Figure 16 Solidworks Model of Final Standing Device in Stowed Position*

The principle operation of rotating the transfer arms from the wheelchair to the standing device and vice versa is through a four-bar linkage driven by an electric motor. The mechanism consists of few moving parts and its operation is not strenuous on the user. The transfer mechanism must not be backdrivable and must be able to withstand all torques, moments and stress. It must also accommodate Felicity's ankle and knee flexion.

When transfer is performed, the device would be moved to the front of Felicity's wheelchair, where the wheels on stabilizing rods are extended to the sides of wheelchair. The aide then positions Felicity in the harness, and depresses a button to actuate the driving mechanism. Once Felicity is transferred to the other position, the aide releases the button to stop the motor. After that, the aide could start strapping Felicity in the standing device and unstrapping the harness.

Several iterations of concept and analysis were required to determine adequate mechanisms of driving the rotation of the arm. Analyses included both mathematical evaluations, such as static and stress analyses, and CAD modelling to observe interference of parts and ensure dimensions of the base can support the design. This design utilizes linear motion to drive the four-bar linkage. The team compared a few harnesses, but none of them fit all of the required specifications. The team successfully contacted a harness manufacturer in China to customize a harness for this design.

### 6.1.1 Driving Mechanism

The driving mechanism was key to this final design. The team determined that the required mechanical advantage could be gained through a linear actuator. The final design of a rotating screw with a travelling carriage attached to the coupler was the most compact mechanism that could provide the required forces (Figure 17). A battery provides the power for the DC motor so that there is no physical effort required by the aide.

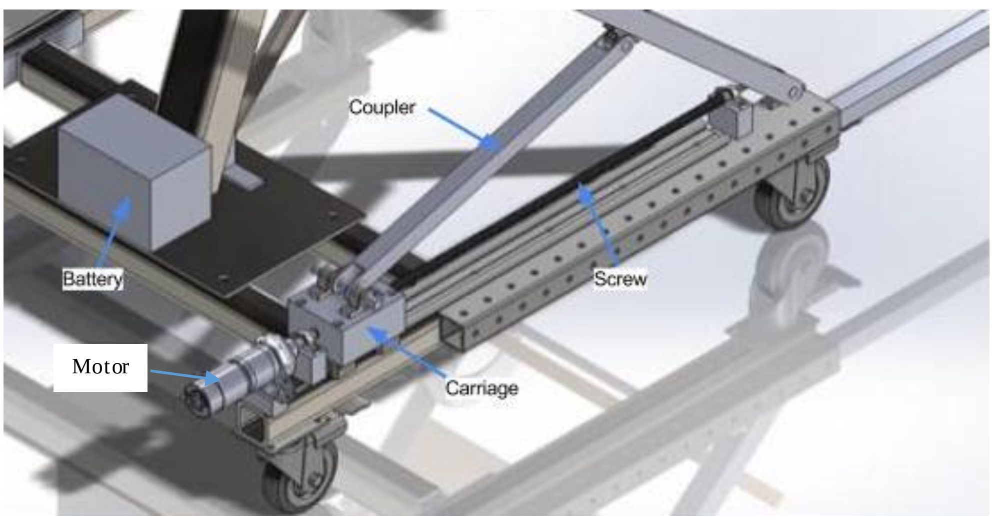



*Figure 17 Solidworks Model of Driving Mechanism*

### 6.1.2 Harness

It took some time to find a quick to don and stable harness for an acceptable price. Gymnastic tumbling belt was the initial choice, but it is designed for rotating so it was deemed too dangerous for Felicity. A bungee jump harness with clipping leg loops was also considered. This product was found on Chinese Amazon (taobao.com), which greatly reduced the cost, but still created a possibility of Felicity rotating with only two attachments to the top beam. The team struggled to find an adequate harness from the market, so they contacted the manufacturer of the bungee jump harness. The team explained their needs and concepts, provided a design concept and successfully convinced the manufacturer to customize a harness for this transfer device.

The customized harness has four harness attachment points, and each of them is connected to a rope with adjustable length. A carabiner connects the rope to the eyebolt on the beam. This customized harness came from a bungee jump harness, where only waist pad is used. To raise the pivot point, two waist pads were sewed together, so the center of gravity (CG) of Felicity when using the harness system is below the pivot point of the carabiners. There are four attachment points on the harness so that the CG could not move outside the footprint of the attachment points to solve the rotating issue (Figure 18). The manufacturer only charged for materials for this harness, greatly reducing the cost.

*Figure 18 Harness*

## 6.2 Final Design Components

### 6.2.1 U-shaped Frame Assembly

The frame assembly includes three aluminum square tubes, four L-shaped brackets, two pins, two eyebolts and a bearing (Figure 19). The sides of the U-shaped arm are 1-¼ inch aluminum square tubes with a ⅛ inch wall thickness. These side beams are 57 inches long. At one end of each of these side beams, a cutout is made to allow for a pin to be inserted and used to rotate the arm. The holes for the pin are ½ inch in diameter and an inch from its center from the bottom edge of the tubing. The faces with the holes were given a full round and the other two faces were cut off an inch and half from the bottom of the tube. This was done to insure there would be no interference as the arm rotates about the pin.

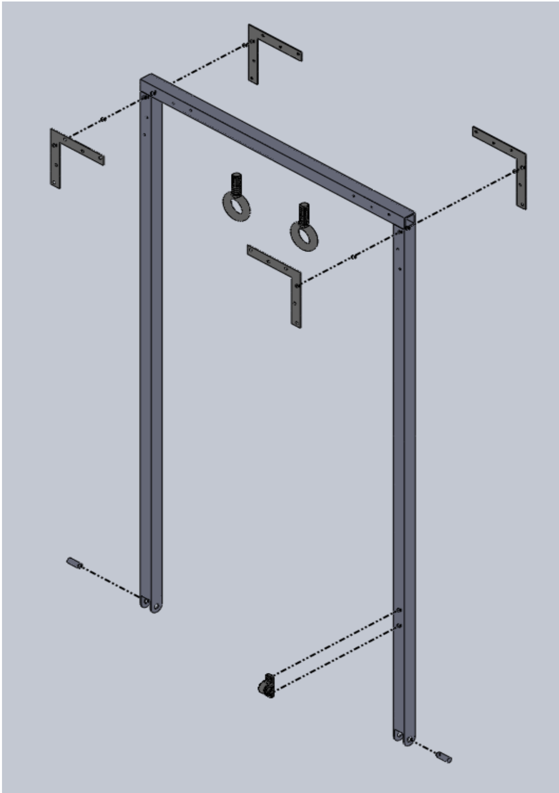


*Figure 19 Exploded View of U-shaped Frame Assembly*

Another 1-¼ inch aluminum square tube is used to connect the two side arm of the U-shape. This tubing is 30 inches long and is connected to the two side arms by L-brackets on the front and back face of each corner. Two eye bolts are drilled into the bottom surface of the top beam to facilitate the connection of the harness cords. A bearing is mounted on the right hand side beam twelve inches above its pivot to allow for the attachment of the coupler assembly.

### 6.2.2 Coupler

The coupler link is made of a one-inch square aluminum tube with a wall thickness of ⅜ inch (Figure 20). Similar to the side beams in the frame assembly, this piece of tubing has cuts made at each end to allow for a pin to be inserted and used for rotation about a bearing. This tubing is 18 inches long measured from the center of each pin with an added inch past the center on each side for the total length of 20 inches. This coupler connects the frame assembly to the screw mechanism later described. This connection allows the linear motion of the screw mechanism to be transferred into angular rotation of the frame.

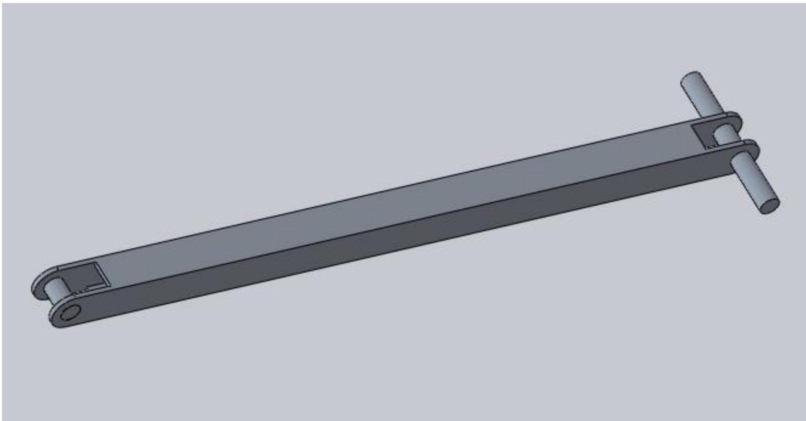


*Figure 20 Coupler Link with Fixed Pins*

### 6.2.3 Screw Mechanism

The screw mechanism provides the linear motion that drives the four-bar linkage. A DC motor provides the power to rotate the screw and drive the carriage along its length. The screw is a ½" Acme threaded rod, modified to have smooth ends to be slip fit into bearings on either end. The motor provides high enough RPM to transfer Felicity from the wheelchair to the standing device or vice versa in 10 to 20 seconds, not including donning or removing the harness. It also removes all physical effort from the aide. All components in the assembly are shown in the exploded view (Figure 21).

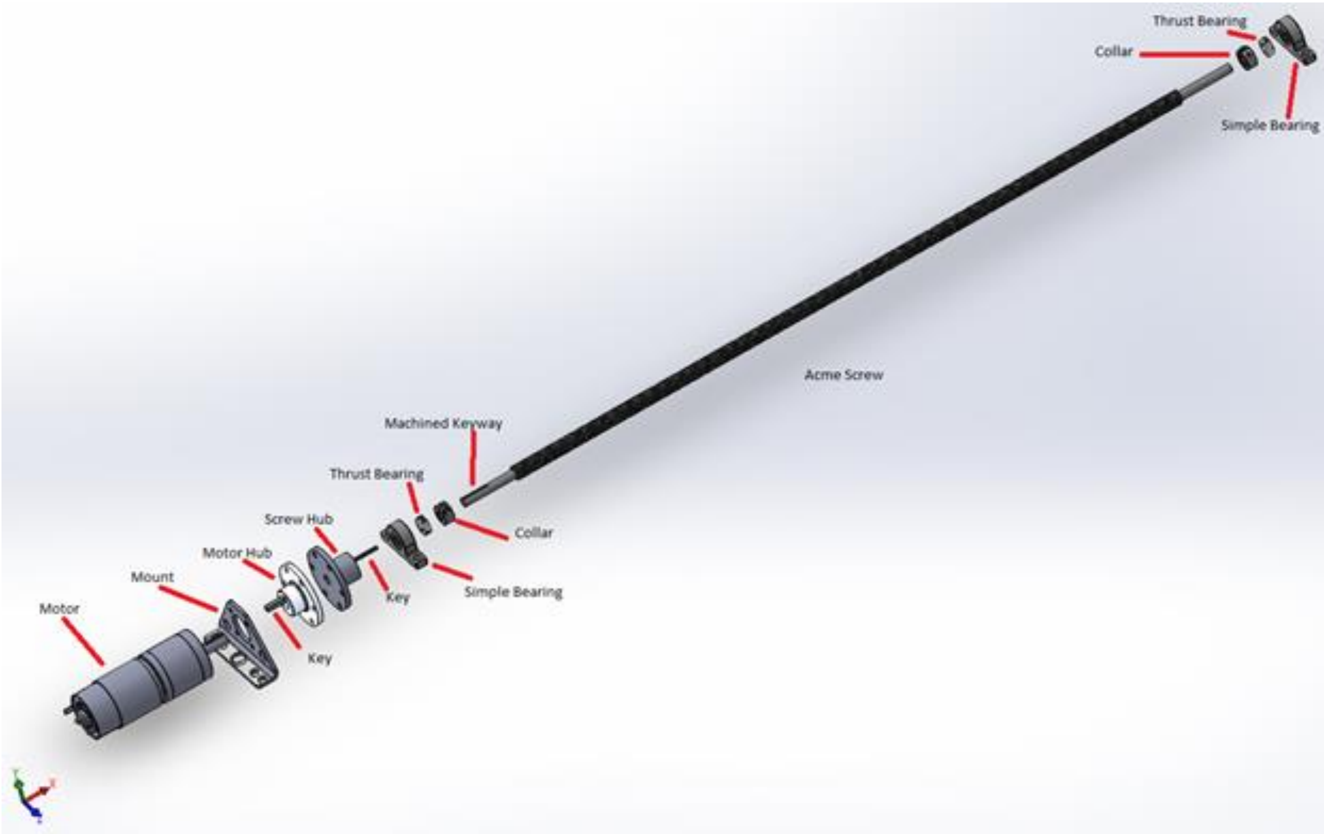



*Figure 21 Exploded View of Screw Mechanism*

The screw rotates freely, supported by simple bearings at either end. It is press fit into these bearings. Axial forces are supported by thrust bearings, also located at either end of the screw inside of the simple bearings. A collar in between the threading and the washers of the thrust bearings ensures that the contact surface between the two is smooth.

Additional support to the screw in the direction perpendicular to its axis is given by a track and carriage (Figure 22). The bearing for the pin joint of the coupler is mounted on the carriage, which travels when the screw rotates. The support from the track prevents bending in the screw.

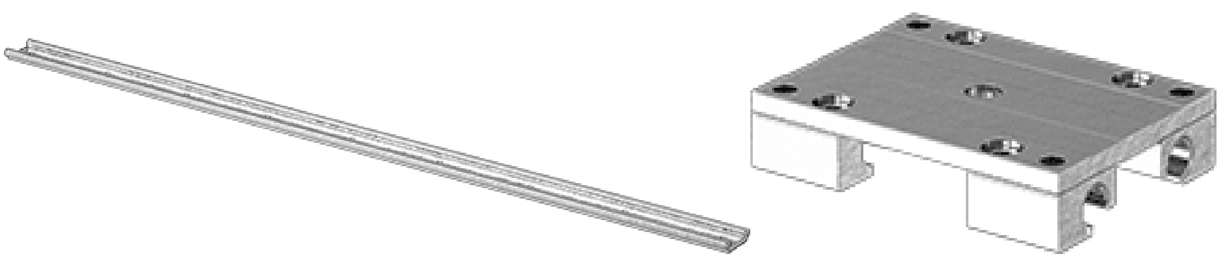


*Figure 22 Track (Left) and Carriage (Right)*

The block on which the coupler is mounted and threaded rod runs through is referred to as the coupler block. This design interfaces the linear motion along the screw with the pin joint of the coupler link. It contains a slot in which a single 1 ¼" nut can be set to provide an interface between the rod and block (Figure 23). By using a single nut there is no potential locking due to misalignment of threading. The length of the nut still facilitates significant contact area between itself and the threaded rod. The rectangular slot is ⅝" in width and 1 ¼" in length. The nuts are placed so that the side walls of the slot fit to the parallel faces of the nut. Two set screws on each side wall are used to ensure the nut is aligned properly and cannot rotate. The nuts cannot be pulled out of the block because of the remaining ⅞" of material remaining at each end. The carriage and track prevent transverse motion of the block to the screw, therefore there is no concern of the nut coming back out of the slot.

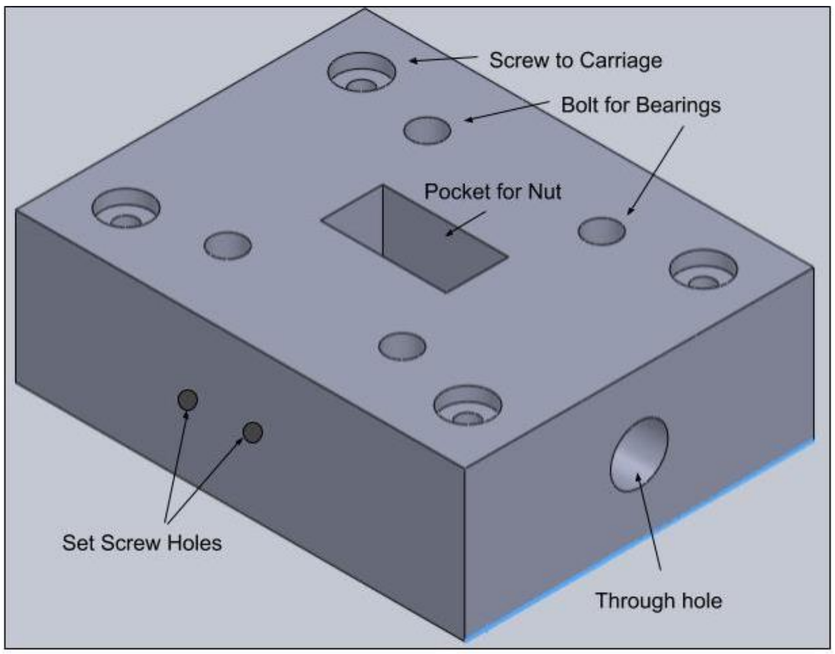



*Figure 23 Coupler Block*

The output of the motor is connected to the rod by way of two keyed hubs. The hub adjacent to the motor has a 4mm key. It is bolted to a second hub that has a 2mm key, which matches the keyway machined into the screw. The motor is mounted at the front of the base and extends past it approximately three inches. It is assembled with a gear train fixed to the output to provide an output speed of 512 RPM at a torque of 42.5in-lb. The motor and hubs are products of AndyMark and are meant for use together (Figure 24).


*Figure 24 AndyMark Motor*

## 6.2.4 Electrical System

The motor is controlled by a Double-Pole, Double-Throw (DPDT) or "On-Off-On" switch. This style switch allows the motor's direction to be easily reversed. It is mounted on the tray so the aide does not have to bend or turn away from the client to use the transfer mechanism. This is powered by a 12V battery, mounted at the base of the main support beam. The circuit is designed such that two switches must be placed into the on position for the motor to be powered (Figure 25). Also, there are switches at each limit of the screw so that the coupler block cannot be driven against the bearings at either end and damage itself if left unattended.

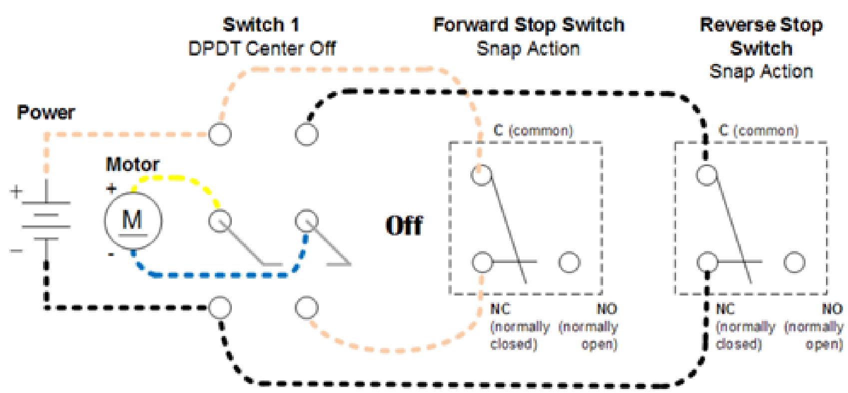



*Figure 25 Electrical Circuit Diagram*

## 6.2.5 Extension Assembly

There is an extension assembly on each side of the base frame. Each extension assembly consists three parts: a flanged tube, a sliding rod and a wheel (Figure 26). The flanged tubes are 1.5 inches square, ⅛ inches thick and 24 inches long and made of anodized aluminum with bolt holes on all four sides. These holes, in conjunction with a stopper pin provide a pin locking mechanism to fix the stabilizing rods. The flanges are bolted onto the base of the standing device using M6 bolts. Each stabilizing rod is made of a 30-inch long, 1 inch square aluminum tube with ⅛ inch wall thickness. A rubber wheel with 3-½ inch diameter and 1-¼ inch width is bolted 1 inch from the end of the rod. The mount height of the wheel is 4-9/16 inches, which is 1/16-inch smaller than the distance between the bottom of sliding rod and the ground. A washer adjusts this height difference.

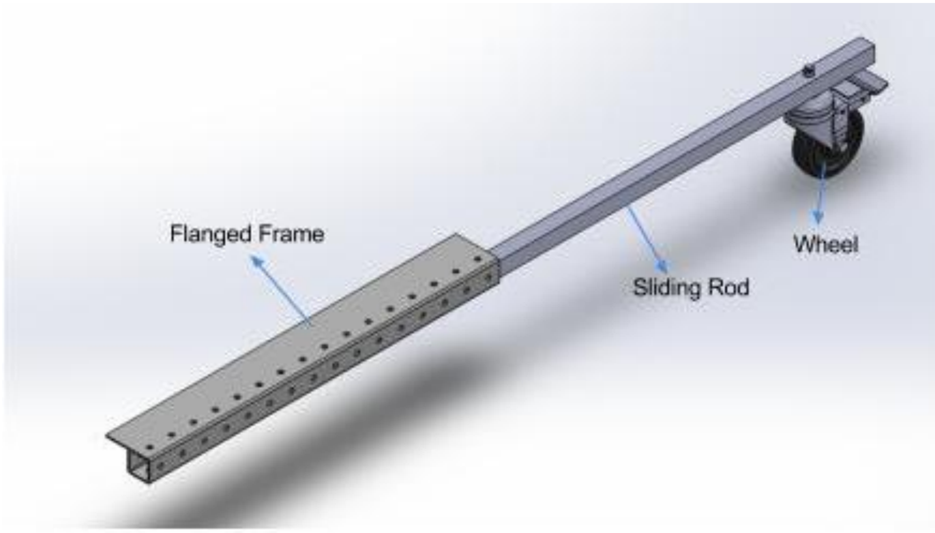



*Figure 26 Solidworks Model of Extension Assembly*

# 7. Final Design Analysis

Analysis of the design was conducted to ensure there would be no failure of the device during normal operation. A safety factor of 3 was used in calculations because the operation of the transfer mechanism could directly put the safety of the user at risk. Analysis of the forces and moments acting upon the mechanism at the base extensions, L-brackets, arm beams, coupler block, harness, and motor were completed. These points were analyzed at positions of maximum stress, which largely occurred when the arm was extended fully over the wheelchair.

## 7.1 Static Frame Analysis

The swing arm and the driving coupler were analyzed using static free-body diagrams. Initially, the top beam was analyzed as a separate body from the side beams. This was the first component of the U-Frame to be analyzed because it is the location of the external applied force. The assumptions made in this analysis are as follow:

1. The corner connections to the side arms are fixed joints which can support all six degrees of freedom
2. There are no forces in the x-axis (axis along the length of the top beam; Figure 27)
3. There is uniform loading at the left and right corner connection

The joint forces are labeled $F_S$ followed by either 1 or 2. "1" refers to the left joint and "2" refers to the right joint. The next character in the force subscript is either x, y, or z correlating to the axis on which the vector lays.

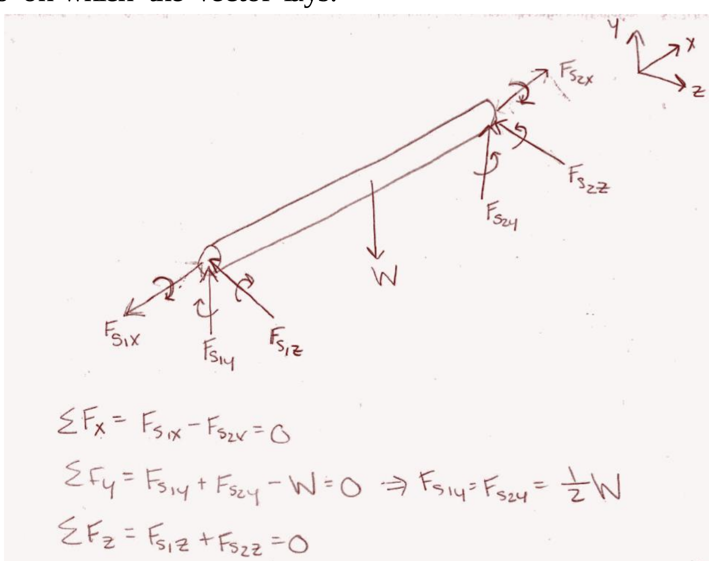



*Figure 27 Free Body Diagram of Top Beam and Static Force Equations*

The following diagrams show the three two-dimensional views of the top rod (Figure 28). These include the x,y plane, the x,z plane, and the y,z plane. In the x,y plane, the beam can be treated as a double fixed beam with the moment at each end equal to the weight multiplied by the length of the beam and divided by 8. In the x,z plane, there are no forces acting on the rod therefore the moments about the y-axis are zero. Lastly, in the y,z plane, the displacement of the harness connection and the center axis of the beam causes small moments about the x-axis at each corner.

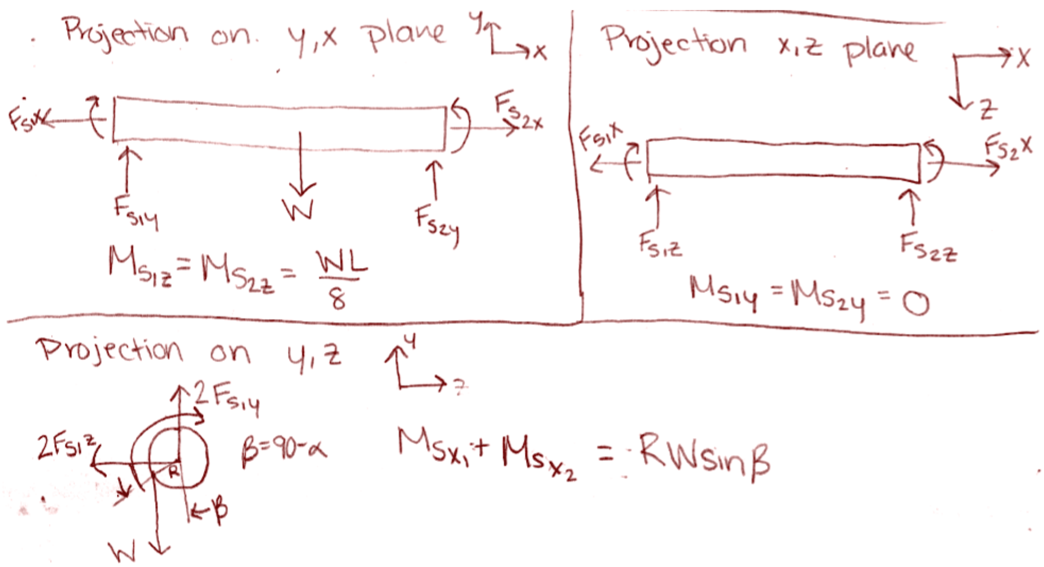



*Figure 28 Moment Diagrams and Equilibrium Equations*

From these calculations, numerical solutions to the joint forces for each position of the swing arm can be easily calculated. At the "least advantageous position" when the swing arm is over the wheelchair with an angle of 40 degrees with respect to the floor, the joint forces are as can be seen in Table 5.

*Table 5 Solution of Forces at the Corner Joints at 30 degree Arm Angle*

| Output | | | |
|---|---|---|---|
| At Elbow Joints | | | |
| Forces (lb) | | Moments (lb*in) | |
| Sx1 | 0 | Mx1 | 152 |
| Sy1 | 132 | My1 | 0 |
| Sz1 | 0 | Mz1 | 429 |

The forces calculated from the top beam were then translated to free body diagrams of the driven and non-driven side arms (Figure 29a, 29b). The assumption made in this analysis is that the coupler only supports a force along the axis of the coupler and does not support a moment. The coupler is a two force member with pins at each end so the line of action of this force can be defined by the angle between the coupler and the driven arm. This angle (phi in Figure 29a) can be found using trigonometry relating it to the angle of the driven arm relative to the floor.

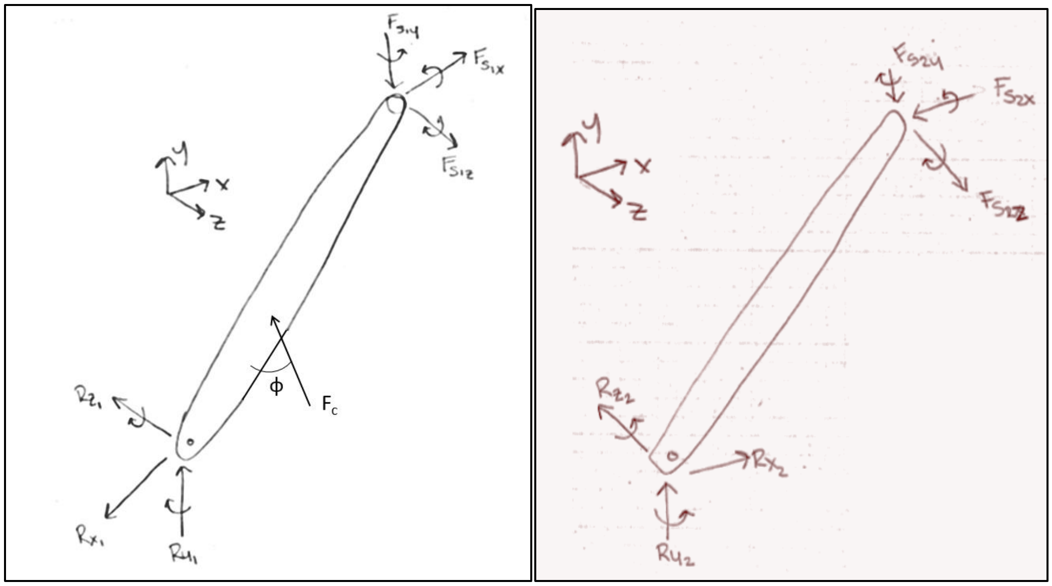



*Figure 29 a. Free Body Diagram of Driven Arm in U-Frame Assembly (Left) b. Free Body Diagram of Non-Driven Arm in U-Frame Assembly (Right)*

The joint forces are denoted by an R followed by a subscript with a 1 or 2 and an x, y, or z. The subscript "1" refers to the driven arm and the subscript "2" refers to the non-driven arm. The subscripts x, y, and z refer to the axis on which the force is being applied. The x-axis refers to the axis parallel to the axis along the top rod, the y-axis in the vertical axis, and the z-axis is perpendicular to the vertical axis and the axis along the top rod.

The non-driven arm base joint forces and moments ($R_{x2}$, $R_{y2}$, $R_{z2}$, $M_{Ry2}$, and $M_{Rz1}$) are equal and opposite to the corner joints with the top beam. The coupler force on the driven arm was determined using the sum of the moments about the x-axis. After the coupler force was known, the rest of the base joint forces could be solved. Unlike the non-driven arm, the base joint forces of the driven arm are not equal and opposite to the corner joint force because of the added force of the coupler. The force of the coupler causes there to be both y and z force components on the base joint of the driven arm (Table 6).

*Table 6 Resultant Values of Bottom Pivot and Coupler Joints of Static Analysis when Driven Arm is 40 degrees with respect to the floor*

| At Coupler | | | |
|---|---|---|---|
| Forces (lb) | | Moments (lb*in) | |
| Fc | 629 | Mcy1 | 0 |

| At Bottom Pivot | | | |
|---|---|---|---|
| Forces (lb) | | Moments (lb*in) | |
| Rx1 | 0 | - | - |
| Ry1 | -477 | $M_{Ry1}$ | 0 |
| Rz1 | -159 | $M_{Rz1}$ | 429 |
| Rx2 | 0 | - | - |
| Ry2 | 132 | $M_{Ry2}$ | 0 |
| Rz2 | 0 | $M_{Rz2}$ | 429 |

## 7.2 Dynamic Mechanism Analysis

A Mechanism Model was used to analyze joint forces at each of the pins in the final design. A simplistic model of the final design was constructed in Creo Parametric (Figure 30). The U-Frame of the Swing Arm was connected to a fixed bearing at the base of each arm by a pin mate. At the center of the top rod of the U-Frame, a pendulum was hung by a pin joint to simulate a weight equivalent to Felicity at the height she is to be hung in the harness. The purpose of adding this pendulum was twofold. First, the pendulum's mass simulated accurate joint forces involved when a weight is being lifted. Secondly, the oscillation of the pendulum created a dynamic load representative of Felicity's movement in the harness during transfer.

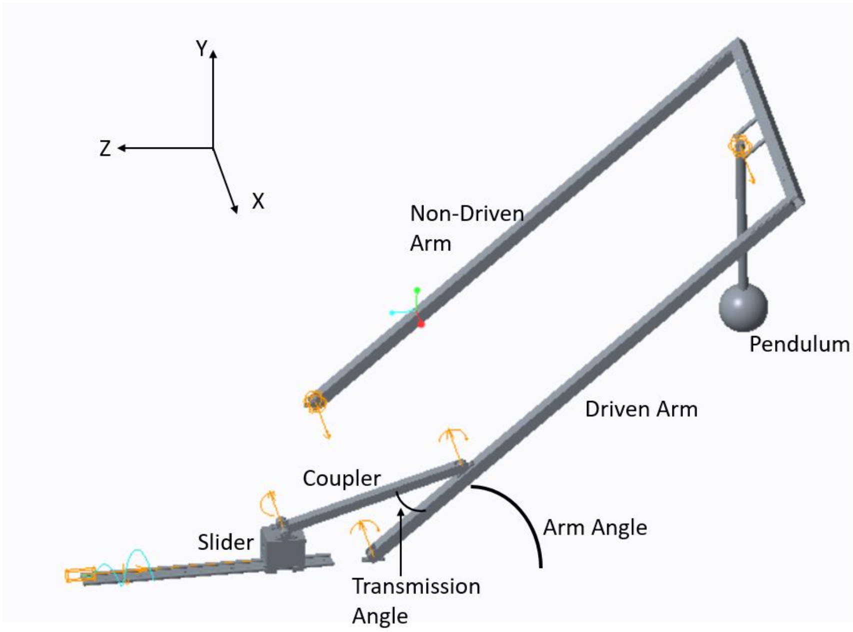


*Figure 30 Creo Parametric Mechanism Model*

The slider is then mated to the track by a cylindrical mate. In reality, the slider is driven by the rotation of the ACME threaded rod and supported by the track, however, for simplicity's sake an equivalent motor was attached to the translational axis of the cylindrical mate between the track and the Slider. The ACME threaded rod has a 1/10-inch translation per 1 rotation. The motor runs at a maximum of 580 RPM. Converting this angular velocity into a translational velocity, 580 RPM becomes 0.97 in/s (58 in/min).

The coupler was mated to the Driven Arm and the Slider by a pin joint at each end. The Arm Angle of the mechanism is measured from the negative Z-Axis. The transmission angle is measured between the Driven Arm to Coupler. The minimum transmission angle is about 25 degrees when the arm angle is at about 42 degrees and the maximum transmission angle is 85 degrees when the arm angle is at about 110 degrees. This shows that the force transmission is at its worst when the arm is over the wheelchair (Figure 31).

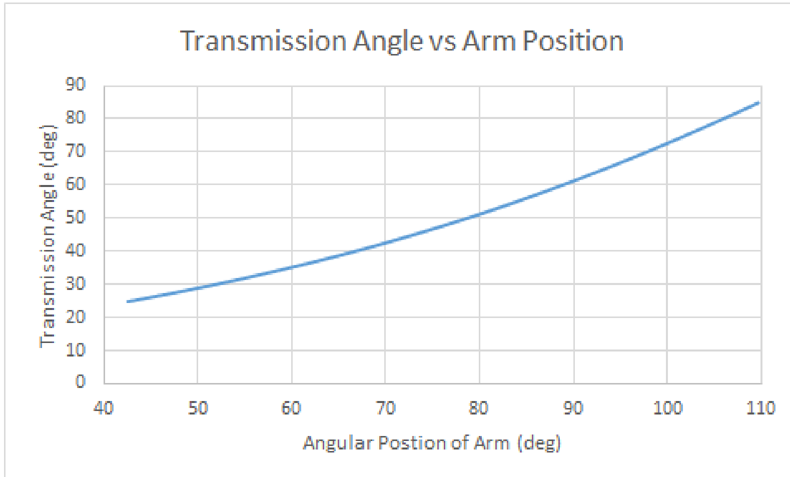



*Figure 31 Transmission Angle vs Arm Position Plot*

The following plots depict trends in the forces at each of the pins—the driven pin, non-driven pin, coupler/arm connection, and coupler/slider—in the Y and Z axes (Figures 32-35). The oscillation in these plots is caused by the oscillation of the pendulum as the arm swings. Specific values along these curves at select points are listed in Table 7.

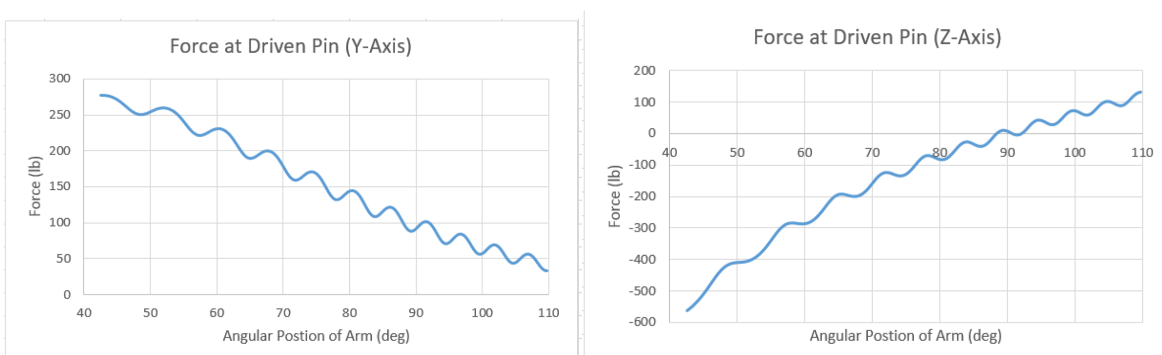



*Figure 32 a. Force at Driven Pin in the Y-Axis (Left) b. Force at Driven Pin in the Z-Axis (Right)*

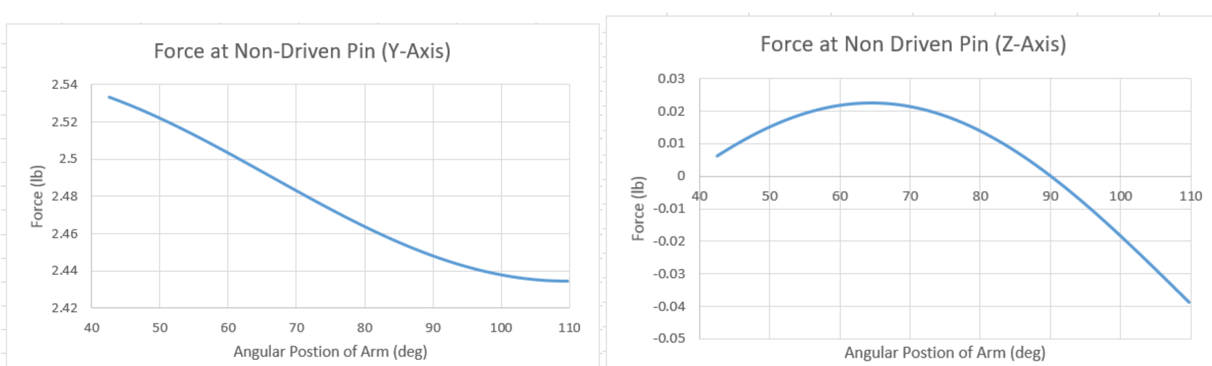



*Figure 33 a. Force at Non-Driven Pin in the Y-Axis (Left) b.Force at Non-Driven Pin in the Z-Axis (Right)*

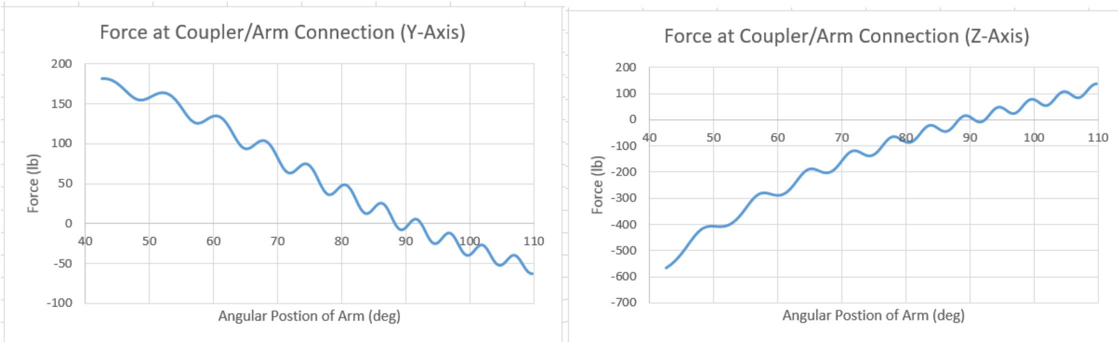



*Figure 34 a. Force at Coupler/Arm Connection in the Y-Axis (Left) b. Force at Coupler/Arm Connection in the Z-Axis (Right)*

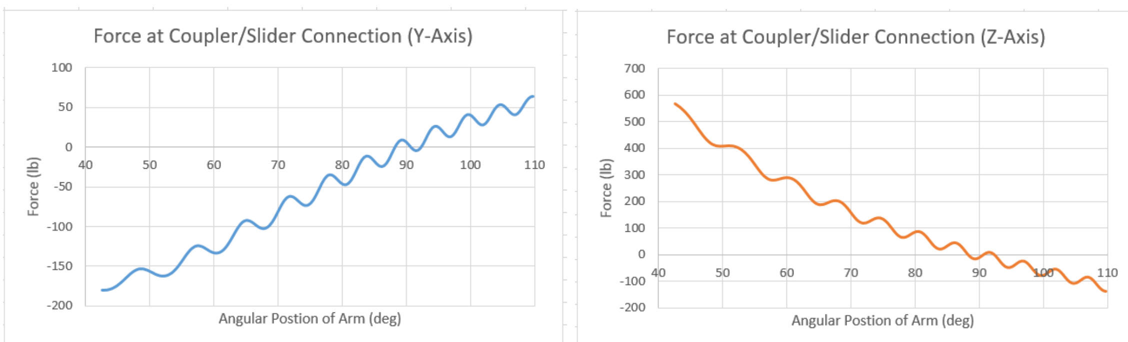



*Figure 35 a. Force Coupler/Slider Connection in the Y-Axis (Left) b. Force Coupler/Slider Connection in the Z-Axis (Right)*

*Table 7 Maximum forces at each Pin (in lbs) and at which angle they occur (degrees)*

| | | Maximum | Arm Angle | Transmission Angle |
|---|---|---|---|---|
| Force at Driven Pin | Y | 277 | 42 | 25 |
| | Z | 561 | 42 | 25 |
| Force at Non-Driven Pin | Y | 2.53 | 42 | 25 |
| | Z | 0.04 | 110 | 85 |
| Force at Coupler/Arm | Y | 181 | 42 | 25 |
| | Z | 566 | 42 | 25 |
| Force at Slider/Coupler | Y | 180 | 110 | 85 |
| | Z | 566 | 110 | 85 |

## 7.3 L-Brackets

The four L-Brackets connecting the top corners of the U-shaped lifting arm were deemed to be a critical part of the design. If these brackets were to fail due to pullout, the whole mechanism would fail catastrophically.

A static free body diagram using the results from the force analysis of the U-Arm Joints was used to determine maximum stresses in the L-Bracket. The worst case scenario analyzed for the L-Bracket was under the assumptions that only two bolts, one at point A and one at point B were supporting the bracket (Figure 36). These two locations were chosen due to their proximity to the edges of the bracket. This proximity creates the greatest chance of the bolt pulling through one of the edges. A second assumption made in this analysis is the direct transfer of the joint forces to point A. Point A is where the L-Bracket attaches to the loaded top beam, therefore, it is a conservative simplification to apply the joint forces at the corner connection (calculated in Section 7.1) directly to this bolt hole. These joint reactions include a y-component of 132 lb, an unknown x-component, and a moment of 492 lbs labeled $F_{y1}$, $F_{x1}$, and $M_1$ respectively in Figure 36.

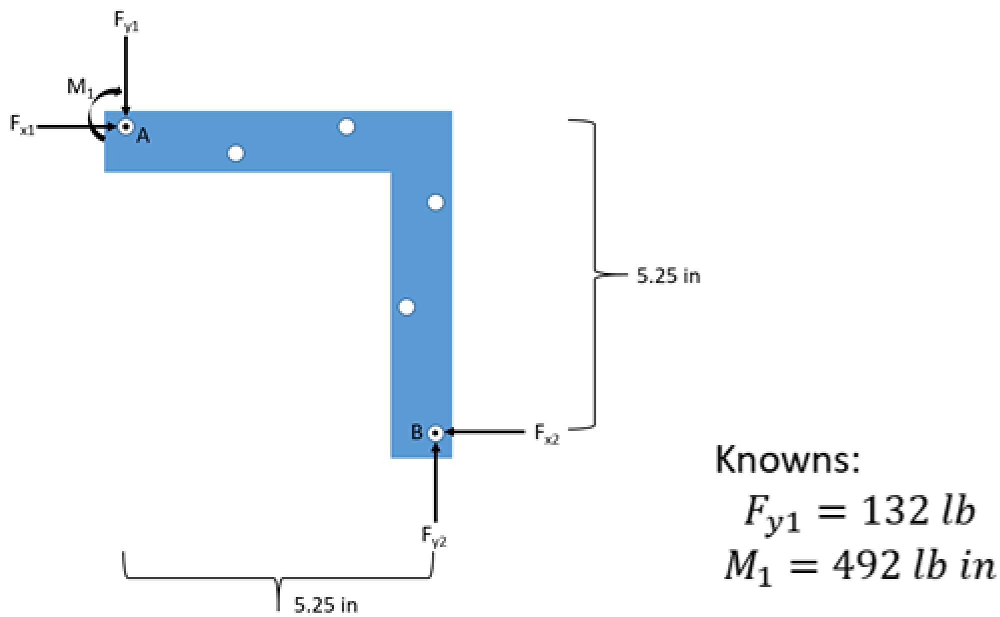



*Figure 36 Free Body Diagram of an L-Bracket*

The area on which the shear stress is applied to the cross sectional area calculated by multiplying the thickness of the bracket by the distance from the top of the hole to the edge of the bracket at its shortest distance. This gave a value for the area of 0.03 square inches. It is also important to note that each corner is supported by an L-Bracket at the front face and the back face. This is why the area is multiplied by a factor of two in the stress calculations (Figure 38).

$$\sum F_x = F_{x1} - F_{x2} = 0$$

$$F_{x1} = F_{x2}$$

$$\sum F_y = -F_{y1} + F_{y2} = 0$$

$$F_{y1} = F_{y2} = 132\ lb$$

$$\sum M_A = -M_1 + (F_{y2} * 5.25) - (F_{x2} * 5.25) = 0$$

$$F_{x2} = \frac{(F_{y2} * 5.25) - M_1}{5.25} = 38.3\ lb$$

*Figure 37 Force Calculation of Unknowns in Figure 35*

The L-Brackets are made of zinc plated steel which has a yield strength between 36 and 57 ksi. According to the stress calculations on the bracket (Figure 38), the max x-component stresses are well below this limit at 0.638 ksi. The y-component stresses was calculated to be 2.20 ksi which is also well below the material limit. Ultimately, this analysis shows that it is unlikely for the bolts to pull out of the bracket.

$$Area = (0.08\ in) * (3/8\ in) = 0.03\ in^2$$

$$\tau_{x,max} = \frac{F_{x2}}{(2A)} = 0.638\ ksi$$

$$\tau_{y,max} = \frac{F_{y2}}{(2A)} = 2.2\ ksi$$

*Figure 38 Maximum Stress Calculations on L-Brackets*

## 7.4 Pins

The pin joints were deemed to have the potential for failure due to the shear forces applied to the pin and the pullout forces at each of the flanges. The pin joints in the system are at the base of each of the side arms, the connection between the coupler and the driven arm, and the connection between the coupler and the coupler block. The latter of these four pin joints is different from the other three. The pin joints at the driven arm, non-driven arm and the coupler/arm connection consist of a bearing between two flanges on the aluminum beams while the pin joint at the coupler/block connection consists of two bearings with the aluminum flanges between them (Figure 39)

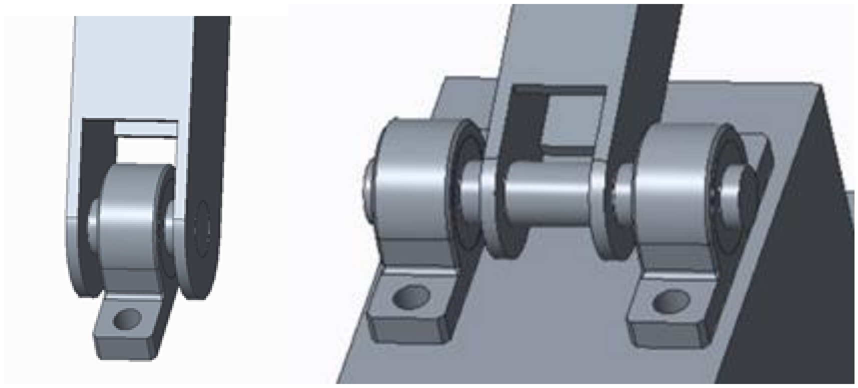


*Figure 39 Model of Pin Joints at the Driven Arm, Non-Driven Arm, and Coupler/Arm Connection (Left); and Pin Joint at Coupler Block Connection (Right)*

These two configurations must be analyzed individually as the stresses on the pins and flanges will be different in each case. The maximum force applied at each configuration is approximately 600 lbs. This force will be used to find the maximum stresses at each of the configurations.

The single bearing configuration puts the pin in double shear (Figure 40). The cross sectional area on which the force is applied was calculated by multiplying the thickness of the flanges (t) by the distance from the edge of the pin hole to the end of the flange (d). This shear was calculated to be 1.5 ksi with the max allowable shear stress of aluminum of 30 ksi. The pullout stress of the outer flanges of the beam was calculated to be 4.8 ksi which also falls under the 30 ksi limit (Figure 41).

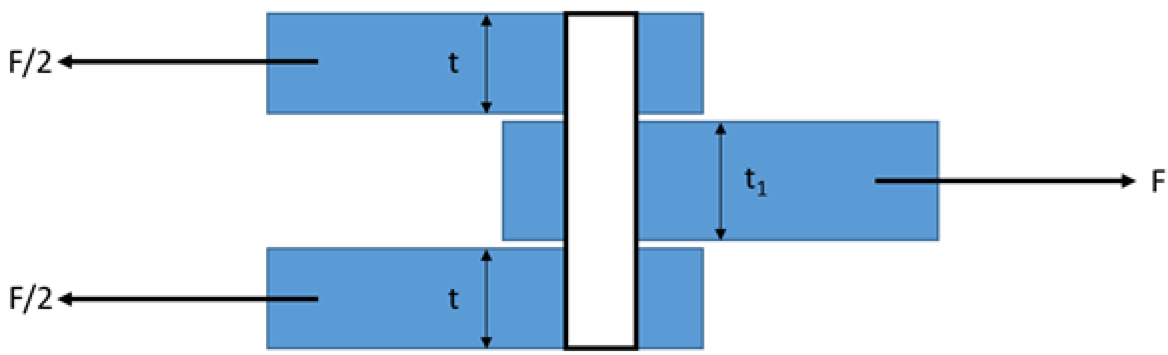



*Figure 40 Free Body Diagram of the Forces on the Pin in the Single Bearing Pin Joints*

$$\tau_{max,Al} = 30\ ksi$$

$$t = \frac{1}{8}\ in$$

$$t_1 = \frac{5}{8}\ in$$

$$d = \frac{1}{2}\ in$$

$$\tau_{pin} = \frac{4(600)}{2\pi(1/2)^2} = 1.5\ ksi$$

$$\tau_t = \frac{600}{2(1/8)(1/2)} = 4.8\ ksi$$

*Figure 41 Calculations for Single Bearing Pin Joint Pull Out and Pin Shear Forces*

The calculation for the second orientation of the pin joint at the coupler/block connection differs slightly from the calculation for the first single bearing orientation. In this instance, the bearings, labeled $t_1$, sit on the outside of the coupler flanges and bear only half the force each. Similarly, the two flanges of the coupler which sit between the two bearings also each only bear half the force applied on the coupler (Figure 42). The pin however is still in the same double shear situation as the previous single bearing pin joint orientation therefore the equations remain the same with the exception of the value of t—now 3/16 inch but previously 1/8 inch (Figure 43). The change in t comes from the need to shave down the inner faces of the flanges to allow clearance for the bearing. The result of these calculations confirmed that the pin in the double bearing configuration would also not fail. The maximum shear in the pin is 1.5 ksi and the maximum pullout stress on the flange is 3.2 ksi which both fall below the 30 ksi limit of aluminum.

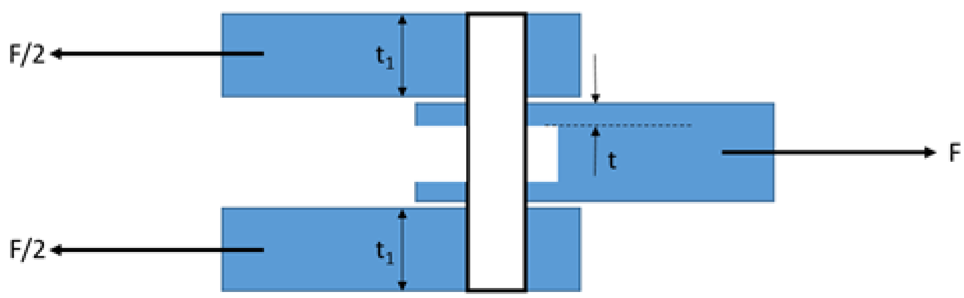



*Figure 42 Free Body Diagram of the Forces on the Pin in the Double Bearing Pin Joints*

$$t = \frac{3}{16}\ in$$

$$t_1 = \frac{5}{8}\ in$$

$$d = \frac{1}{2}\ in$$

$$\tau_{pin} = \frac{4(600)}{2\pi(1/2)^2} = 1.5\ ksi$$

$$\tau_t = \frac{600}{2(3/16)(1/2)} = 3.2\ ksi$$

*Figure 43 Calculations for Double Bearing Pin Joint Pull Out and Pin Shear Forces*

## 7.5 Beam Bending/Buckling

Buckling forces are a concern in driven and non-driven arms as well as the coupler. The cross-section of the driven and non-driven arm is a hollow 1-¼ inch square tube with a ⅛ inch wall thickness. Each of these tubes is 56 inches in length. The cross-section of the coupler is a hollow 1-inch square tube with a ⅜ inch wall thickness. The coupler is 20 inches in length. The Modulus of Elasticity of Aluminum is 10 x $10^6$ psi. The "n" factor for the end conditions of the pinned ends of the coupler and side arms is 4 (Figure 44). The axial forces on the coupler and the side arms is substantially below the critical buckling force of each beam (Table 8)

$F_c = Critical\ Buckling\ Force\ (lb)$

$n = factor\ accounting\ for\ the\ end\ conditions$

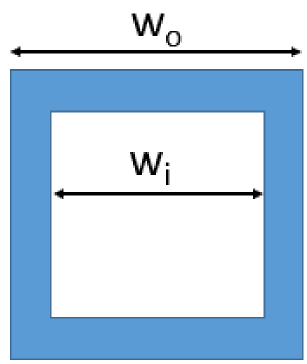
$E = Modulus\ of\ Elasticity\ (lb/in^2)$

$L = Length\ of\ Column$

$I = Moment\ of\ Inertia\ (in^2)$

$w_o = Outer\ Width\ (in)$

$w_i = Inner\ Width\ (in)$




$$F_c = \frac{\pi^2 * n * E * I}{L^2} \qquad I = \frac{{w_o}^2 - {w_i}^2}{12}$$

*Figure 44 Equations and Variables Used to Calculate the Critical Buckling Forces*

*Table 8 Buckling Force Comparison*

| | Cross Sectional Area (in^2) | Critical Buckling Force (lb) | Maximum Axial Force (lb) |
|---|---|---|---|
| **Coupler** | 0.61 | 17323 | 623 |
| **Side Arm** | 0.56 | 7561 | 132 |

## 7.6 Harness Connection Pullout

The harness is connected to the top beam through two eye bolts. The entire load is applied to only these two eyebolts, which make them a critical component for the transfer device design. The two eyebolts are 20'' apart, and the harness rope is 19.5'' long. The harness is 18'' below the top beam (Figure 45) and the weight of Felicity is 264 lbs with a safety factor of 3.

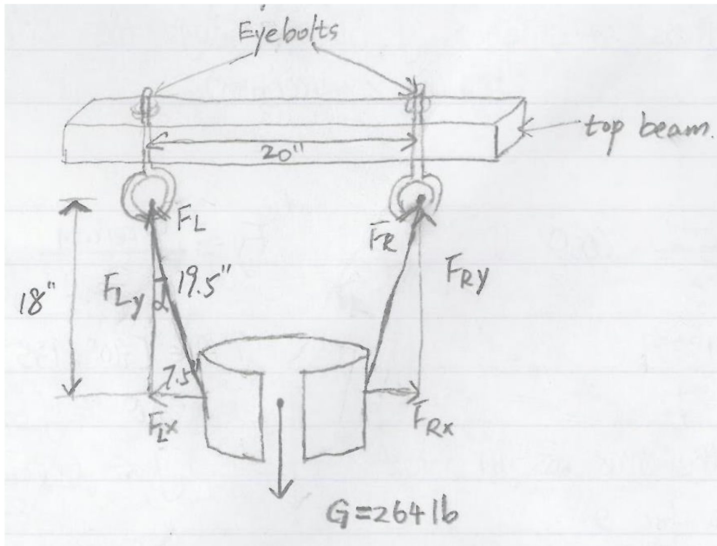



*Figure 45 Eyebolt Pullout Free Body Diagram*

The force applied to each eyebolt is determined to be 143 lbs through the following calculation (Figure 46). The force is applied 23 degrees from the eye bolt screw.

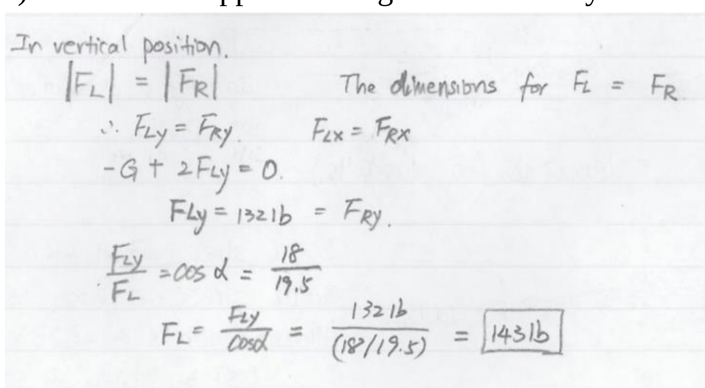



*Figure 46 Eyebolt Force Calculation*

The team utilized the forged eye bolt capacity and strength calculator from the Advanced Mechanical Engineering Solutions (AMES) website [16] (Figure 47). The eye bolts are ⅜'' and plain. With those inputs, the force capacity is 200 lbs at 60 degrees off the bolt (Figure 48).

| INPUT PARAMETERS | |
|---|---|
| Nominal eye bolt size (inches) | 3/8 ▼ |
| Eye Bolt Type | ◉ Plain Pattern Eye Bolts<br>○ Shoulder Pattern Eye Bolts |
| Calculate | |

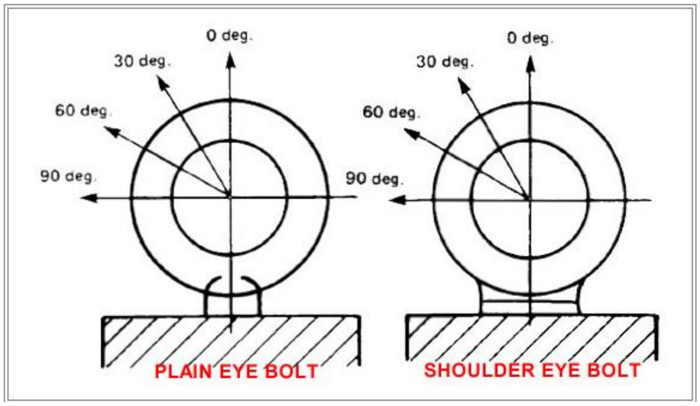


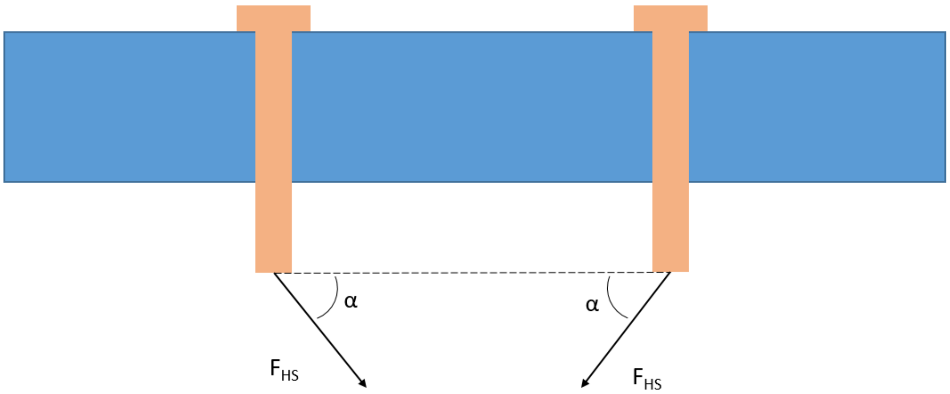

*Figure 47 Eye bolt Pull Out Calculation Input [16]*

| RESULTS | | |
|---|---|---|
| Parameter | Value | Unit |
| Nominal Size | 3/8 | - |
| Thread Size | 3/8 - 16 | |
| Eye Bolt Type | Plain Pattern Eye Bolts | |
| Breaking Strength, min | 5000 | lbf |
| Proof Load, min | 2000 | |
| Rated Capacity @ 0 deg. | 1000 | |
| Rated Capacity @ 30 deg. | 375 | |
| Rated Capacity @ 60 deg. | 200 | |
| Rated Capacity @ 90 deg. | 155 | |

*Figure 48 Eye Bolt Pull Out Calculation Result [16]*

The minimum and maximum arm angle are 42 and 110 degrees, thus, the angle at the eye bolt would be 48 and 20 degrees at those extreme positions. From the calculator results, the eye bolt rated capacity is between 200-375 lb. Therefore, a 143 lb force applied to the eye bolt is deemed safe at any point during the transfer process.

The eye bolts connecting the harness to the top rod of the U-shaped arm are susceptible to thread pull out forces. The diagram below (Figure 49) shows the bolts in tan and the top rod in blue. A force with magnitude W/2 is applied to the ends of the bolts in the y-axis where the eye of the bolt would be. This force is applied at some angle (alpha) dependent on the length of the rope. The rectangle at the top of the bolt represents the nut securing the bolt to the rod.




$$F_{HS,y} = \frac{W}{2}$$

$$\alpha = 67°$$

*Figure 49 Diagram of Forces Applied to Eye Bolts in the Top Rod*

To ensure the bolt will not fail due to shearing of the bolt or shearing of the threads on the bolt it necessary to analyze the bolts under worse case scenarios. For the susceptibility of the threads shearing, comes from Felicity's weight applied in the y-axis. The maximum shear stress applied to the threads of the nut is 100 psi as calculated in Figure 50. These stresses are well below the 59 ksi shear stress limit for steel.

$$A_n = \text{Shear Area for Nut Threads} \qquad n = 16$$
$$n = number\ of\ threads\ per\ inch \qquad E_n = 0.3\ in$$
$$E_n = \text{Max Pitch Diameter of Internal Thread} \qquad D_s = 0.375\ in$$
$$D_s = Min\ Major\ Diameter\ of\ External\ Threads \qquad L_e = 0.25\ in$$
$$L_e = Length\ of\ Thread\ Engagement$$

$$A_n = \pi * n * L_e * D_s\left(\frac{1}{2n} + 0.57735(D_s - E_n)\right)$$
$$A_n = 1.32\ in^2$$

$$\sigma = \frac{0.5 * W}{A_n} = 100\ psi$$

*Figure 50 Calculations for the Shear Forces on the Threads of the Nut*

## 7.7 Motor requirements

The two main specifications for the selection of a motor were its output torque and RPM. These values indicate its ability to drive the coupler and the speed at which the transfer takes place. The torque required to turn the screw is found from the major diameter of the screw, the coefficient of friction and axial force on the screw. The axial force required is equal to the maximum value found in the analysis of the coupler (Figure 51).

Major Diameter = 0.5"
Coefficient of Friction = 0.20
Axial Force = 561lb

$$T = cDF \qquad T = 0.20 \times 0.50" \times 561lb = \mathbf{56\ in * lb}$$

*Figure 51 Calculation of Ideal Output Torque Required by Motor*

The required output speed of the motor is determined by the number of times the screw must rotate to cause the coupler block to move the required distance along it and how long the motion is desired to take (Figure 52). It was decided that 10-20 seconds would be an appropriate duration for the motion to occur in while maintaining the client’s safety.

Duration = 10-20s
Rotation of Arm = 70° which equates to 9" linear motion
#10 Acme rod = 10 rotations/inch

$$\frac{9in}{10s} = \frac{0.9in}{s} \qquad \frac{9in}{20s} = \frac{0.45in}{s}$$

$$\frac{0.9in}{s} \times \frac{10rev}{in} = \frac{9rev}{s} = \mathbf{580\ \mathit{RPM}} \qquad \frac{0.45in}{s} \times \frac{10rev}{in} = \frac{4.5rev}{s} = \mathbf{270\ \mathit{RPM}}$$

*Figure 52 Calculation of Acceptable Motor Output Speed*

The motor that is used is powered by 12 volts, direct current. With the specifications determined above, it had to be a form of gear motor to reduce the speed and increase the output torque. Additional research found brushless electric motors to be significantly cheaper than brushed. Although brushless motors have decreased durability, the intermittent use of the motor in this device did not prioritize that factor.

## 7.8 Stabilizing Rod Extensions

Two stabilizing rod extensions were designed to prevent the device from tipping when the U-shaped arm was extended over at the wheelchair position. Detailed analysis was completed to determine the length of the stabilizing rods and to verify the chosen materials would not fail. A free body diagram in the side view of the device presents the calculations for the extra length x needed to prevent the device from tipping (Figure 53a, 53b).

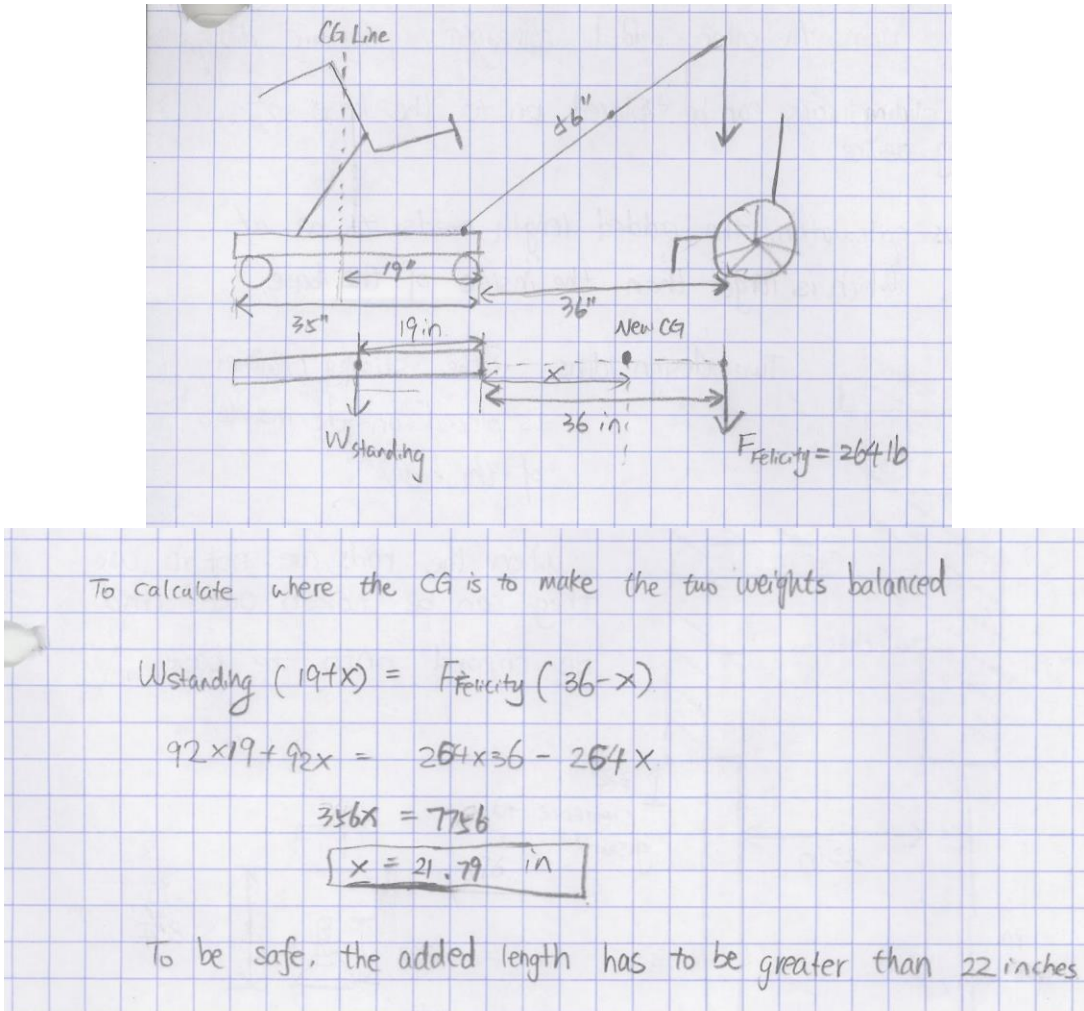



*Figure 53 a. Side View of Free Body Diagram for Stabilizing Rod Length Calculation (Top) b. Stabilizing Rod Length Calculation (Bottom)*

The moment at the new CG of the system should be 0 to prevent tipping. The equation is set up when the values of moments in the clockwise and counterclockwise direction equal each other. The extra length needed was then determined to be at least 21.79” (Figure 53). Therefore, the team decided to add 26’’ to the base of standing device.

After the length of the stabilizing rod was determined, proper materials were chosen and analyzed for prospective failure. The device is now supported by six wheels, and for analysis purposes, the team assumed the worst case scenario where the weight at the front wheels (N1 in Figure 54a) to be 0. With this assumption, each wheel on the stabilizing rod supports a weight of 143 lbs (Figure 54b).

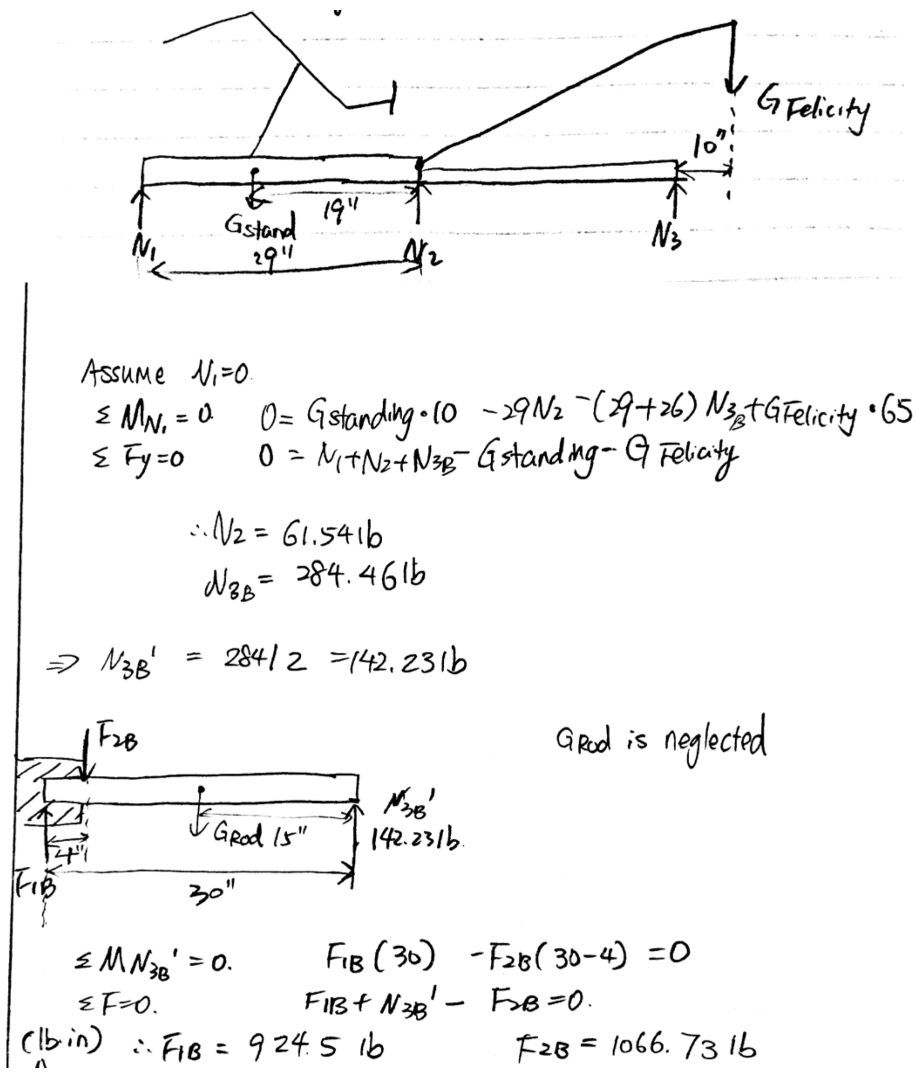


*Figure 54 a. Side View Free Body Diagram for Stabilizing Rods Load Distribution (Top) b. Free Body Diagram and Calculation for Normal Forces on the Stabilizing Rod(Bottom)*

The maximum shear force was determined to be 925 lbs through an online bending moment and shear calculator [17]. The maximum shear stress is therefore 2114 psi (Figure 55), and occurs at 4'' from the end of the sliding rod that is inside the flanged tube (Figure 54b). The shear strength of multipurpose 6061 aluminum tube is 30000 psi [18], so the material is deemed safe for shear strength.

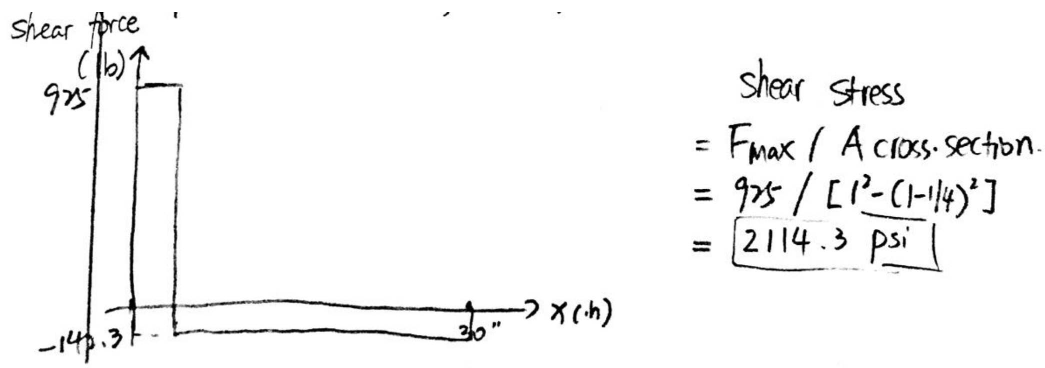



*Figure 55 Shear Force and Shear Stress Calculation on the Stabilizing Rods*

Allowable moment equals to yield strength (35000 psi for aluminum tubes) times section modulus. For the multipurpose 6061 aluminum rod, the allowable moment was calculated to be 3990 lb.in (Figure 56). The maximum bending moment is determined to be 3699 lb.in through the online bending moment calculator [17] (Figure 57), so the chosen material is deemed safe for bending moments.

$$M_{allow} = \sigma_{allow} * S_x$$

$S_x$ = Section Modulus

$$S_x = \frac{W_o^4 - W_i^4}{6W_o} = 0.114\ in^3$$

$$M_{allow} = \sigma_{allow} * S_x$$

$$M_{allow} = 35000\ psi * 0.114\ in^3$$

$$M_{allow} = 3990\ lb.in$$

*Figure 56 Stabilizing Rod Allowable Moment Calculation*

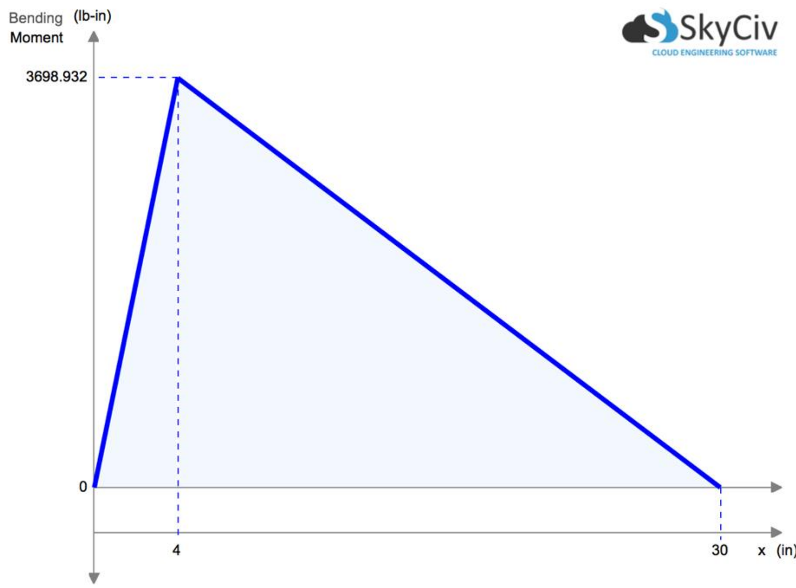
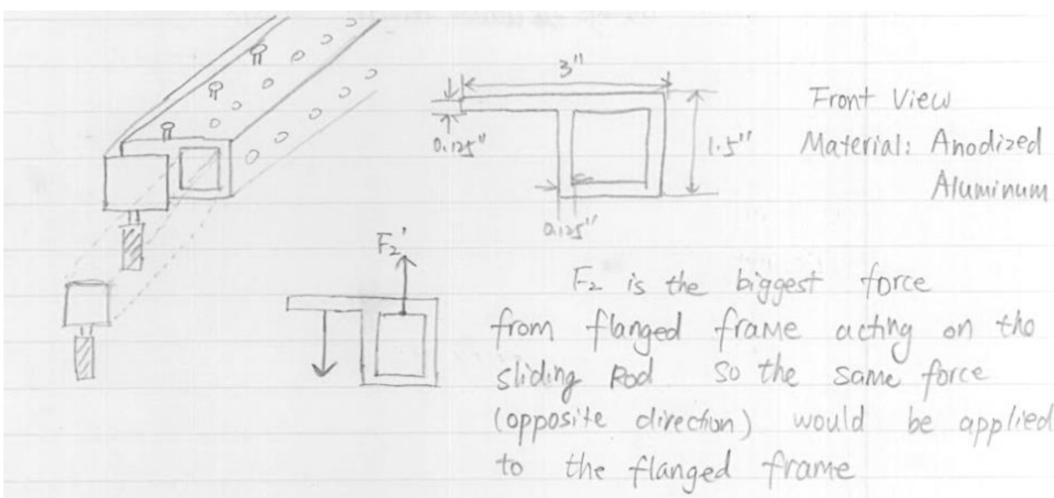



*Figure 57 Bending Moment Diagram on Stabilizing Rod [17]*

A shear stress is exerted on the flanges, created by the normal force acting upward from the sliding rod. The maximum shear force is 925 lbs, and the area balancing the shear 0.125'' wide and 4'' long, so the shear stress at the flanges is calculated to be 1850 psi (Figure 58b), which is safe due to regular aluminum's shear strength being 30000 psi.




$$\tau = \frac{F_2'}{A} = \frac{925\ lb}{(0.125'')(4'')} = 1850\ psi$$

*Figure 58 a. Flanged Tube Free Body Diagram (Top) b. Shear Stress Calculation (Bottom)*

Four bolts balance the force ($F_2$' in Figure 58a) acting upward from the sliding rod. The analysis was done assuming all the shear force is acting on one T type bolt. The bolt tension at this bolt is 0.925 kip, so the yield on the bolt is 2.093 ksi (Figure 59b). The allowable bolt tension is 19.4 kip/bolt and the yield strength is 28 ksi from AISC Table-J3.7 [19]. Thus, all components of the stabilizing rods are deemed safe.

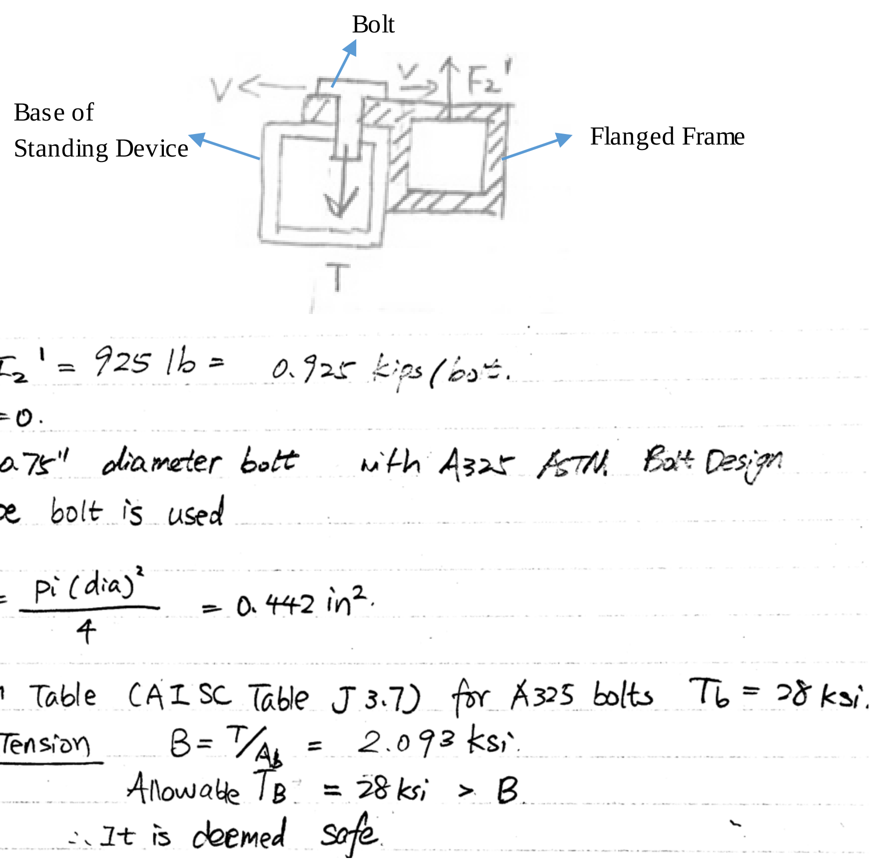



*Figure 59 a. Free Body Diagram for the Bolt on Flanged Tube (Top) b. Bolt Pull Out and Yield Calculation (Bottom)*

# 8. Manufacturing

The manufacturing process began following the completion of the design and analysis of each component. The most complex components were purchased pre-assembled and the remainder of the parts were manufactured from stock materials. Assembly required careful measurement for the placement of bolts and cuts in the stock material. The manufacturing process occurred in essentially five stages: U-shaped arm frame, harness, base extension, screw mechanism, and electrical components.

## 8.1 U-Shaped Arm Frame Assembly

The U-shaped arm was constructed of 1 ¼” square aluminum tubing. Key structures of the U-shaped arm are the vertical arms which make up the rocker of the four-bar linkage described previously, the coupler connecting the screw and arms, and the top crossbar that attaches to the harness.

### 8.1.1 Arms

The arms were cut to 57” in length. They required ½” holes at the base where an aluminum pin was fixed using brazing. This pin allows the arm to rotate about the bearings mounted to the base of the standing device. The faces perpendicular to the drilled hole were cut out using an angle grinder and the faces containing the holes then ground to an arc of 3/8” radius concentric to the pin hole so that there would be no interference of the arm with the bearing or standing device base when rotating. The ¼” holes to mount the coupler bearing were drilled 13” up from the center of the pin at the base of one arm. Three holes sized to fit #10 machine bolts were drilled at the top of each arm for the mounting of L-shaped brackets that fixed the arms and crossbar together (Figure 62).

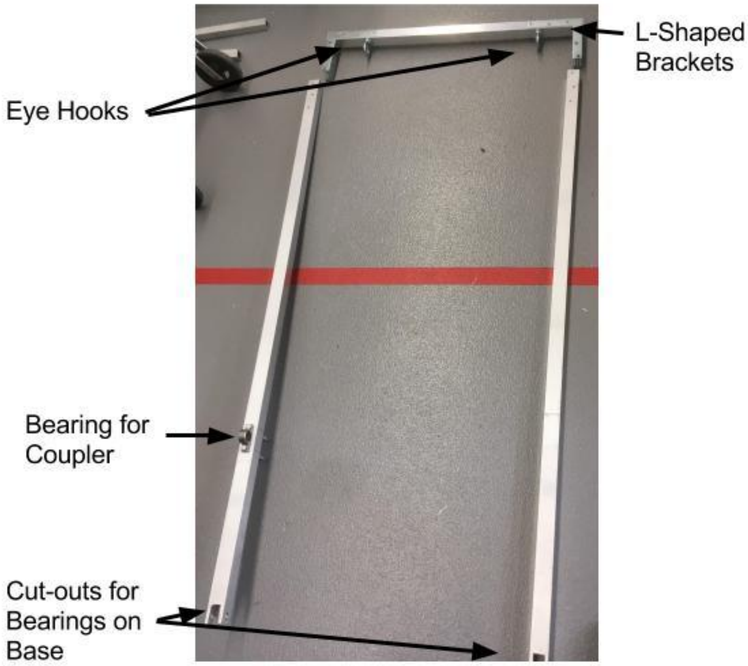



*Figure 60 U-Shaped Arm Frame*

## 8.1.2 Crossbar

The crossbar was cut to 30" in length and required drilling for the L-shaped brackets for fixation to the arms and eyebolts for attaching the harness. Three holes were drilled on either end of the crossbar to fit #10 bolts. An L-shaped bracket is fitted on either side of the crossbar and fixes the arms and crossbar together. The 3/8" eyebolts are mounted on the face perpendicular to the bracket holes.

## 8.1.3 Coupler

The coupler was constructed of 1" square aluminum tubing. It connects the coupler block of the screw assembly to the arm. Bearings are fixed to both ends of the coupler with a ½" pin. On the screw assembly side the pin extends outwards to fit two bearings on the coupler block. On the arm side, a single bearing bolted to the arm fixes to the pin of the coupler (Figure 63).

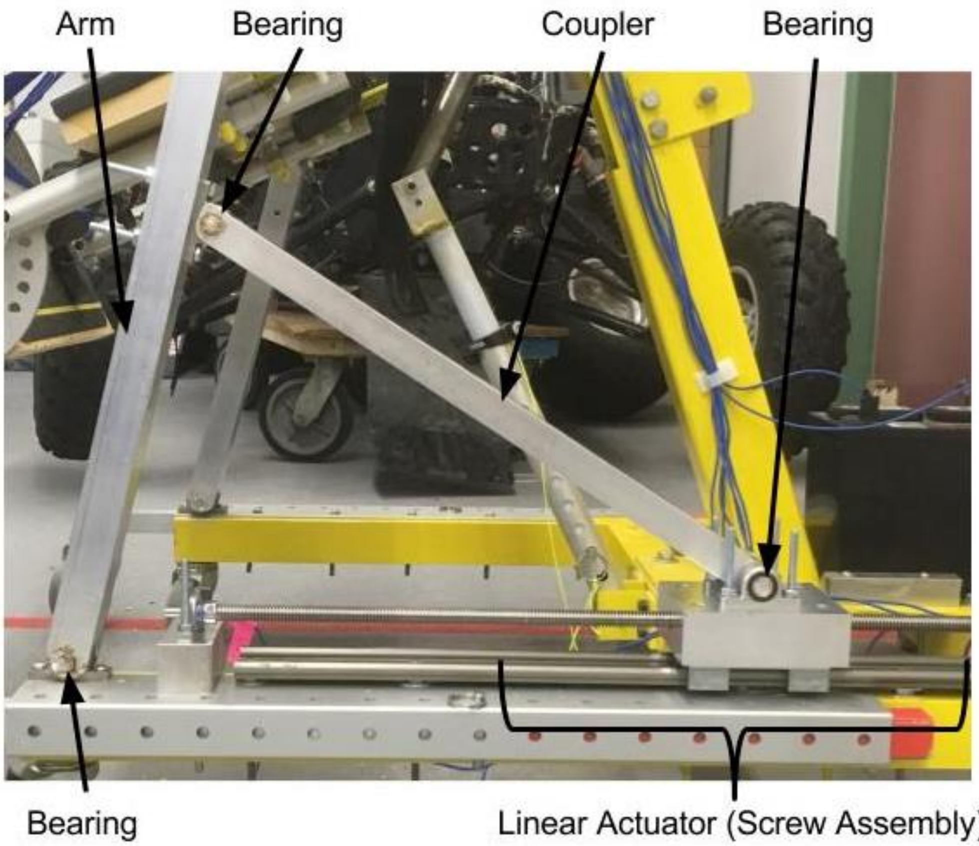



*Figure 61 Four-bar Linkage Created by Linear Actuator, Arm, and Coupler*

## 8.2 Harness Assembly

The team provided the harness design concept to the bungee jump harness manufacturer in China. The manufacturer had all the required materials on site, including rope, clips, straps, waist pads, anchors and rope adjusters. The waist belt is 23'' long, and consists two regular waist pads, which raise the attachment points to above the center of gravity (CG) of the harness assembly with Felicity in it. Two buckles that tighten the belt around Felicity's hips and torso with their respective straps were sewed onto the waist belt using an industrial sewing machine. Four anchors were sewn on to the top strap. The first anchor was placed 2 cm from the end of the clip, the second anchor was placed 5 cm from the first anchor, and the third anchor was positioned 10 cm from the second anchor. The final anchor was placed 5 cm from the third anchor. (Figure 64). Carabiners are used to clip rope from each of the anchors to the eye bolts, two on each side.

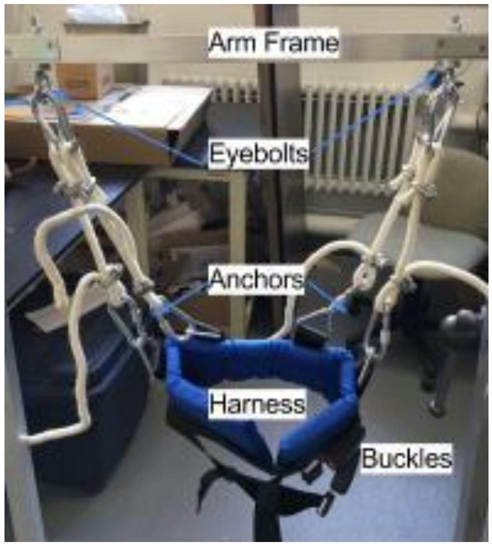


*Figure 62 Harness Full Assembly Attached to Crossbar*

## 8.3 Base Extension Assembly

There is an extension assembly on each side of the base frame. For manufacturing, a ⅝'' hole was drilled on the sliding tube at an inch from the end. The wheel is then fastened to the sliding tube using a nut. The sliding tubes are 30'' long, 1 ¼'' square aluminum tubing with ⅛'' wall thickness (Figure 65).

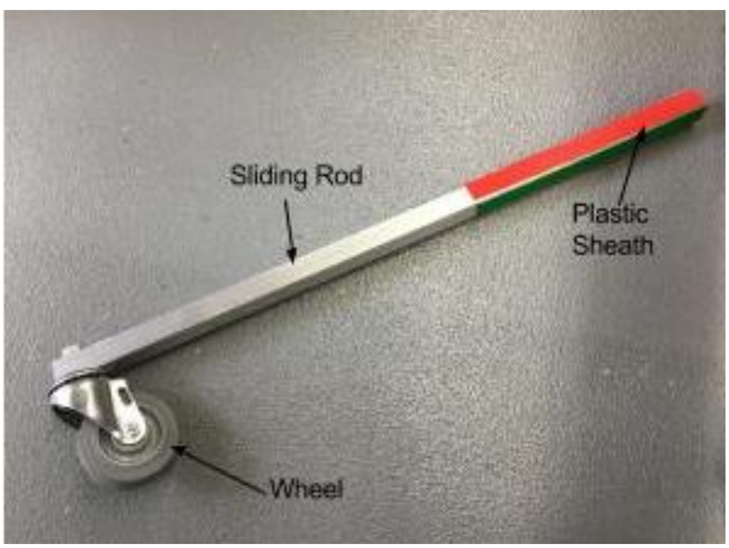


*Figure 63 Sliding Rod with Wheel*

To secure the flanged tubes on the base, the four holes through the carriage track were continued through the flange so that a single bolt was placed at each point. The bolts went fully through the base to the nuts at the bottom of the device. Excess bolt length was removed upon total assembly of the transfer device.

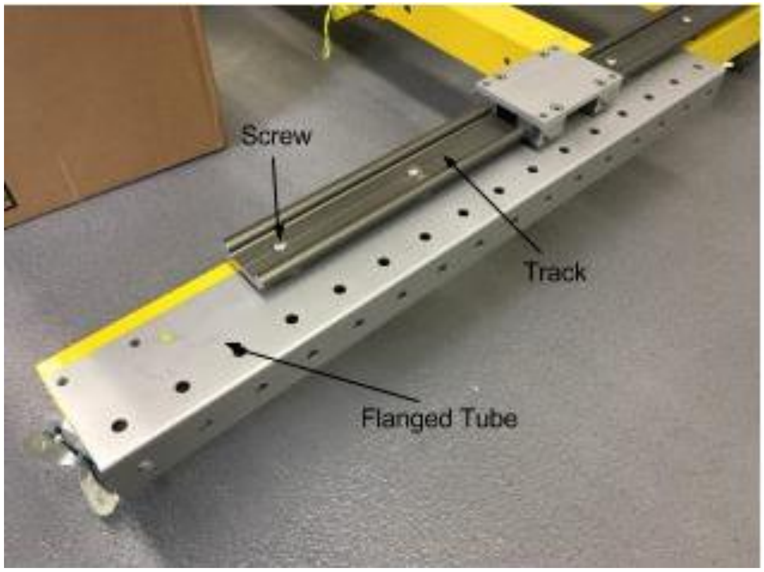



*Figure 64 Flanged Tube Connection to the Base*

After securely attaching the flanged frame and the track on the base, the team realized that the ⅛" gap between the stabilizing rods and their mounts allowed for too much movement and would lead to the device lifting slightly off its front wheels when loaded at the point over the wheelchair. To correct this, some plastic sheaths are glued to the end of the stabilizing rod that will be loaded during transfer. The sheath is made of strips of a polypropylene cutting board glued to the stabilizer. The plastic is 0.75" thick; two strips are glued to each of two adjacent sides and one strip is glued to each of the other two sides.

When the sliding rods are in use (Figure 67) in the wheelchair position, they successfully prevent the device from tipping.

*Figure 65 Stabilizing Rod in Fully Extended Position*

## 8.4 Screw Mechanism Assembly

An electric motor rotates the acme threaded rod, which creates linear motion of the coupler block along its length. The screw mechanism provides the linear actuation to drive the four bar linkage consisting of the screw, coupler, arm, and ground links.

### 8.4.1 Screw

The screw is a ½" - 10 Acme threaded rod. The threads on each end were removed by a manual lathe so that they are equal to the inner diameter of the rod and smooth. Simple support of the rod is provided by a bearing at either end (Figure 68). A collar and thrust bearing between the end of the threads and the bearing at each end provide the screw the ability to rotate with minimal friction (Figure 69).

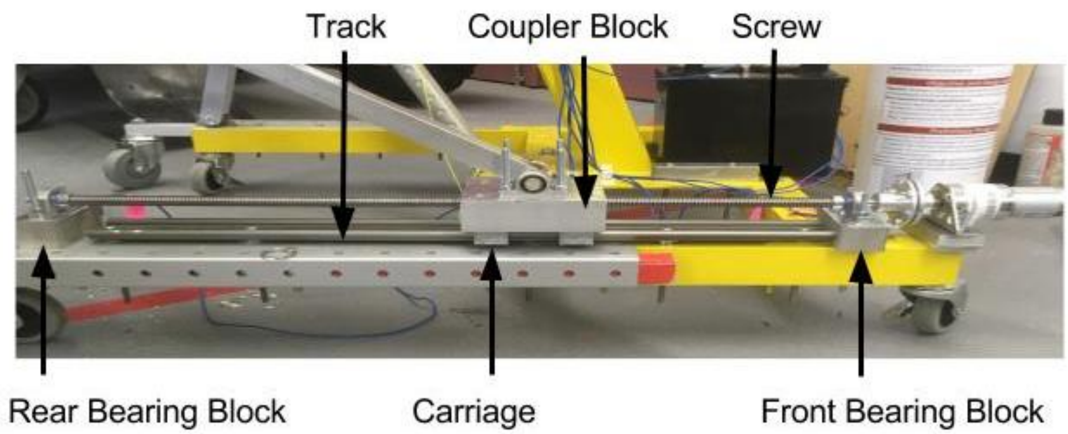



*Figure 66 Screw Mechanism Fully Assembled as Linear Actuator*

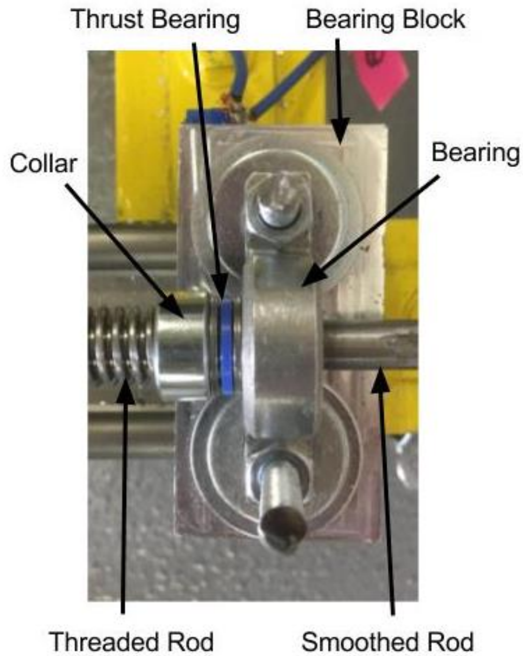



*Figure 67 Details of Screw Ends and Bearings*

## 8.4.2 Coupler Block

The coupler block was designed in Solidworks and manufactured using the Haas Minimill. It is mounted onto a carriage and track to support the load transverse to the direction of the screw. This prevents bending in the screw and protects the motor, which can only operate under a load of less than 28 pounds perpendicular to the output shaft. Two bearings are used to support the end of the coupler so that the bolts used to fix them do not interfere with the screw below. A nut placed into a pocket in the block provides the female threads that the screw interfaces with (Figure 70). The nut is fixed in place with set screws, two from each side perpendicular to the screw axis. The axial load of the coupler is transferred from the block to the screw by the contact of the block and nut.

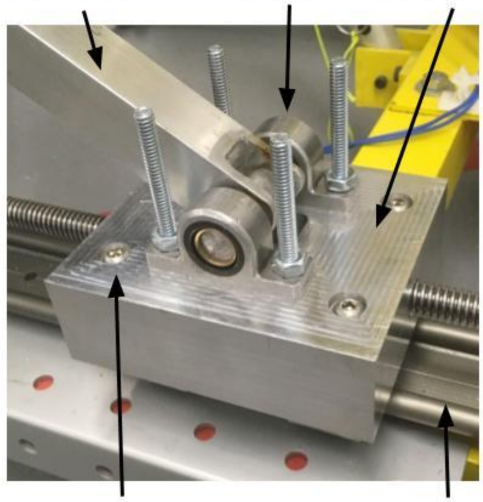



*Figure 68 Coupler Block  Mounted on Screw and Track*

### 8.4.3 Motor

The motor selected was an AndyMark brushless 12V DC motor with a gear train attached to the output.  This motor produces 42.5in-lb of torque at a maximum of 512 RPM.  These specifications do not meet the required torque to drive the screw. When loaded and equate to a linear speed of 0.98 inch/second, which completes the rotation of the arm required for transfer in 18 seconds.  The output of the motor is fixed to the screw by way of hubs bolted to each other, each with the appropriate diameter and key to fix to the end of their respective shaft (Figure 71).

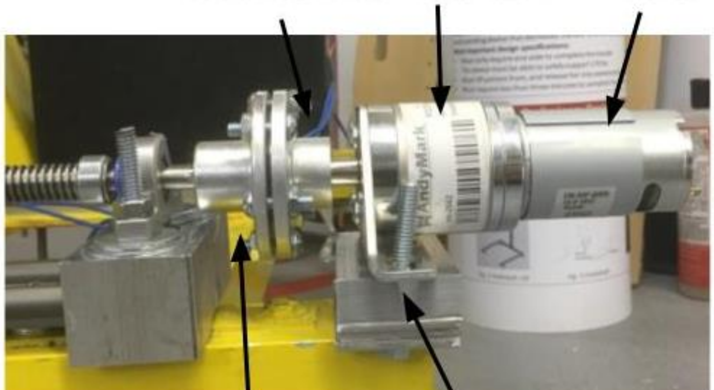
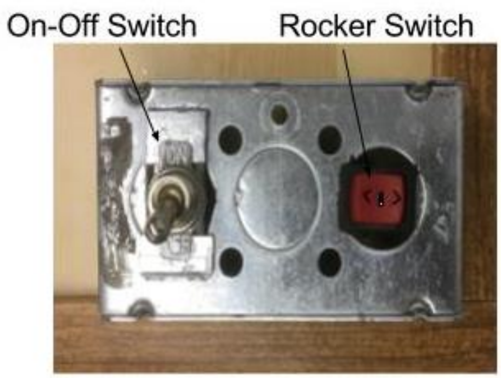



*Figure 69 Motor Mounted to Standing Device Frame*

## 8.5 Electrical

The rotation of the U-shaped arm is controlled with an On-Off-On rocker switch mounted on the tray of the standing device. Several safety mechanisms are built into the circuit. The rocker switch controls the direction the current travels through the motor, which in turn controls the direction the arm rotates. Arrows designate which way the arm will rotate when that side of the rocker switch is depressed. The first safety feature is a simple On-Off switch located next to the rocker switch (Figure 72a). This switch must be placed to On for the ability to complete any operation of the U-shaped arm by the rocker switch. Additionally, two normally closed snap switches are located at either end of the screw to serve as "kill" switches (Figure 72b). When the coupler block reaches the end of the screw, the switch is pressed and opens the circuit, but only for the flow of current across the motor that drives the coupler block in that particular direction. Therefore, the rocker switch may be depressed in the other direction and the arm will still rotate away from the extreme that it had reached. These measures ensure that accidental movement of the U-shaped arm will not occur and user error will not cause damage to the screw assembly.



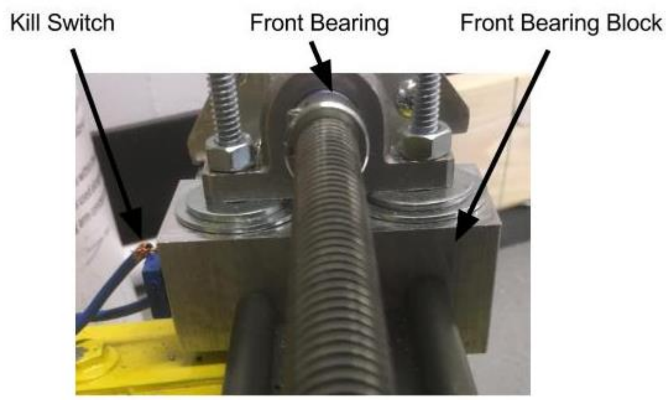




*Figure 70 a. Kill Switch on Front Screw Bearing Block (Left) b. Arm Control Panel Mounted to Standing Device Tray (Right)*

# 9. Verification and Testing

The purpose of testing is to ensure the design can safely support and transfer Felicity between her wheelchair and her standing position. The user must not face danger at any point while the device is in use. The test has to ensure that no failures occur or are about to occur while the device is being used and that the device is stable at all positions during the transfer. The procedures designed for testing a fully functional transfer device include tests done when the device is unloaded, loaded in a static position, experiencing dynamic loads and through user evaluation. Due to its failure to pass the entire static testing, not all tests identified were completed.

## 9.1 Unloaded Tests

The first test conducted was driving the linear actuator along its full length in both directions to ensure the U-shaped arm frame followed its full path without interference. The device travels the full length of the screw, reaching the kill switch at either end.

## 9.2 Static Tests

The device's ability to support the target load of 176 lbs at any given position without tipping was first tested by hanging incrementally larger loads to the harness. The load started at 25 lbs and was incremented by a factor of 25 lbs. The system was loaded in the upright over the standing device position (Figure 71a) first. The system showed no deflection with a 75 lb load in this position. However, when the U-shaped arm was loaded with 75 lbs when in the angled over the wheelchair position, there was significant deflection in the U-shaped arm (Figure 71b) and an appearance of imminent failure. This deflection led the team to stop testing and deem the mechanism unsafe for further testing. The upper end of the non-driven vertical bar was approximately four inches lower than the upper end of the driven arm.

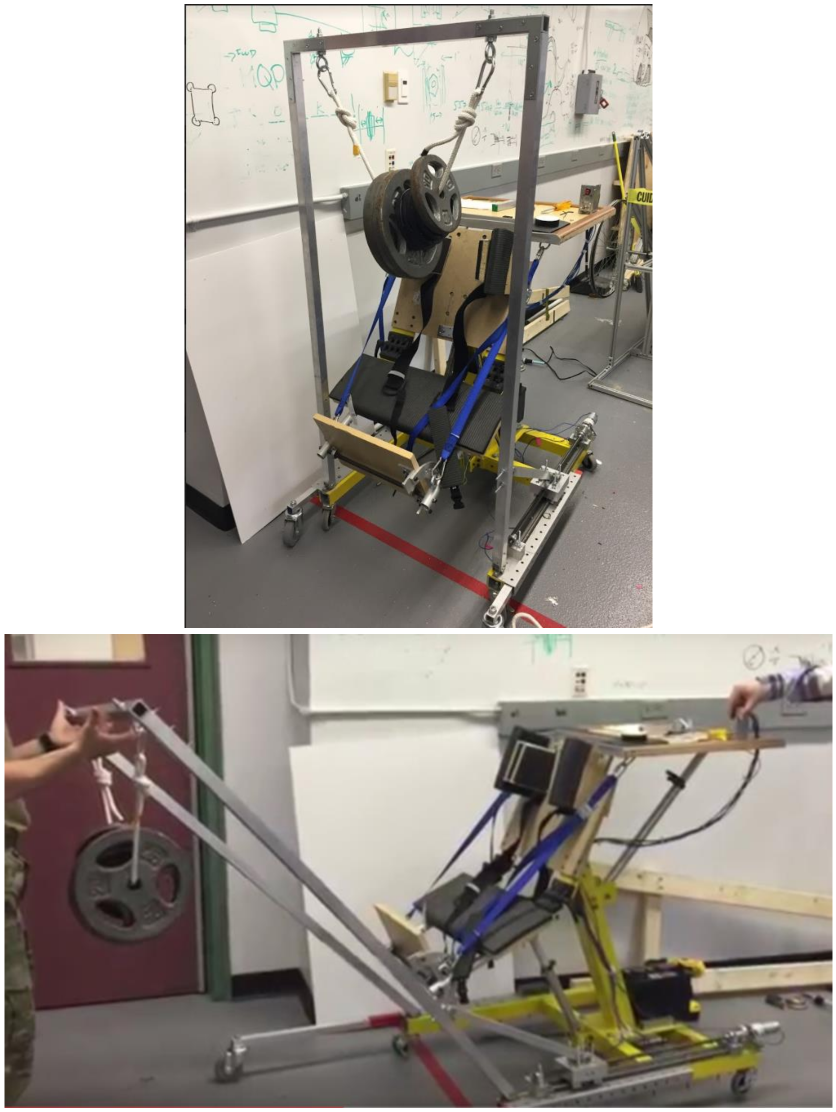


*Figure 71 a. Arm Loaded with 75lbs in Position over the Standing Device (Top) b. Arm Loaded with 75lbs in Position over the Wheelchair*

If the device could pass the static loading test at 175 lbs, an additional test would be to place a sandbag in the harness to represent Felicity's torso and ensure that she will not slip out of the harness when buckled. A sandbag allows the diameter and weight to be controlled to most accurately represent Felicity's anthropometric measurements during testing.

## 9.3 Dynamic Tests

The weight bearing test was then completed again, but rather than unload the harness to move the position of the U-shaped arm, the motor was used to drive it fully from stander to wheelchair position and back. This test was successfully completed at 50 lbs and 75 lbs after which testing was stopped due to the observations made in the static test. Had the U-shaped arm been capable of supporting the entire weight, the test would have continued to the maximum weight of 175 lbs. Then the test would be repeated with the greatest weight while being pushed to create a gentle swinging motion during the transfer. This would also serve to exhibit how much the harness is capable of swinging and how quickly it comes to a stop.

## 9.4 User Evaluation

The device was not found to be safe and therefore could not be returned to the client for use. However, if the device had been successful in lab testing, the team would explain and demonstrate its use to the physical therapist, Sally Goodhile, without Felicity, following along with a written instruction manual. The team would then observe Ms. Goodhile complete the transfer with Felicity to and from the standing device. Ms. Goodhile would be able to provide feedback on her observations and Felicity's acceptance of the process.

# 10. Results and Discussion

When the device was fully assembled, various problems occurred. The first issue involved alignment within the drive train. The coupler block travelled the full length of the screw easily when driven by hand. However, when fully fixed in place and driven by the motor, even with no load from the coupler link, the block jammed and the motor stalled. This issue was narrowed down to a misalignment of the screw itself due to bending, the axes of the motor output and screw, or a combination thereof. Using a laser level, the team identified movement in the rod laterally when rotating. The level was placed on the coupler and a flat surface at the rear end of the screw mechanism. When the screw was rotated the left and right limits of the laser level on the flat surface was marked. Three set ups were recorded: bearings and carriage loose, bearings and motor bolted with the carriage loose, all pieces fixed into final positions. The lateral movement identified by the laser decreased at each set up from 5.42 mm to 3.53 mm and finally no movement at all, respectively. The angle of the screw was also identified at the point where the lateral movement changed direction. These points were close to the location of each key in the hub, but the correlation was not confirmed to have any meaning. It was also observed that when the entire screw mechanism was fixed on this occurrence that the device functioned fully by hand, powered by drill, and finally powered by the motor as it should be. It was observed that the rear screw bearing was fixed so that it sat in its most outside position from the base. Whether the location of this bearing equated to the sudden functioning of the driving mechanism was not further investigated because testing for client use was now possible.

Static and dynamic load tests were started when the transfer device was capable of travelling its entire path without failure. These tests identified a third flaw for the project that could not be addressed in the time requirement. When a load greater than 50 lbs was hung from the transfer device at its most extended position, over the wheelchair, there was significant deflection between the two vertical bars of the U-shaped arm frame. The non-driven arm dropped lower to the ground than the driven arm with the coupler link. With 75 lbs at the wheelchair position, the end of the non-driven bar at the crossbar was 6" lower than the driven arm. This deflection also placed a torque on the pin at the base of the bar, which caused deformation of flange that the pin was fixed to. Additionally, it was noted that the motor ran slower and the tone of the motor changed pitch when running loaded at 75 lbs. Although it did not fail at this weight, it is very possible that it would not be able to drive the U-shaped arm with the full 175 lbs. Because an appropriate safety factor cannot be reached when placing a load on the transfer device, it is not safe for the client to use.

# 11. Redesign and Future Work

## 11.1 Redesign

A weakness in the design is the stability of the U-shaped arm frame. At first it experienced both translational shifting left and right along the axis of the bearings as well as a twisting motion due to only a single side being driven. The translational shift was taken up with the addition of bearing shims to the pivots at the base of the U-shaped arm. This also helped with the twisting motion, but did not fully solve that flaw. The twisting motion was an issue because it introduced a greater torque than was anticipated that could lead to the failure of the frame, most likely at the top corners. Additional twisting would also likely occur due to Felicity's motion in the harness. A significant factor allowing the twisting is the level of misalignment allowed by the bearings. They bearings are designed to allow 5-10 degrees of misalignment in any direction, which extends to the arms pivoted on them. Bearings that truly allowed only one degree of freedom would not undergo the twisting motion without significantly greater forces. Another solution could be to add additional support, such as a small truss to the top corners of the U-shaped arm to help resist the motion. The most effective solution to this problem, however, takes the most time and money to complete. This would be adding a second mechanism, just like the one already in place, to the currently non-driven arm so that both arms could be driven. This would require the same parts from the coupler arm down to the motor and track as are currently in place on the driven arm. These two mechanisms would also have to be checked to ensure they are in phase with one another and driving the two arms at the same angular velocity and at the same position.

Another weakness of the mechanism is that the motor appears to be undersized. When the mechanism was run with the 75 lbs, the tone of the motor changed significantly signaling that it may have been struggling to handle the amount of torque required from it. This may have to do with a calculation error on the part of the output torque requirement or have something to do with the force distribution within the mechanism. If a second motor is added to the currently non-driven arm, the current motor size may be okay as it will only need to handle half of the load. However, a better understanding of the torque required to move the mechanism and the force distribution throughout the mechanism would be very beneficial to future work on this device.

## 11.2 Future Work

The standing device is still capable of functioning in its original capacity completely unhindered with the additional hardware of the transfer device on the base. In order to fix the alignment issue with the transfer device, as well as address other flaws, the team recommends driving both arms as well as finding a more precise mounting method than the many bolts used.

# 12. Conclusion

Due to the instability in the non-driven arm, the transfer device remains unusable by the client. The concept of Swing Arm design remains sound and reasonable, but due to manufacturing obstacles, the team was unable to provide a functioning transfer device to the client. The standing device however, was successfully repaired and is fully functioning (Appendix B). The repair cost was $54. The client is now able to use the standing device again for her in-class activities, supporting her physical and social growth.

The transfer portion remains unfinished at this point. The harness, linear actuator, electrical components and extension assembly are all working properly at this point. The concept of the transfer device remains valid, because it is tailored towards Felicity and the school's needs. The fact that it implements the transfer device onto the existing standing device was favored by the school staff due to the limited storage space they have at the school.

Once the client and school staff develop a sufficient level of comfort with the standing device again, it could be utilized on a frequent basis and implemented to Felicity's school activities.

# References

[1]"Britannica Academic", *Academic.eb.com*, 2016. [Online]. Available: http://academic.eb.com/levels/collegiate/article/22137. [Accessed: 11- Sep- 2016].

[2]"Cause of Cerebral Palsy", *cerebralpalsy.org*, 2016. [Online]. Available: http://www.cerebralpalsy.org/about-cerebral-palsy/cause. [Accessed: 11- Sep- 2016].

[3] M. C. Staff, "Cerebral Palsy," *Mayoclinic*, Aug. 2016. [Online]. Available: http://www.mayoclinic.org/diseases-conditions/cerebral-palsy/home/ovc-20236549. Accessed: Oct. 13, 2016.

[4]"Surgery for Cerebral Palsy - Improving Movement and Walking", *Cerebral Palsy Guide*, 2016. [Online]. Available: https://www.cerebralpalsyguide.com/treatment/surgery/. [Accessed: 11- Sep- 2016].

[5] Warner, M. P. (2007). "Standing Tall: The Benefits of Standing Devices." Exceptional Parent 37(3): 2. [Accessed: 11- Sep- 2016].

[6] Nordstrom, B., Naslund, A., Eriksson, M., Nyberg, L., and Ekenberg, L. (2013). *The Impact of Supported Standing on Well-Being and Quality of Life*. [Online]. Available: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3817885/

[7] C. Glynn, M. Guarino, J. Ordonez, Z. Zheng, "Standing Device for a Six Year Old Student," Major Qualifying Project, ME Dept., WPI, Worcester, MA, 2015.

[8] Tobii Dynavox. (2016). *Software* [Online]. Available: http://www.tobiidynavox.com/software/

[9] Invacare. (2016). *Invacare Get-U-Up Hydraulic Stand-Up Lift*. [Online]. Available: http://www.invacare.com/cgi-bin/imhqprd/inv_catalog/prod_cat_detail.jsp?prodID=GHS350

[10] Preferred Health Choice. (2016). *Hoyer Hydraulic Patient Lifter HML400*. [Online]. Available: http://www.phc-online.com/Hoyer_Patient_Lifter_p/hoyer_hml400.htm

[11] Jolly Jumper. (2016). *Jolly Jumper Exerciser with Stand*. [Online]. Available: http://www.jollyjumper.com/show/29

[12] P. P. Poncy & M. Chzanowski, "Chair with Assistance Mechanism," U.S. Patent 4 690 457, Sep. 1, 1987.

[13] L. Sharps, "Patient Transfer System," US Patent 7 197 778, Apr. 3, 2007

[14] Rehabmart.com. (2016). *Romedic TurnTable Patient Turner*. [Online]. Available: http://www.rehabmart.com/product/romedic-turntable-patient-turner-35944.html

[15] Peterson, Lyle, "How a Hydraulic Jack Works," April 5, 2016. [Online]. Available: https://www.youtube.com/watch?v=OpIsQqhgZNw

[16] A. (n.d.). FORGED EYE BOLT CAPACITY AND STRENGTH. Retrieved April 21, 2017, from http://www.amesweb.info/Fasteners/ForgedEyeBolts/Forged_Eye_Bolt_Capacity.aspx

[17] Beam Calculator. (n.d.). Retrieved April 25, 2017, from https://bendingmomentdiagram.com/solve/

[18] Aluminum 6061-T6; 6061-T651. (n.d.). Retrieved April 25, 2017, from http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6

[19] Design of Connections V14.0. (n.d.). Retrieved April 26, 2017, from http://www.structuresworkshop.com/files/AISC_14th_Ed_Design_Examples_-_Spec_Ch_J.pdf American Institute of Steel Construction

# Appendix A: Preliminary Concept Decision Matrix & Grading Rubric

## Preliminary Concept Decision Matrix

| Design Attributes | | % | Lifting Chair | Hydraulic Sling | Crank-shaft | Swing Arm |
|---|---|---|---|---|---|---|
| **Functionality** | Weight-bearing capability | 30% | 4 | 5 | 5 | 3 |
| | Neck Support | 9% | 1 | 1 | 3 | 1 |
| | Torso Support | 8% | 5 | 5 | 5 | 5 |
| | Leg Support | 8% | 4 | 2 | 1 | 2 |
| | Transportability | 10% | 5 | 5 | 5 | 4 |
| | Number of Aids Needed | 15% | 5 | 5 | 5 | 5 |
| | Time for Transport | 20% | 1 | 4 | 3 | 4 |
| | **Total** | **30%** | **3.46** | **4.20** | **4.10** | **3.50** |
| **Dimensions** | Width | 34% | 5 | 1 | 4 | 4 |
| | Height | 33% | 5 | 5 | 5 | 5 |
| | Length | 33% | 5 | 1 | 3 | 1 |
| | **Total** | **20%** | **5.00** | **2.32** | **4.00** | **3.33** |
| **Safety** | Tipping Susceptibility | 20% | 1 | 3 | 5 | 1 |
| | Sharp Edges | 10% | 5 | 5 | 5 | 4 |
| | Weight supported by Aide | 15% | 1 | 5 | 4 | 5 |
| | Aide's Body Rotation | 15% | 2 | 5 | 5 | 4 |
| | Aide's Lifting Distance | 15% | 1 | 5 | 5 | 5 |
| | Stability of Locking Mechanism | 15% | 3 | 2 | 5 | 3 |
| | Joint/Hinge Safety | 10% | 3 | 3 | 5 | 2 |
| | **Total** | **40%** | **2.05** | **3.95** | **4.85** | **3.35** |
| **Manufacturability** | Number of Complex Parts | 40% | 5 | 4 | 5 | 2 |
| | Estimated Cost | 60% | 3 | 4 | 4 | 4 |
| | **Total** | **10%** | **3.8** | **4** | **4.4** | **3.2** |
| **Weighted Score** | | | **3.23** | **3.70** | **4.41** | **3.37** |

# Grading Rubric

| Design Attributes | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Fuctionality | Weight-bearing capability | < 88 lbs | 88 lbs max | 132lbs max | 154lbs max | 176 lbs max |
| | Neck Support | range of motion is greater than 90 degrees | | range of motion is 30-90 degrees | | range of motion is 0-30 degree |
| | Torso Support | greater than 90 degree range of motion | | torso is partially supported (20-90 degree range of motion) | | torso is fully supported (0-20 degree range of motion) |
| | Leg Support | legs may move freely | | partial leg support | | legs are immobilized |
| | Transportability | more than 40 lbs | 40 lbs | 30 lbs | 20 lbs | 10 lbs |
| | Force to Operate | more than 40 lbs | 30-40 lbs | 20-30 lbs | 10-20 lbs | Below 10 lbs |
| | Number of Aids Needed | >2 | | 2 | | 1 |
| | Time for Transport | >11 | 8 < time < 11 | 5 < time < 8 | 3 < time < 5 | less than 3 min |
| Dimensions | Width | >32" | 32" | 31" | 30" | 29" |
| | Height | >78" | 78" | 75" | 72" | 70" |
| | Length | >48" | 45" | 43" | 40" | 36" |
| Safety | Tipping Susceptability | patient is suspended outside of the base | | patient is suspended at the edge of the base | | patient is only suspended within the the base |
| | Sharp Edges | more than 6 danger points | less than six danger points | less than four danger points | less than two or in non-accesible areas | 0 sharp edges |
| | Weight supported by Aide | >50 | 50 | 50<W<30 | 30<W<20 | 20<W<0 |
| | Aide's Body Rotation | >30 degrees | 30 degrees | 20 degrees | 10 degrees | 0 |
| | Aide's Lifting Distance | more than 2' | 2' | 1.5' | 1' | 0.5' |
| | Stability of Locking Mechanism | <20lbs | 20lbs | 30lbs | 40 lbs | 50 lbs |
| | Joint/Hinge Safety | more than 3 uncovered hinges | 3 uncovered hinges | 2 uncovered hinges | 1 uncovered hinge | no uncovered hinges |
| Manufacturability | Number of Complex Parts | >4 | 4 | 3 | 2 | 1 |
| | Estimated Cost | more than $750 | $600-750 | $500-600 | $350-500 | less than $350 |

# Appendix B: Failure Report Summary

## Failure

The failure occurred at the bottom of the front board, where it is connected to the telescopic support. The telescope tube is bolted to a metal bracket which was then glued to a 2" x 3" particle board spacer (Figure 69). This telescope tube connection component was then attached to the front board by two bolts, one on each side of the tube. These two bolts pulled through the particle board of the front board which caused a large fracture in the board and the disconnection of the telescope support from the front board. At the time of the failure, the front board had two holes larger than the circumference of the bolts located where they had been and was split internally parallel to the board two thirds of the way through. The steel attachment and 2"x3" particleboard spacer suffered no failures. After the failure, the front board remained in one piece, however, due to the fragility of the post-failure structure, the thinner section of split particle board separated entirety from the front board with time.

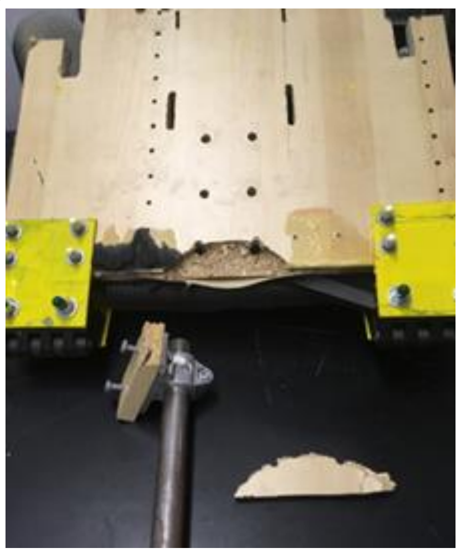


*Figure 72 Failure of Front Board at Telescoping Support*

## Hypothesis of Failure Mechanism 1

This first assumption the team made was that the standing device failed while under the additional load of the patient, Felicity. It was made because the addition of Felicity's weight would increase the stress placed upon the standing device and may have resulted in overcoming the strength of the mechanism if concentrated in the right manner. A free body diagram of the standing device was created, but difficulties were faced trying to have enough defined variables to solve for the force at the location of the failure. This path was pursued for several weeks with a number of iterations of calculations. Despite the difficulties, ballpark results clearly depicted that the standing device was designed well to withstand the load placed upon it in the downward direction. The shear and flexural strength of particleboard could withstand the potential stress concentrations with a comfortable margin for error.

## Hypothesis of Failure Mechanism 2

The failure of the front board of the standing device has been determined to be the result of a single applied force and not fatigue. This was realized from the description of the event in which the aide described a sharp crack at the time of the failure rather than a more gradual degradation of its mechanical properties. The team hypothesized that this applied force which caused the failure was a torque caused by an upward force on the footboard of the standing device. This would have had to occur when the connection between the telescope tube and the front board was rigid (ie when the telescope tube was locked in position). The bolts at the bottom of the front board pulled out of the particleboard in the direction of the underside of the board. The failure therefore, must have been due to the force applied by the aide upon lifting footboard while the frame was locked in a rigid position. This scenario must not have been considered during failure analysis in the design process of the standing device. What can be seen in the previous MQP report is that the team spent most of their efforts anticipating downward forces on the device, they did not thoroughly considered forces applied in the upward direction.

# Calculations

Pullout Force is determined by the shear strength of the material undergoing failure and the size of the object being forced through it (Eq. 1).

$$P_f = \tau \pi l D_{major} \qquad (1)$$

Bolt

$$l = 0.55''$$
$$D_{major} = 0.25''$$

Particle Board

$$\tau = 1200\ lb/in^2$$

$$P_f = (1200)\pi(0.55)(0.25) = 518.37\ lb \qquad (2)$$

To relate the pullout force to the force applied at the time of failure, the moments about A are summed (Eq. 3). The body is rigid and therefore the sum of moments should equal zero (Figure 70). When the applied force causes the sum of moments about A to be greater than zero, it will cause failure.

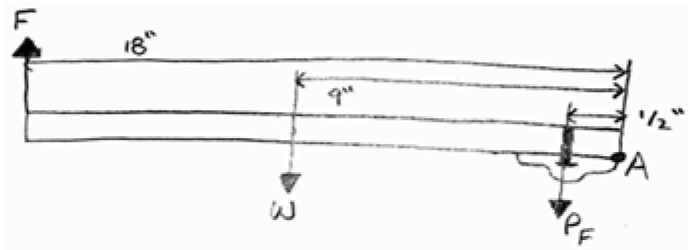


*Figure 73 Simplified Moment Diagram at Failure*

$$\Sigma M_A = 0 \quad (3)$$

$$P_f(0.5") + W(9") - F(18") = 0 \quad (4)$$

$$F = \frac{518.37(.05)+15(9)}{18} = 21.9\ lb \quad (5)$$

It was deemed reasonable for the aide to apply a force of 22 lbs lifting the foot board of the standing device during use, movement, or storage. The standing device is used, most commonly, in an almost horizontal setting. The footboard is relatively vertical in this position which makes it easy to grab and pull up on The mechanical advantage gained from the lever action of applying force so far from the bolt as well as the lack of washers on the bolts must have overcome the pullout force required to cause a failure.

## Proposed Solution

To repair the standing device and prevent further failures during use, the front board will need to be rebuilt and reinforced at the failure point. The dimensions of the board will remain the same. The material will be ½" plywood (5-ply) because it is cheap and durable as well as easy to manufacture into the appropriate shape. The point where the adjustable support attaches to the front board will also be reinforced to prevent pull through. A 3" x 5" x ¼" aluminum plate was placed on the top side of the front board so that the bolts pass through the steel plate, front board, spacer, and connecting plate at the bottom of the board. This will prevent pull-through of the bolts as the metal-to-metal interface of bolt and plate will not shear under manually applied forces. The weight of the front board assembly will not be significantly different from that of the original and the surface that Felicity interacts with will still be covered in the soft foam layer.

## Analysis of Solution

The loads placed upon the reconstructed standing device will still match those of the original analysis. It was determined that the analysis of downward forces completed by the previous MQP team were accurate and appropriate. Because little has changed in the construction of the standing device with the fix, it will still withstand downward forces well.

The presence of the steel plate will keep the front board fixed at the adjustable support. Therefore, when locked in a rigid position, lifting on the footboard will create bending of the front board at the location of the steel plate because the connection from the shin board to front board is on the wood, which will flex (Figure 71). The flexural strength of plywood is a minimum of 4.35ksi.

$$\sigma = \frac{3FL}{2bd^2}, \qquad 4350 = \frac{3(Fx18)(6)}{2(18)(0.5)^2}, \qquad F = 90.6lb$$

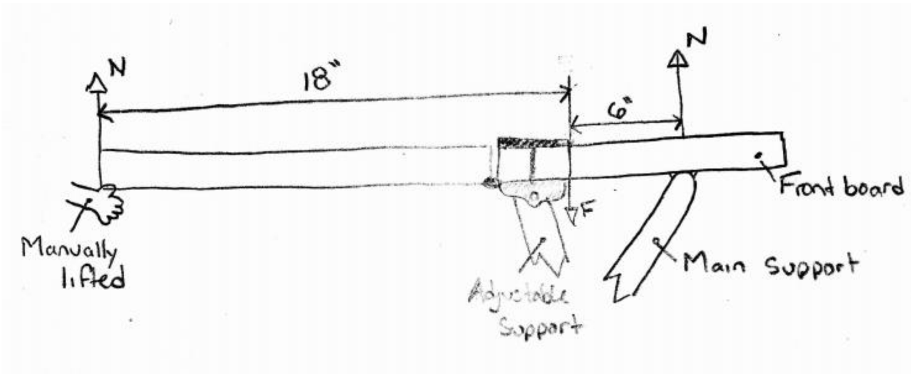



*Figure 74 Flexural Stress in Redesigned Standing Device*

Calculating the stress due to 3-point bending between the adjustable support and main support, with the load due to the moment created by lifting on the footboard; a 90lb force is required to fracture the front board. Lifting this amount of weight would in fact raise the end of the standing device off the ground rather than cause a failure. Therefore, this solution is safe and prevents a repeated failure due to passive misuse of the device.

## Budget

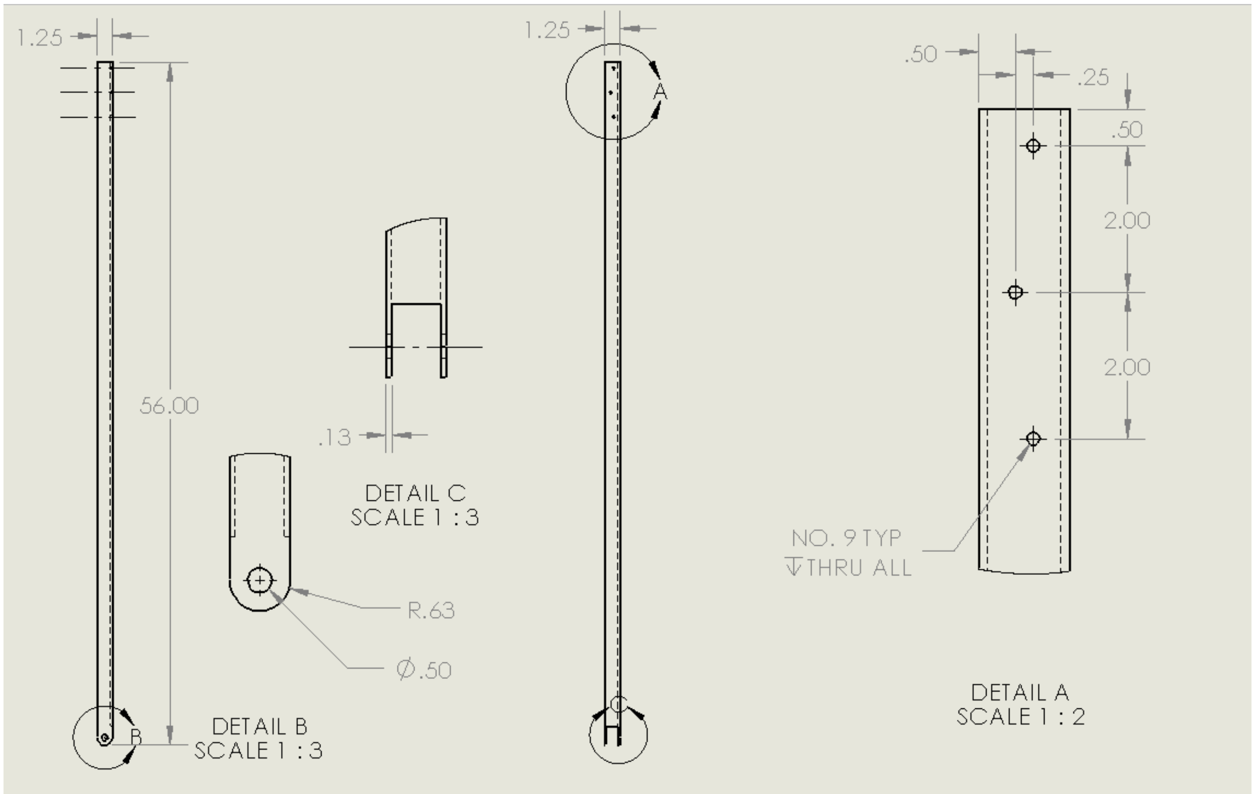
The materials that must be purchased to fix the standing device are minimal. All of the bolts were saved from the original device. The only remain parts are the plywood for the board, steel plate, and foam covering. Glue and washers have been recovered from the Rehab Lab and will be used.

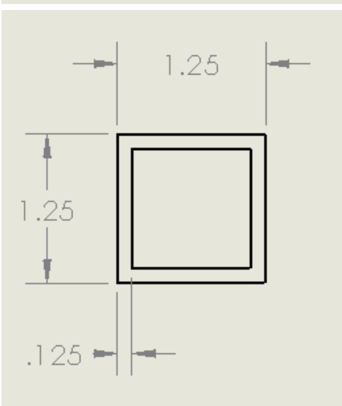
*Table 9 Budget to Fix Standing Device Failure*

| | Unit Price | Quantity | Cost | Link |
|---|---|---|---|---|
| ½" Birch Plywood | $25.95/4'x4' | 1 | $25.95 | Lowes |
| ¼" Aluminum | $13.81/3"x6" | 1 | $13.81 | McMaster-Carr |
| ¼" Foam | $6.71/12"x12" | 2 | $13.42 | McMaster-Carr |
| Total | | | $53.18 | |

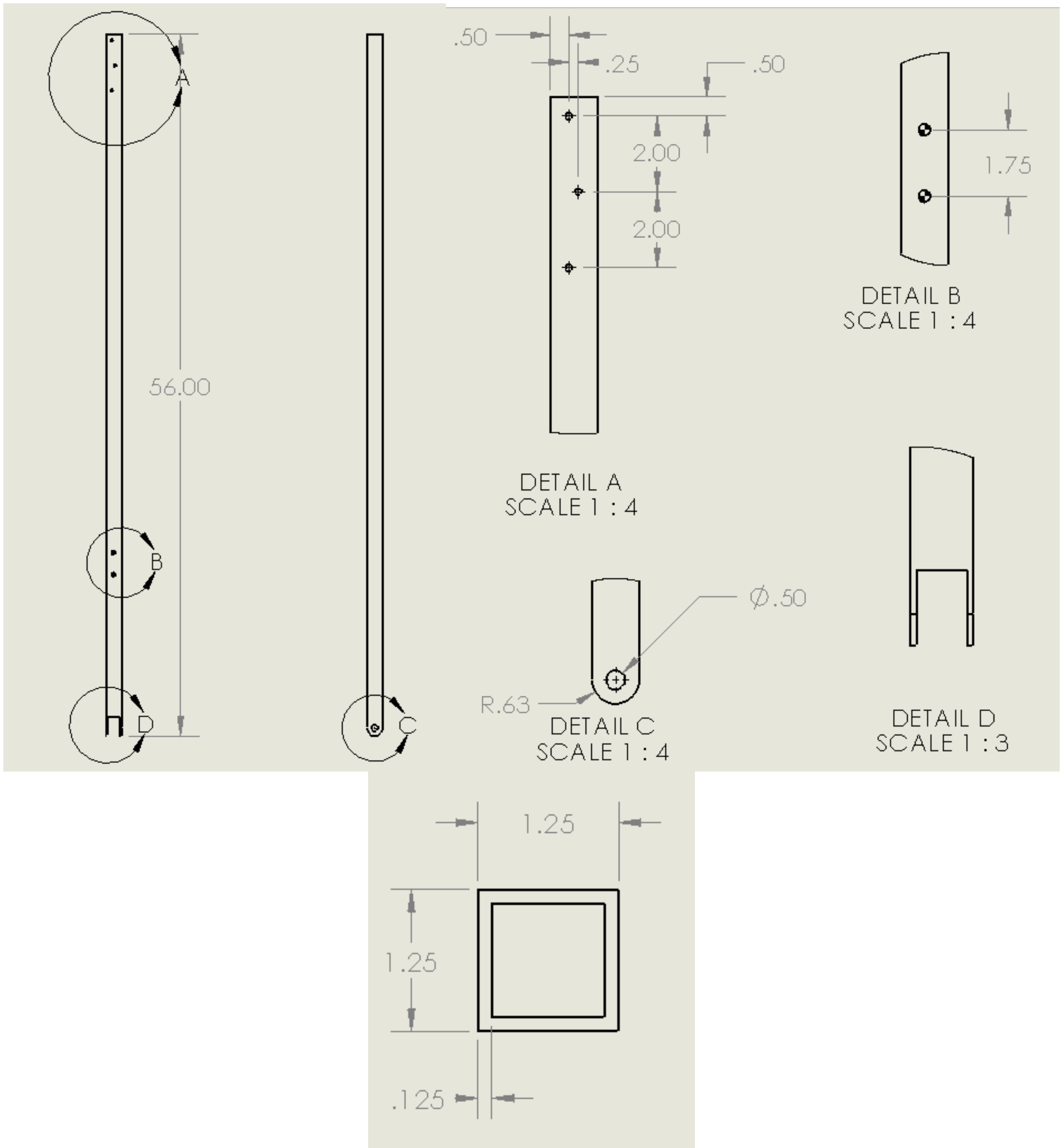
# Appendix C: Part Drawings

## Non-Driven Arm Drawings



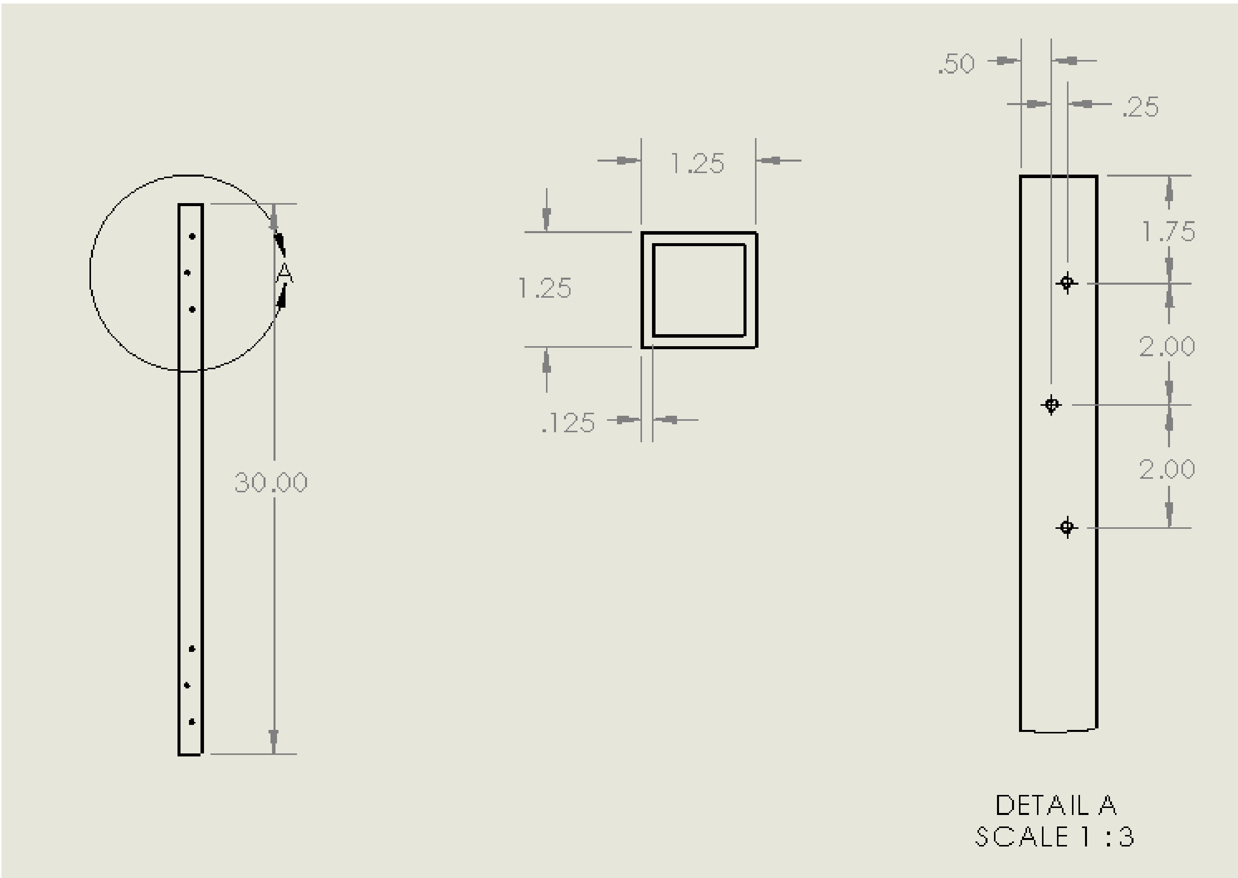



Driven Arm

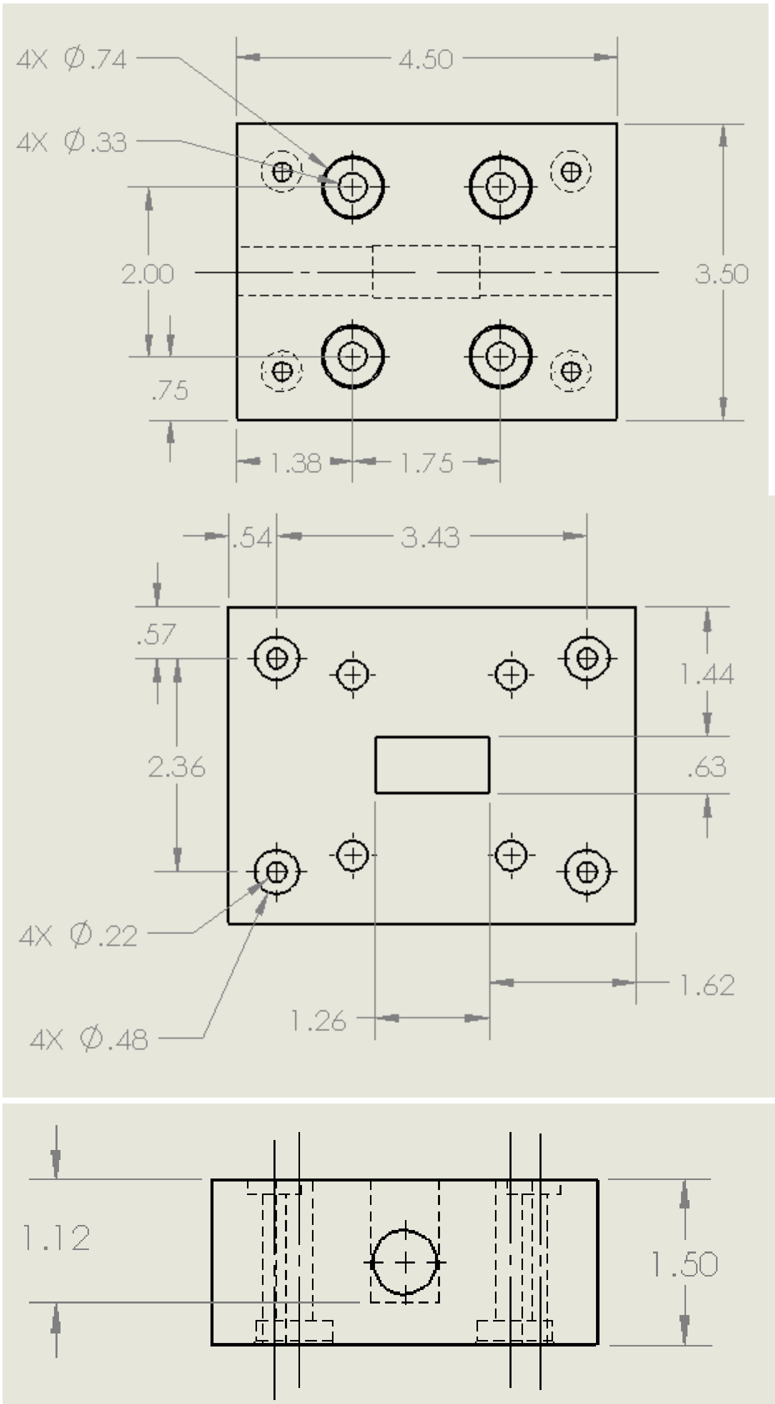


A
B
C
D
56.00
.50
.25
.50
2.00
2.00
DETAIL A
SCALE 1 : 4
1.75
DETAIL B
SCALE 1 : 4
Ø.50
R.63
DETAIL C
SCALE 1 : 4
DETAIL D
SCALE 1 : 3
1.25
1.25
.125

Top Rod



# Coupler Block



# Coupler Link