# Brace to Facilitate Increased Mobility and Improved Posture for Patients Suffering from Spinal Abnormalities


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| Course: | BME 200/300 |
| Date: | December 12th, 2012 |



**Abstract**

Camptocormia is defined as a forward bend in the thoracic or lumbar region of the spine of at least 45 degrees when upright, which dissipates in the supine position. The cause of this condition is unknown and few treatments exist. Currently, the market for braces to treat this unique spinal condition is limited. The client and patient have reached out to the UW-Madison BME Department to design and fabricate a brace for the unique rehabilitation needs of camptocormia. The purpose of the brace is to facilitate and upright posture, while retaining a range of motion that will allow the patient to bend and perform daily tasks such as using the restroom, cooking, and gardening. Relevant calculations to understand the dynamics of the condition and the forces possible with such a brace were performed, involving free body diagrams, work energy equations, and Newton's 2nd law. The team developed three design alternatives. All featured a corset interior, to straighten the spine, and a metal hardware exterior with lever arms on both sides of the body spanning from the hip to the upper chest and from the hip to the thighs to hold the patient upright. The designs varied in their ability to generate the forces and corresponding moment about the hip needed to provide resistance and return the patient to a vertical position. After contrasting helical torsion springs, flat coil torsion springs, and a cam system, the cam method yielded the highest score in the design matrix. After producing a model of the brace in SolidWorks, manufacturing took place. Follow up tests were conducted including deformation and force analyses using the final prototype.

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# Introduction

## Problem Statement

Design, develop, and build a brace or support to aid in holding a person in an upright position when standing or sitting, while also facilitating increased mobility.

## Background

According to Doherty, et al., camptocormia is a disorder in which the spine bends severely at the thoracic or lumbar regions. This leads to a stooped posture in milder cases, but in more severe cases could mean completely bent to a point where the thoracic cavity appears to be near parallel with the ground, as shown in Figure 1. Unfortunately, no specific definition, in terms of physiological, neurological, or other explanation exists for diagnosing camptocormia. Therefore, doctors make subjective diagnoses by looking for at least 45° of thoracolumbar flexion that arises when upright but is corrected in the supine position.[1] This ambiguity is a direct result of the absence of a known cause for camptocormia.

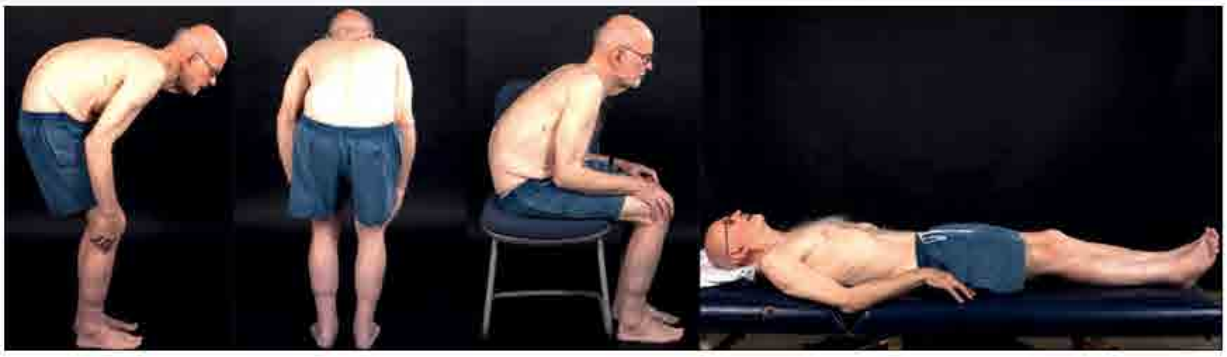


**Figure 1:** Depiction of a man with severe camptocormia. As evident from the figure, the man's thoracic cavity nears parallel to the ground and is still severely curved while seated. The curve is not present while lying down

Two different theories have developed for propagation of the disorder. One idea pertains to degenerative spinal issues. Studies of those with camptocormia have shown spinal muscles with low density on CT and MRI scans.[2] Additionally, lobulated fibrosis and atrophy of fibers have been observed from muscle biopsies.[2] These results suggest myopathic complications in the spinal muscles. The second theory pertains to neurological issues including striatal damage in the brain, which affects the basal ganglia and thus motor control.[2] Of course, some simply combine these two theories saying muscular and neuromuscular disorders both contribute to the cause of camptocormia.[3] Furthermore, there is a positive correlation between the severity of Parkinson's disease (PD) and the development of camptocormia. On average, camptocormia sets in seven to eight years after the onset of Parkinson's.[1] This is logical as Parkinson's is a neurological disease that hinders a person's ability to control their muscles.

Those with camptocormia often experience pain, and it is unclear whether camptocormia has something to do with previous back problems. In some cases patients may feel as though they are being 'pulled' forward or as though their abs are flexing.[1] Rarely able to pull themselves upright, patients' spinal erector muscles are either not engaging or are rigid. Conversely, our patient has not experienced pain associated with her case of camptocormia.

A number of patients have been able to utilize 'sensory tricks' to correct their bent posture—for example, one man used a low set, weighted backpack to straighten himself upward.[4] Some can push off of their thighs using their hands, which allows them to walk more upright.[5] Others are able to put themselves upright against a wall or hold themselves upright via their arms on a walker.[5]

Due to the absence of an exact cause for camptocormia, few treatments exist for the disorder. Drugs have not worked thus far, as camptocormia does not respond to levodopa, a drug used for PD. In fact, those who have this complication also do not respond well to the levodopa for treatment of their Parkinson's symptoms.[1]

Some orthoses have been developed but have either been very rudimentary or have not worked well. A study done by de Sèze, et al., out of Bordeaux, France used a thoraco-pelvic anterior distraction (TPAD) device, shown in Figure 2, for patients with camptocormia as well as a physiotherapy regiment to treat the disorder.[3] The device used a rigid bar between a hip belt and a chest belt to force the chest away from the hips causing the person to be upright. The study did exhibit positive results in increased lumbar lordosis, thoracic kyphosis, and sagittal balance.[3] However, the orthosis does not allow for the patient to bend forward and would prove troublesome for using the bathroom and other daily activities. A newer, more mobile brace is highly sought after.

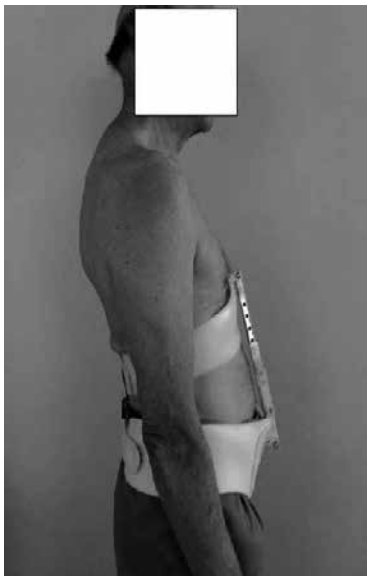


**Figure 2:** Thoraco-Pelvic Anterior Distraction (TPAD) device. The figure shows the orthosis used in the study done by De Séze et. al., consisting of a rigid bar to separate the chest and pelvis.

Other devices exist such as back belts and braces for diseases like scoliosis. However, there are various reasons as to why these devices have not been used to treat those with camptocormia. A French study utilizing a corset treatment for patients provided results showing that a leather corset treatment did lead to improved functionality in some patients.[11] However, the study also states that some refused a corset for aesthetic and personal reasons suggesting people do not feel comfortable wearing a corset. Furthermore, in some cases plastic-type corsets were abandoned due to comfort issues and the fact that the patients were not finding improvements in functionality.[11] In fact, some were actually suffocated by corsets causing difficulty breathing and even death in a few severe cases.[11] Back belt devices offer support for the back but would not work in the case of camptocormia since they are not adequate to combat such a severe bend at the lower hip region. Thus, our patient would still bend if she wore a back belt. The belt may offer some resistance to bending but it would by no means prevent her from bending at the

hips causing her upper back to slouch over her waist region. Similarly, many scoliosis devices hinder the bending in the spinal region and keep the patients that use them rigid. These devices also do not hinder the very low bend at or just above the hips that our patient exhibits due to camptocormia as they lack attachment around the ball and socket hip joint and the legs. Scoliosis braces also hinder mobility or range of free motion which is something that, although will aid in holding our patient upright, would not allow for the range of mobility she desires. Concurrently, no brace exists that would both hold the patient upright as well as facilitate mobility.

Our patient has a more severe case of camptocormia in which her torso is parallel to the ground. She cannot pull herself upright without the use of a walker and a wall simultaneously. The 65-year-old would like a mobility brace that would allow her to use her kitchen and garden again. This requires the brace to allow the user to bend over and return to an upright position. Currently, a patent exists for a torso assist device and our client has been in contact with the inventor for nearly a year trying to get a suitable and functioning prototype made.[6] The orthoist recently claimed bankruptcy and cannot provide her with the prototype originally promised. Thus, the team will produce a prototype for the patient in hopes that the project can continue until a full-functioning final design is fabricated.

## Project Motivation

Team motivation for this project arises from the patient's harsh condition as well as what she has been through as a result. Once a great cook in a wonderful kitchen, she has been reduced to looking at the floor and straining to reach anything on her counter. Her passion for gardening that has been severely hindered due to her unstable bent position. The physical and emotional impacts camptocormia has had on the patient are apparent. Our patient has recently lost her husband, which leaves her both mournful and lacking a companion to assist her. She has been promised a functioning brace by an orthoist who kept missing deadlines and will no longer fulfill his promise due to financial reasons. The loss of her husband and issues with the other orthoist cannot be changed, but progress can certainly be made in terms of developing a functional brace to make her world a better place. The team thus intends to develop a functional brace for her and allow her to once again cook in her kitchen, garden, and be able to look people in the eyes when she meets them instead of looking at their waists.

## Project Design Specifications (PDS)

The brace needs to function to hold our patient upright while at the same time facilitate mobility as further described in Appendix A. In a minimal sense, this includes combating the camptocormia to the point where our patient is upright and allow for walking along with minor twisting or movement. Further specifications are contained in two topics, our client's requirements for the design and the requirements with which the team came up.

In order for the brace to be properly fitted for our client, it must be geared toward a petite sized woman weighing 556.03N. A concern of our patient is weight of the brace and

she requests that it be less than 44.48N (10lbs.). A key point here being that although the brace should have a low weight, it still needs to be able to offer a reported 13.34-22.24N on her mid-section to hold her upright. Unfortunately, new measurements conducted on November 10th, indicated that the force required is truly much higher. The value is 160.14N (36 lbs.). Mechanically, this is comparable to replacing her lack of lower lumbar strength to do the straightening that she is no longer able to do. However, the brace needs to be operable and attachable from the front where she can see everything and be able to reach the most important components. Ideally the brace would be able to be quickly put on and removed for bathroom usage while at the same time offer the capability of concealment under clothing. These are both challenging aspects and will obviously be considered once the more basic goals of holding her upright and facilitating walking are met. This is not to say they are not as important, but rather getting her upright is the first priority. Lastly, the client hopes the brace facilitates everyday activities such as cooking and gardening.

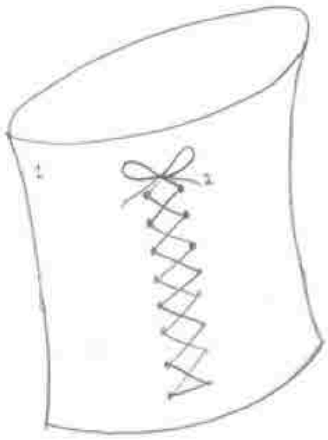
The team's design requirements cover eleven important categories, reflecting of course our patient's requests as well as our own design specifications. In terms of performance, the team desires the design should allow for a load of 13.34-22.24N to our patient's midsection in order to put her in an upright position. Safety is one of the more important categories and to facilitate a safe device, breathable materials are desired to prevent bedsores as well as easy removal for emergency situations. Furthermore, our client should not be fully reliant on the device due to the event that it may fail and could cause her injury. Next, the device must be accurate and reliable by providing the correct loads, at the correct locations, in various bodily positions (sitting, bending, standing, etc.). The life in service of the brace is quite demanding at seven days a week, 10 hours a day for 20 years yet these values help eliminate the worry of failure or repeated cost from our patient. Due to the life in service requirements, the shelf life of the device is only existent when the patient is sleeping, in which case the same requirements are demanded from the device save the applied loadings. Operating constraints require that when in use the patient avoid chemicals that could corrode the aluminum frame. Additionally, the steel plates may rust if heavily exposed to water and thus the brace should not be worn in the shower or for bathing. Picking up heavy objects (exceeding 44.5N) must also be avoided to ensure return to upright after bending. Ergonomically, the brace should not restrict our patient's motion and needs to incorporate extension, bending, and some twisting. More detail of these movements is described in Appendix A, section g. Correlating with our patient's needs and requests, the device should be sizeable for her petite stature and weigh less than 44.48N. Materials of the device should not be flammable especially due to the device's projected use in a kitchen environment. Additionally, the materials should be rigid enough to provide support, not rust to allow for wiping and cleaning, and should last the 20-year lifetime of the brace. Finally, aesthetics correlate with our patient's desires to have the device be concealable by clothing but the foremost priority is function not aesthetics. More detail of the design specifications can be found in the attached Appendix A.

# Design

## Design Alternatives

With goals to get the patient upright, allow for mobility via bending and sitting, and enable the patient to conduct daily tasks such as cooking and gardening, the team converged on two components—a corset to hold the patient's spine rigid and a frame to facilitate rotation about the hip. The alternatives to this two-part device tried to accomplish both tasks with one piece. This was decided to be less effective since it would involve trade-offs. For example, the C.A.S.H. Orthosis brace, shown in Figure 3, is an excellent way to hold the body rigid.[8] The team discussed modifying this centerpiece to be fiberglass or some analogous material but ruled out the option since it would significantly restrict the possible range of motion. The corset, shown in Figure 4, utilizes a corset body with a shoelace tightening mechanism and is used in conjunction with each of the three designs.

**Figure 3.** C.A.S.H. Orthosis device. The figure shows an available orthosis that could be modified and used as an alternative. Such devices were ruled out due to their limited ability to meet design criteria.

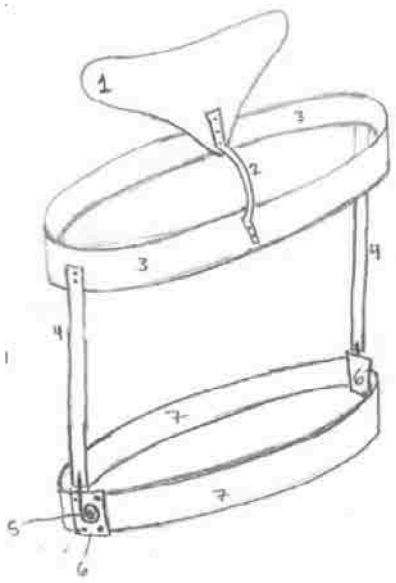


| Corset Design Reference Number | Design Component |
|---|---|
| 1 | Corset Body |
| 2 | Shoelace Tightening Mechanism |

**Figure 4:** Corset Component. This is the corset component that will be used in conjunction with each of the three frame component designs.

The first design, which will be referred to as "Flat Coil Torsion Spring", (Figure 5) consists of a rigid frame (parts 3 and 4) that is hinged by a flat coil torsion spring (part 5) to the metal anchoring plate (part 6). This metal plate will be housed on the sides of the lower anchoring ring (part 7) that will fit the patient's hips like a glove. Furthermore, there will be a padded chest plate (part 1) that will be attached to the frame via a connection piece (part 2). This design meets the design criteria as the anchoring ring will be secured to the body, so the rigidity of the frame will hold her body upright and keep it straight. The chest pad will distribute the applied force thereby reducing pressure and providing added comfort. The flat coil torsion spring will allow the patient to bend forward when the

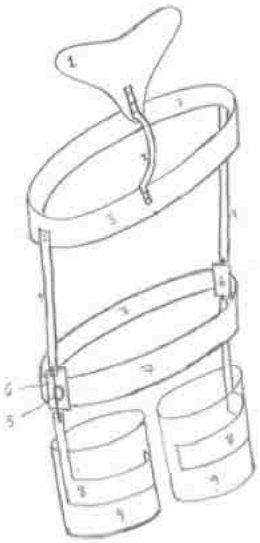
abdominal muscles are contracted, yet will supply the force needed to bring the body back to equilibrium under normal conditions.




| Design One Reference Number | Design Component |
|---|---|
| 1 | Chest Plate |
| 2 | Chest Plate Connection Rod |
| 3 | Upper Anchoring Ring |
| 4 | Vertical Connection Arm |
| 5 | Flat Coil Torsion Spring |
| 6 | Metal Connection Plate |
| 7 | Lower Anchoring Ring |

**Figure 5:** Flat Coil Torsion Spring Frame Component. This is the frame component design that utilizes a flat coil torsion spring so that no leg cuffs would be needed.

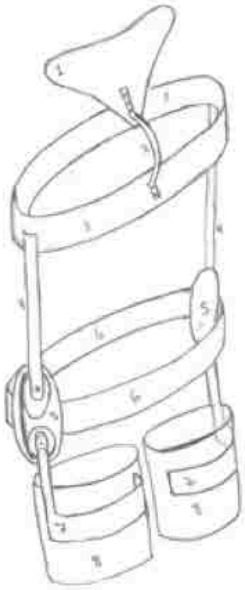
The second frame design, "Helical Torsion Spring", can be seen in Figure 6. Again, a metal frame (parts 3 and 4) is used in conjunction with a chest plate (part 1); however, this design utilizes a helical torsion spring (part 5) to hinge the metal frame to the metal anchoring plate (part 6) that is housed in the lower anchoring ring (part 7). Moreover, the other end of each of these springs is connected to metal leg inserts that extend down and wrap around the front of each thigh (part 8). These metal inserts are secured to her leg with leg bands that will wrap around the whole circumference of her thigh, functioning to keep the device in place (part 9). In this case, the metal frame is still functioning to grab the body and the chest pad again distributes the load for maximum comfort, but the use of the helical torsion spring makes it easier to ensure that her equilibrium will be upright. This is due to the fact that it draws a straight line from the legs, via the leg inserts, through the the patient's upper body. The helical torsion spring will function analogously to the flat coil torsion spring in the first design in that it will allow a forward bend when the abdominal muscles are contracted, and will provide a counter force proportional to the amount of bend in order to bring the body back up to equilibrium.



| Design Two Reference Number | Design Component |
|---|---|
| 1 | Chest Plate |
| 2 | Chest Plate Connection Rod |
| 3 | Upper Anchoring Ring |
| 4 | Vertical Connection Arm |
| 5 | Helical Torsion Spring |
| 6 | Metal Connection Plate |
| 7 | Lower Anchoring Ring |
| 8 | Metal Leg Inserts |
| 9 | Leg Anchoring Band |

**Figure 6:** Helical Torsion Spring Frame Component. This is the frame component design that utilizes a helical torsion spring to connect the upper metal frame to the leg cuffs.

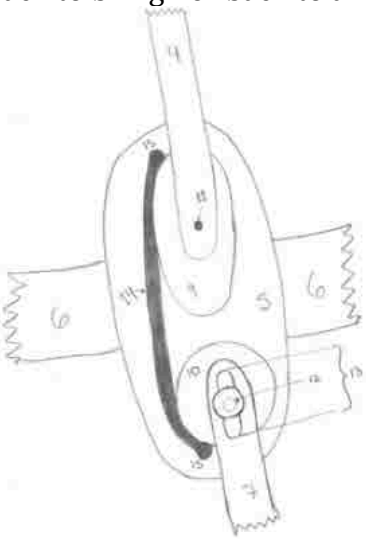
The third design, "Cam Mechanism" (Figure 7) incorporates the same metal frame and chest plate apparatus for the upper section and utilizes the same leg bands with metal inserts for the lower section as design two (Figure 6). However, instead of a torsion spring, this design uses a cam device housed in the metal connection plate (part 5). The upper apparatus provides the same function as it does in the previous two design alternatives, while the cam functions analogously to the flat coil and helical torsion springs—except the cam utilizes an elastic region to provide counterforce proportional to the bend of the patient.



| Design Three Reference Number | Design Component |
|---|---|
| 1 | Chest Plate |
| 2 | Chest Plate Connection Rod |
| 3 | Upper Anchoring Ring |
| 4 | Vertical Connection Arm |
| 5 | Metal Connection Plate |
| 6 | Lower Anchoring Ring |
| 7 | Metal Leg Inserts |
| 8 | Leg Anchoring Band |
| 9 | Ellipsoid Wheel |
| 10 | Circular Wheel |
| 11 | Upper Axis of Rotation |
| 12 | Lower Axis of Rotation |
| 13 | Pin Activation System Knob |
| 14 | Cam Band |
| 15 | Cam Band Anchor Points |

**Figure 7:** Cam Mechanism Frame Component. This is the frame component design that utilizes a cam mechanism to connect the upper metal frame to the lower leg cuffs.

Figure 8 displays a close up of this cam mechanism. The ellipsoid wheel (part 9) moves with the vertical connection arm (part 4) from the metal plate about the upper axis of rotation (part 11). In the same manner, the circular wheel (part 10) moves with the metal leg insert (part 7) from the metal plate about the lower axis of rotation (part 12). On the side of the cam device towards her dorsal side, there is an elastic component cam band (part 14) that is connected to each of the wheels (part 15). When the angle between her torso and lower body starts to decrease below 180°, there will be tension in the cam band, creating resistance. The cam band will be made of an elastic material so that the patient is able to bend her upper body forward or bend her legs at the hip, but there will be some degree of kickback to bring her back to an upright position.



| Reference Number | Design Component |
|---|---|
| 4 | Vertical Connection Arm |
| 5 | Metal Connection Plate |
| 6 | Lower Anchoring Ring |
| 7 | Metal Leg Inserts |
| 9 | Ellipsoid Wheel |
| 10 | Circular Wheel |
| 11 | Upper Axis of Rotation |
| 12 | Lower Axis of Rotation |
| 13 | Pin Activation System Knob |
| 14 | Cam Band |
| 15 | Cam Band Anchor Points |

**Figure 8:** Cam Mechanism Front View. This is a close up of the cam mechanism used in the design seen in Figure 5. The cam band connects two wheels that will move with the body producing a resistant force in the band.

## Decision Matrix

With these three designs, a design matrix was created (Figure 10). It consists of the seven following categories, in descending importance: functionality, self-operability, feasibility, durability, comfort, cost, and aesthetics. Functionality was ranked based on how well the device would work. It took into consideration the range and ease of motion that would be provided by each design. The helical torsion spring received the lowest score in this category because it would restrict leg motion and make sitting very difficult. The cam device received the highest score in this category, but just a few more points than the flat coil torsion spring because although both would allow for the patient to sit, the cam stems from the legs instead of the hips—which is believed to accomplish uprightness better. Furthermore, the client has mentioned to the team that all past braces that have failed because of their spring components. The flat coil torsion spring requires that the lower anchoring ring be in the perfect position in order to function correctly, while the cam will function even if the lower anchoring ring is moved slightly.

Self-operability was the second highest priority and was gaged based on how easily the device could be put on and used without assistance. The helical torsion spring won here because although it does not have the highest functionality, the patient just needs to put it on and lean forward and it does what it was designed to do. The flat coil torsion spring lost a point here because it needs to be put on with the exact positioning. This may be difficult to ensure when putting it on independently. The cam also lost a point here because the pin activation system requires an extra step in order for the design to meet its maximum functionality.

Points for the feasibility category were assigned with regards to how difficult the fabrication process would be. The flat coil torsion spring demands that the lower anchoring ring be form-fitted to her hips. This may require some sort of mold, which makes fabrication difficult. It does not use leg bands, however, which simplifies the entire process. Therefore, it only lost four points. The helical torsion spring does require fabrication of the leg extensions and bands, but it does not demand the lower anchoring ring to be as perfectly form-fit. Thus, it only lost four points as well. The cam mechanism design lost one extra point because it would be very similar to the helical torsion spring design in terms of fabrication except the hip piece has a lot more components. This complicates fabrication.

The cam won in durability since, ideally, the cam band would be replaceable, while the springs in the other two designs might break over time. It would be a little more expensive than the other two and a little less aesthetically pleasing, but it should be relatively comparable in comfort. Ultimately, the winner was the cam design due to its high scores among the overall design matrix criteria, especially functionality and durability. It may be concerning that it only won in two of the seven categories, but taking a closer look reveals that it was only one point value behind the winning design of each of the other criteria. Also, functionality was the most pressing concern and the cam design won in that category by a large measure.

| Category | Point Allocation | Flat Coil Torsion Spring | Helical Torsion Spring | **Cam** |
|---|---|---|---|---|
| 1. Functionality (range of and ease of motion) | 30 | 25 | 18 | 29 |
| 2. Self-Operable | 20 | 18 | 19 | 18 |
| 3. Feasibility | 20 | 16 | 16 | 15 |
| 4. Durability | 10 | 6 | 4 | 9 |
| 5. Comfort | 10 | 7 | 8 | 7 |
| 6. Cost | 5 | 4 | 4 | 3 |
| 7. Aesthetics | 5 | 3 | 4 | 3 |
| Total Points: 100 | 100 | 79 | 73 | **84** |

**Figure 9:** Design Matrix. This is the design matrix for the three different frame components. The highlighted portions represent the winners for each respective design matrix criterion and also the winner in overall points, the cam mechanism.

## Final Design

The cam mechanism was ultimately chosen as the final design. Looking strictly at the design matrix, this design won in total point value and won by a large measure in functionality, the most important category. In terms of how the device would be put on, the patient would first put the corset on like a t-shirt, which would straighten out the torso. Next, the patient would step into the leg bands. Then he/she would fasten the lower anchoring to the hips via a buckle mechanism. Following this, the patient has the option to make themselves upright using a wall, to lay down on a bed or floor and roll into the device, or to use their arm muscles to bring the upper anchoring ring to the body. The upper anchoring ring will have a hinge that the patient will close once the upper body is inside of it. Some concerns include that because the elastic cam band is always under pretension—which is necessary to provide upright equilibrium—the device will be deformed in the opposite direction and will prove difficult to put on. Because of this, a pin will be incorporated into the cam mechanism to prevent the brace from increasing in angle beyond $180^{o}$ in attempt to reduce its deformation (i.e. pulling the patient's torso and legs in the dorsal direction, if the brace were to be on).

## Calculations

Calculations were performed to obtain the necessary strength of the cam component of the brace and prove the ability of the designs to hold the patient upright. This involved obtaining the forces and moments generated from the weight of the upper body, and also considering additional weight that may be picked up by the patient. Referring to Appendix B Figure 1, the forces and their resultant moment arms were calculated with use of an anthropometric table and measurements of the patient's height and weight. The body was modeled at the most extreme possibility, with the upper body parallel to the ground (Appendix B Figure 3). Additionally, an upright figure was developed (Appendix B Figure 4), modeling the condition in two equivalent ways—with an applied moment at the location of the cam (the hip), and with a coupled force pair. A function was generated to determine the required moment magnitude the cam must produce to counteract the moments generated by the camptocormia condition as a function of the angle from the vertical (Appendix B Figure 5). Due to the complex nature of the condition, the moment generated by camptocormia could not be mathematically determined, and was obtained through patient testing.

Angular acceleration assumptions were made in order to generate the force and moment equations for this dynamic system. A five second duration was decided for the patient to go from the horizontal to vertical position. Utilizing kinematic equations, tangential acceleration was obtained, which could be translated into angular acceleration with the radius of curvature, the distance from the hip to the center of mass (Appendix B Figure 7).

Using work energy equations, the torsional spring constant was obtained. Considering two distinct orientations of the patient—one upright and the other horizontal—the potential energies were compared. As shown in Appendix B Figure 7, the torsional spring constant was determined to be 79.75 Nm/rad. Equivalently, this translates

to a translational spring constant of 19.939 N/m. These values were initially calculated to be able to contact bungee cord manufacturing companies to obtain a product with the necessary specifications; however, these values are not provided, as it is a liability to the company. Therefore, spring constants needed to be obtained by experimentation. It should be noted that these calculated values are the minimum needed for the device to hold since the moment caused by camptocormia was not incorporated into the work energy equations. This moment is a constant value that will exist in all patient spatial positions. When the patient is upright, gravity is not generating a moment about the hip, because the force runs vertically through the hip. Therefore, this moment is the only force to counteract when the patient is vertical. This counterforce will be contributed by the pretension in the rope when the patient is upright.

Returning back to Newton's 2nd law, pertinent force and moment equations showed that increasing the radius of the cam decreases the resultant force on the bungee cord, which after experiments have shown, is the weakest point of the system (Appendix B, Figure 8).

$$T = \frac{Fl}{2r}$$

This is because increasing the radius increases the moment arm of the tension (r), which resultantly decreases the tension required in the cam elastic region (T), as apparent by the equation above. With that being said, it was decided to maximize the diameter of these rotational pieces to the width of the patient's hips. More detailed calculations, describing this tension determination are featured in Appendix B, Figure 8.

Through these calculations, it was determined that some data needed to be experimentally found. Additional testing was essential to finding the forces that the brace needed to produce in order to hold the patient upright, and to determine which materials could provide this loading. To obtain this necessary data, the mechanical behavior of bungee cords and the patient loading requirements to position upright were experimentally determined.

**Preliminary Patient Testing: Determining Necessary Forces**

Human subject testing was performed on the patient to determine the force necessary to hold her upright. In preparation, the team organized a formal procedure equipped with a chart to organize data to obtain. To ensure abidance by human subject testing requirements, the client, Erick Oberstar, made all physical contact with our patient. Only the group members with the Human Subjects Testing Certification were present.

To obtain the force measurements, an initial force contact point was determined, recorded and used throughout (chosen to be slightly above the breast line, .2921 m above the hip). Then, using a hand-held dynamometer force sensor, our patient was brought from her natural slouched position, upward to a specified angle. Defined with zero degrees as upright and 90 degrees as natural, the angle was increased chronologically at 15-degree intervals. Each angle was tested three times, the forces were recorded and then averaged. The results are displayed in Figure 11. The process also included obtaining additional

anatomical measurements. The group encouraged our patient to rest at any point during the process.

The maximum force to hold the patient upright was 36 lbs. when placed slightly above the breast level. This location is where the upper anchoring ring of the brace has been designed to be—for maximum moment arm and comfort. However, this value is significantly greater than the initial values given to the team (3-5lbs.). With that being said, the forces needed within the brace became substantially greater. As a result, the elastic component of the cam mechanism initially proposed was far too minimal—for the true required tension increased significantly. To help reduce this tension in the cam, it was decided to maximize the radius of the rotational pieces. Additionally, the team then obtained stronger bungee cords and metals for the hardware components of the brace.

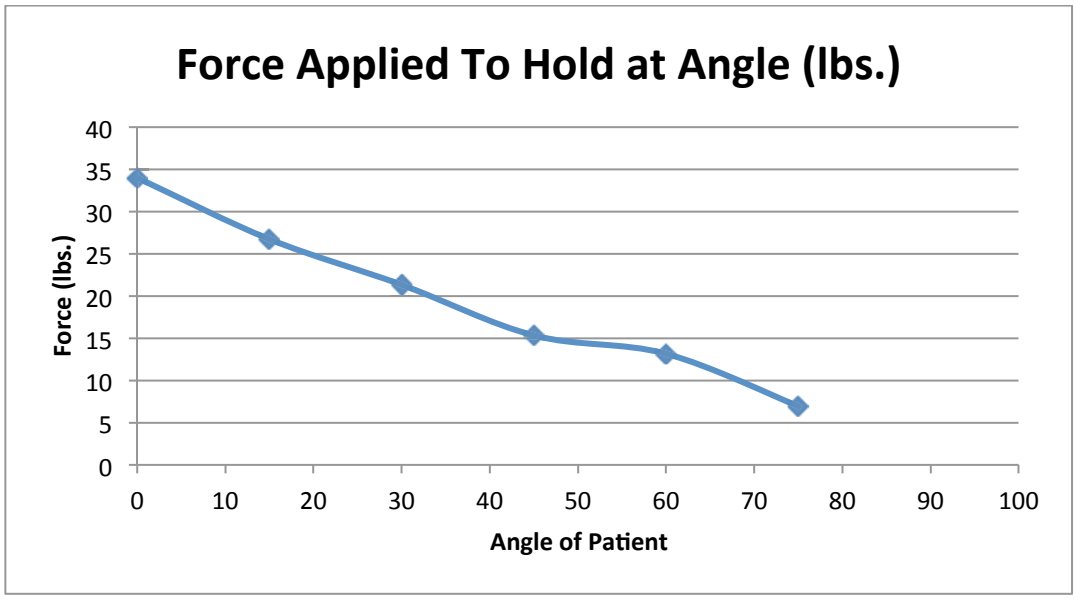



**Figure 10:** The graph displays the obtained forces needed to hold the patient upright at specified angles.

## Preliminary Bungee Testing – Bungee Cord Behavior: Ultimate Strength and Deflection

Upon researching bungee cords, specifications sheets were unable to be found. A call to Versales, Inc. revealed that, as a general practice, commercial bungee companies do not post specifications or publicly release any relating information due to liability reasons. Therefore, no information regarding spring constants or maximum yield strengths can be obtained through online research, emails, or phone calls. However, it is recommended that bungees be stretched to a maximum of 150% of their initial length for safety reasons. The purpose of this pretesting was to find the maximum load that can be applied to the bungee before it is deformed past 150% of its initial length by applying a series of different loads to the bungee cord assembly and measuring the deformation at each respective load.

The plan was to hang the assembly from a bar on a weight lifting bench, record the length of the unstretched bungee between the metal fixing on either end of the assembly using a seamstress tape, and hang weights of varying increments beginning at 60 lbs. from the fixture using a chain. Weight was added until the maximum deformation was achieved. The weight that caused stretching of 150% initial length would be the ultimate loading of the elastic region. Following completion of testing on the first bungee, the entire procedure was to be repeated using a second bungee assembly, identical in specifications.

The minimum tension to hold the patient upright was determined to be 667 N (145 lbs.)—found through patient testing and further calculations (shown above in Figure 11). Since acceptable deformation is 150% of the assembly's unstretched length and 60 lbs. stretched it to 196.9% in the first assembly, testing was discontinued because the bungee's strength proved insufficient. Because anything past 150% is unsafe, testing was stopped at this time as a precautionary measure and it was concluded that the bungee assemblies used were not sufficient to support the forces needed for the device. The second bungee reinforced these conclusions as 60 lbs. stretched this second assembly to 189.2%. From these findings, it was determined that the elastic region of the cam needed to be reconsidered. At the time of testing, it was proposed that stronger bungee cords should be purchased, or bungee cords should be placed in series to increase loading capacity.

**Quantitative Bungee Testing: Deflection**

Testing was performed with a series of different bungee cords to determine their quantitative deformation and percent elongation capabilities. Two pairs of four unique bungee cords were purchased from Versales, Inc.: (1) Diameter: 5/32", Length: 6"; (2) Diameter: 5/32'', Length: 8''; (3) Diameter: 3/16'', Length: 8''; (4) Diameter: 1/4'', Length: 8''. These bungee cords underwent testing immediately after unwrapping from mail packaging, so as to ensure no deformation occurred. The cords were initially measured, spanning between the inside edges of the attached metal hooks. Then, one team member applied a maximum tensile force across the long axis of the bungee; the length of the bungee cord while experiencing this loading was recorded. Finally, the length of the un-stretched bungee after loading was recorded.

After this data was obtained, percent elongation was calculated as the difference between initial and maximum length, divided by the initial length. Additionally, deformation was calculated as being the final length (after the loading was performed) minus the initial length. These calculations were compared between bungees, to determine what characteristics control what aspect of bungee mechanical behavior. In one scenario, the diameter was held constant and the length was increased. In another scenario, the length was held constant and the diameter was varied. When the length was the variable, as the length increased, the percent elongation decreased, but the deformation was increased. When the length was constant, but the diameter was variable, both the percent elongation and deformation were sporadic, and did not vary with a noticeable trend. The data collecting during pretesting is shown in Figure 12.

## Pretesting – Bungee cord behavior

| | Diameter: 5/32", Length: 6" | | | Diameter: 5/32", Length: 8" | | | Diameter: 3/16", Length: 8" | | | Diameter: 1/4", Length: 8" | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Initial length* | *Max length* | *Ending length* | *Initial length* | *Max length* | *Ending length* | *Initial length* | *Max length* | *Ending length* | *Initial length* | *Max length* | *Ending length* |
| *Trial 1* | 9.5 | 22 | 9.5 | 10.4 | 19.3 | 10.7 | 14 | 32 | 14.5 | 10 | 19 | 10 |
| *Trial 2* | 10.4 | 23 | 10.4 | 10.4 | 19.2 | 10.6 | 14.7 | 35.1 | 15.12 | 8.4 | 21.1 | 8.7 |
| *Average:* | 9.95 | 22.5 | 9.95 | 10.4 | 19.25 | 10.65 | 14.35 | 33.55 | 14.81 | 9.2 | 20.05 | 9.35 |
| | *% elongation:* | | 1.261306533 | *% elongation:* | | 0.850961538 | *% elongation:* | | 1.337979094 | *% elongation:* | | 1.179347826 |
| | *deformation:* | | 0 | *deformation:* | | 0.25 | *deformation:* | | 0.46 | *deformation:* | | 0.15 |
| | | *inches* | *centimeters* | | *inches* | *centimeters* | | *inches* | *centimeters* | | *inches* | *centimeters* |
| | *radius:* | 0.078125 | 0.1984375 | *radius:* | 0.078125 | 0.1984375 | *radius:* | 0.09375 | 0.238125 | *radius:* | 0.125 | 0.3175 |
| | *length:* | 6 | 15.24 | *length:* | 8 | 20.32 | *length:* | 8 | 20.32 | *length:* | 8 | 20.32 |
| | *volume:* | 0.1149902 | 1.88435233 | *volume:* | 0.153320313 | 2.512469773 | *volume:* | 0.2207813 | 3.617956474 | *volume:* | 0.3925 | 6.43192262 |

**Figure 11:** Pretesting-Bungee cord behavior. This chart shows the results of testing the bungees when they were received according to the methods describes.

### Materials

Several materials were chosen for this prototype. For the elastic cam band, standard bungee cords—continuous rubber elastic strands with an outer nylon sheath—were utilized. This choice was based on its superior elastic properties. The nylon sheath was included to ensure that the cam band would not stick to the wheel. For the fittings on the assemblies, dichromate steel hooks were used. Since steel is extremely strong, this choice helped ensure that the fittings were not the site at which deformations or failure occurred.

In regards to the frame, including the cam wheels and lever arms, aluminum was the selected material. This was in response to the concern for a lightweight final product. Aluminum is not very dense, and so it can provide a satisfactory rigidity while making fabrication simple and keeping the device lightweight.

The cam plates, however, were made out of steel. Although steel is much heavier than aluminum, it is also much stronger. Therefore, the amount of force a thinner sheet of steel can sustain would require a much thicker piece of aluminum be used to match the ability to withstand an equivalent force. Thus, based on a greater availability of steel sheets and the benefits of a thinner sheet for functionality as well as aesthetic purposes, steel was deemed a better choice than aluminum for the cam plates (Figure 8, part 5).

Lastly, in order to attach the device to the client's body, 1-1/2" height bulk straps, adjustable buckles and buckle slide locks were purchased. The thickest bands were chosen so as to increase the area of the applied force, thus reducing pressure. These were assembled into the leg bands and upper and lower anchoring rings that function like a backpack strap to form fit to the patient's body.

### Fabrication: Hardware Components of the Final Design and the Student Shop

The design required the team to fabricate the following components of the design: steel cam base, aluminum cam rotational pieces, and aluminum upper and lower lever arms.

Two members of the design team had Green Permits for the Student Shop, permitting the usage of the mills and lathes. Three evenings were spent using the lathe, band saw, drop saw, drill press, and sander to fabricate the final design.

A lathe was reserved to make the indentation of the cam rotational pieces. The material was first faced to make a smooth surface. Then, a central hole was drilled—the rotational axis of the cam. The indentation was then made, and the part was filed with a hand file, to ensure clean, safe edges. A drop saw removed the cam rotational piece from the stock aluminum rod, and final facing and sanding was performed. The cam rotational pieces required an additional hole—to provide a second point of contact to make the lever arms rigid. Holes were inserted with a drill press and the holes were then tapped to allow for screws to be used. Then, to enable the bungee cords to attach to the rotational pieces of the cam, eyelet screws were secured into the indentation 1'' anterior to the lever arms—to enable the necessary stretching (and corresponding tension) of the elastic cam band. The screw hole was made with use of a drill press, and then was tapped. This process was repeated four times—for two wheels on each side of the body.

The steel cam base pieces were measured from a larger piece of steel, and then cut out with a band saw. A drill press was used to insert two holes into each frame, which will house the rotational axis of the cam. Corners were rounded with an electric sander to eliminate sharp edged, and the pieces were hand filed.

The upper and lower lever arms of the brace were cut from an eight-foot long piece of aluminum. The cross section of the purchased aluminum was correct, so the only cuts were to reduce the length of the long axis of the piece. This cut was performed with a drop saw.

After all parts were fabricated, the cam mechanism was assembled, one for each side of the body—each was equipped with a plate, two rotational pieces with eyelets, two lever arms, the necessary screws, and bungee cord(s). The two identical hardware systems were then connected via buckles and straps.

The final weight of the prototype was 36.7 N. The dimensions are as follows: maximum length of 66 cm, maximum width of 4.5 cm on each side of the body, and maximum depth of 10 cm.

**Bungee Testing on Cam Device Prototype**

The bungees purchased from Ver Sales were tested on the cam mechanism. Placing one cam in a vice with the two lever arms attached, the lower lever arm was held rigid while the upper was bent forward to 90° from the vertical position with a bungee attached to the eyelet from the lower wheel to the eyelet on the upper wheel. Then, certain masses were hung from the upper lever arm at a distance of 31.5cm from the rotating axis (the same point at which the upper anchoring ring and patient force testing was applied). When the cam and mass were in equilibrium at the 90° position, the mass the system could support was recorded. Thus, the bungee cord was capable of holding that amount of force

at a 90° angle. The idea behind this testing is that the patient must be able to apply this much force through their muscles to get them down to this angle. Then, when relaxing their muscles, the force would decrease, and the system would bring them upright again to a system with the cam providing the pre-tensioned force previously determined as necessary. Furthermore, the deformation of the bungee was measured by subtracting the initial length from the stretched length at 90°. It should be noted that this testing is entirely dependent on the elastic cam band region of the cam.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| length from center of bolt to point of force application (cm): | | | | | | | 31.50 | | | | |
| **SIZE 1** | | | | | | **SIZE 2** | | | | | |
| diameter cm | 1.91 | | | | | diameter cm | 0.48 | | | | |
| length (L)cm | 8.25 | | | | | length (L) cm | 9.50 | | | | |
| length to deform to (1.5L) | 12.38 | | | | | length to deform to (1.5L) | 14.25 | | | | |
| force to horizontal | g | N | cm | δ | k=N/(δ/100) | force to horizontal | g | N | cm | δ | k=N/(δ/100) |
| 1 bungee | 1200.00 | 11.76 | 23.50 | 15.25 | 77.11 | 1 bungee | 1000.00 | 9.81 | 23.50 | 14.00 | 70.07 |
| 2 bungees | 2100.00 | 20.59 | 23.50 | 15.25 | 67.51 ea. | 2 bungee | | | | | |
| 3 bungees | | | | | | 3 bungee | | | | | |
| 4 bungees | | | | | | 4 bungee | | | | | |
| | | | | | | | | | | | |
| | | | | | | bungees exceeded length when attempting to add 2nd bungee, the cords appeared to be near snapping | | | | | |
| **SIZE 3** | | | | | | **SIZE 4** | | | | | |
| diameter cm | 0.41 | | | | | diameter cm | 0.41 | | | | |
| length (L) cm | 14.90 | | | | | length (L) cm | 8.90 | | | | |
| length to deform to (1.5L) | 22.35 | | | | | length to deform to (1.5L) | 13.35 | | | | |
| force to horizontal | g | N | cm | δ | k=N/(δ/100) | force to horizontal | g | N | cm | δ | k=N/(δ/100) |
| 1 bungee | 75.00 | 0.74 | 30.50 | 15.60 | 4.74 | 1 bungee | 1000.00 | 9.81 | 27.00 | 18.10 | 54.20 |
| 2 bungee | 300.00 | 2.94 | | | | 2 bungee | 1700.00 | 16.67 | 27.00 | | 46.05 |
| 3 bungee | 500.00 | 4.90 | | | | 3 bungee | | | | | |
| 4 bungee | 800.00 | 7.86 | | | | 4 bungee | | | | | |
| | | | | | | | | | | | |
| ** bungee exceeded alotted deflection -- unsuitable | | | | | | Testing was stopped after 2 bungee cords because the bungee cord began necking. Yield point exceeded and testing discontinued. | | | | | |

**Figure 12:** Data chart illustrating quantitative mechanical properties of cam from bungee testing.

The results of the testing show the largest diameter bungee displayed the highest spring constant of $77.11\frac{kgm}{s^2}$. Likewise it was able to generate the most force at 11.76N. The tests utilizing multiple bungees seemed to show that the addition of a second bungee did not double the force, which was contrary to initial hypotheses. This may have been due to different bungee lengths or differing attachment of the hooks. Nonetheless, the SIZE 2 bungee displayed a spring constant to rival that of the larger one. This seemed to suggest there might be an ideal size between the two that would give a larger force readout. The SIZE 3 and SIZE 4 bungees had the same diameter as SIZE 2 but they did not have the same spring constant. In fact, the longer length had an extremely low force read out whereas the shorter one had a fairly high read out. However, this high readout of the shorter one was probably due to the fact that it was fully tense and was close to snapping (acting more as a rope than an elastic bungee cord).

Unfortunately, to reach the desired 90° angle of our patient's bend, all the bungees were stretched farther than their recommended deformation of one and a half times their

original length. Therefore, different longer bungee cords are necessary in the future. Additionally, the pretension required to hold the patient upright when the lever arms are at an angle of 0° would need the bungee to generate a force of 80N per cam. The tested bungees exceeded maximum deformation when exposed to forces less than this 80 N. A longer bungee would allow for a safe deformation with the rotation to 90° but it may not allow for the pretension necessary to hold our patient up vertically. Therefore, diameter of the bungee cord should increase as well, to hopefully increase loading capacity. The SIZE 3 bungee (with a thicker diameter) could be scaled up to possibly yield a force loading higher and more in the region of 80N. If an idealized bungee is not strong enough, other materials will need to be looked into, perhaps a ductile metal alloy.

### Subjective Brace Testing

Testing was conducted after the prototype was completed. Two team members tried on the brace and subjectively rated the braces functionality on a one out of ten scale. The primary categories that were ranked included various components of functionality such as comfort, overall device weight, resistance to bending, range of motion, self-operability and durability. Both team members were in the brace for a thirty-minute time period and contributed comments for each of their rankings as seen in the chart below.

| Team Member (each for 30 min.) | Comfort | Overall Device Weight | Resistance | Range of Motion | Self-Operability | Durability |
|---|---|---|---|---|---|---|
| Michelle Chiang | 6 | 6 | 7 | 7 | 5 | 8 |
| Comments: | Comfortable however awkward and unusual | Definitieley has a presence but not inhibitng | Holds above a 90° angle | Can sit and stand from a chair although | Somewhat challenging to put on. | Components are durable |
| Carie Fantl | 7 | 9 | 5 | 10 | 5 | 10 |
| Comments: | Rigid but necessary | The weight is not too noticeable although wasn't worn all day | Need stronger bungees | The range of motion is great since resistance is not all that constricting | A lot of components to fasten and attach | Structurally solid |

**Figure 13:** Data chart subjective device testing based on a one to ten scale for each category.

## Future Work

For future work, the brace needs to be improved in terms of functionality and comfort. More extensive testing of the fabricated cam mechanism will be carried out to improve the effectiveness of the device in making sure equilibrium is exactly upright. This is entirely dependent on identifying an appropriate elastic cam band. More research will be conducted to look into alternatives for the cam band material. Since a model of the cam mechanism already exists in SolidWorks, this will be a valuable tool for stress analysis to compare the different possibilities for this elastic piece. If testing reveals the discovery of a more effective alternative, the material will be assessed in the previously developed prototype.

Some research has been conducted on an alternative material for the cam mechanism considering the issues with the strength of bungee cords. One high-potential material, Nitinol, or a Nickel-Titanium alloy, is a memory metal. In other words, the metal can be deformed and becomes more flimsy when it is cold. However, if heated, the metal snaps back to the 'memorable state' or original configuration. A 20°C difference is required for the metal to deform and spring back.[9] This type of material would be excellent in terms of allowing the patient to deform the system when bending is desired. Then, through activating a heat mechanism of sorts, presumably a circuit element, the Nitinol would retract back to its original state, pulling her upright into a locked position. Reportedly, Nitinol is able to retract with strength of 55 tons per square inch, which would exceed the force necessary to hold the patient upright and thus has more potential than the current bungee cords available.[10]

Another concern for future work is the range of mobility. Once this new and improved brace is complete, testing will be conducted with the patient in the brace. Such testing will be focused on observing how much motion the brace allows. If this happens to be too much or too little for some unanticipated reason, the team will reflect on past steps in attempt to improve the brace's function in terms of mobility. This will involve human subject testing, which two of the four-team members have certification to do. Thus, before this step, the design team will be sure to research whether this is an adequate percentage of the team, and if not, the team will take necessary measures to certify all team members. Additionally, IRB approval and need for this approval for further human subjects testing will be investigated.

Next, the chest and leg bands will be further developed. In the future, these distal anchoring units are hoped to be molded to the unique specifications of the user. Due to fabrication constraints of the team and their resources, these units were not able to be integrated into the current prototype.

Future work also requires determination of a more effective way to anchor the cam mechanism to the hip/torso region—for alignment is key for the cam to function appropriately. Initially, a body-molded corset was chosen; however, a corset could not be purchased. Cost as well as uncertainty about whether the corset would actually prove beneficial in terms of force distribution by taking load off of the cam prevented the purchase. Nonetheless, the group feels such a component would be a good anchoring platform for the brace even if only certain parts of the corset were used such as the waist and chest regions.

Attempts to modify the brace for a more ideal mobility range and improved comfort will probably lead to improving and installing the pin-activation system— to make it more user-friendly by only allowing anterior rotation of the cam system. More specifically, extensive research into available pin-activation system components will be done to eliminate the need to fabricate this intricate product. Hopefully, companies will be found that would be willing to design and manufacture one with unique specifications tailored to the project. If not, the team will fabricate as necessary.

## Conclusion

The design project as outlined in this paper presented a process of designing, fabricating and testing a mobility brace support device. Based on constraints and specifications provided by the client and background research on camptocormia, the team was able to develop several designs, assess them using a design matrix, and proceed with the most functional and viable option. The brace prototype was fabricated using primarily aluminum, steel, nylon, and plastic. Upon completion of all design components, testing was performed both subjectively, through team members trying on the brace and evaluating resistance, and quantitatively, through bungee loading capacity tests. Based on results and data analysis, the cam system requires a stronger, more ductile elastic region to generate necessary tensions while also preventing permanent deformation. The project will be continued next semester through the BME design program with a new team, due to the current team's differing schedules next semester. The current team hopes that the research, design, prototype, and testing already done will benefit the new team in their continuation of the project. Furthermore, the team genuinely hopes that in the near future a device will be produced that meets all needs of the client—holding the client upright, allowing forward bending range of motion with the ability to return to an upright position, and additionally both standing and sitting. In time, the team hopes that this system will be able to help patients suffering from camptocormia around the world.

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## Acknowledgements

The design team would like to take this opportunity to thank Dr. John Puccinelli for advising the Mobility Brace project. Thank you to the client, Mrs. Linda Oberstar, for allowing the team to work on a mobility device for her. Additionally, thank you to Mr. Erick Oberstar, for assisting us in communication with his mother, our client, and advising the team. Finally, thank you to the BME Department as a whole for providing the resources needed for the course and this design opportunity.

# Appendix A: PDS

## Function

Design, develop, and build a brace or support that can be worn to aid in holding a person in an upright position when standing or sitting, while also facilitating increased mobility. The client, Linda Oberstar, is a 65-year-old petite female who has suffered from Parkinson's disease for over 15 years and has developed a common complication called camptocormia. Camptocormia has caused Mrs. Oberstar to have abnormal flexion in her trunk that occurs when standing or sitting but disappears when lying down. Due to this abnormal trunk flexion, Mrs. Oberstar has lost the ability to perform every day movements due to a significant reduction in her mobility. The brace or support device must hold Mrs. Oberstar in an upright position so that she is able to comfortably perform everyday tasks, especially cooking in her kitchen.

## Client Requirements

- Brace must fit a petite sized woman weighing 556.03 N (125 lbs.) with average strength.
- Device must be less than 44.48 N (10 lbs.), as per patient request.
- Originally, a weight of 13.34-22.24 N (3-5 lbs.) on her mid-section is enough to hold her upright.
- New measurements show the amount needed to hold her as closer to 160.14N (36 lbs.) applied above the breast line.
- Manageable from the front of the body, to ensure independent use.
- Device should be able to fit over and underclothing; adjustable for differing daily conditions.
- Brace must be able to withstand and work with body functions including walking, minor twisting or arm movement, and using the restroom.
- Device must be quickly and easily put on/removed—to enable simple and independent dressing and undressing.
- Device must have a quick release, in case of emergency or bathroom usage.
- Provide adjustable mechanical settings, to facilitate an upright position while both standing and sitting.
- Must replace lack of lower lumbar strength, in order to straighten spine.
- Must be comfortable enough for client to wear for most of the day.
- Facilitate activities such as kitchen and garden usage.

## Design Requirements

1. **Physical and Operational Characteristics**
    a. *Performance requirements*: The device will be used as needed throughout the day when the client is not lying down or sleeping, and allow for comfortable sitting, standing and minor twisting. The device must apply a load of at least

13.34-22.24 N (3-5 lbs.) to patient's midsection to effectively pull spine upright, and be comfortably worn all day. However, as of November 10th, force measurements via a handheld dynamometer on the patient indicate that the force required is much closer to 160.14N (36 lbs.) when applied above the breast line.

**b.** *Safety*: Material must be breathable in order to prevent skin irritations such as bedsores. Device must be able to be removed quickly and easily, in case of emergency. For the sake of retaining muscle strength, the patient should not be able to become completely reliant on it upon use.

**c.** *Accuracy and Reliability*: Device must apply necessary forces in correct locations and amounts—which are unique to patients—in both standing and sitting position. An adjustable system will provide this benefit for patient wearing different clothing. Device should be usable over a lifetime.

**d.** *Life in Service*: The device will be used seven days a week, 10 hours a day, for approximately 20 years.

**e.** *Shelf Life*: Device is not assumed to be "on shelf" unless patient is sleeping. In that case, conditions will be the same as those endured when brace is being used.

**f.** *Operating Environment*: Operating environment constraints include situations where the Aluminum used would corrode such as in contact with chemicals. Furthermore the steel plates may be subject to rust if the brace frequently comes into contact with water. Lastly, large heavy should not be picked up considering this will cause for higher force and stress on the cam mechanism.

**g.** *Ergonomics*: The brace should ideally have no restrictions of motion for the patient. It should allow for both extension upward (to reach high cabinets) and to sit/bend (to garden). Patient expressed interest in being able to twist to approximately 60° left and right. Device should be comfortable enough to wear throughout life in service.

**h.** *Size*: Device should be less than 44.48 N (10 lbs.) and fit to the patient's unique body type. Should be portable.

**i.** *Weight*: Less than 44.48 N.

**j.** *Materials*: Device materials should not be flammable, as device will be used often in a kitchen environment. Material should be stiff, assuming that it will provide support. Device should be washable, and not rust/tarnish over time. Material should be durable for the life in service, 20 years.

**k.** *Aesthetics*, *Appearance, and Finish*: Disguisable, if possible. Potentially hidden beneath some clothing. However, patient expressed interest in function over fashion.

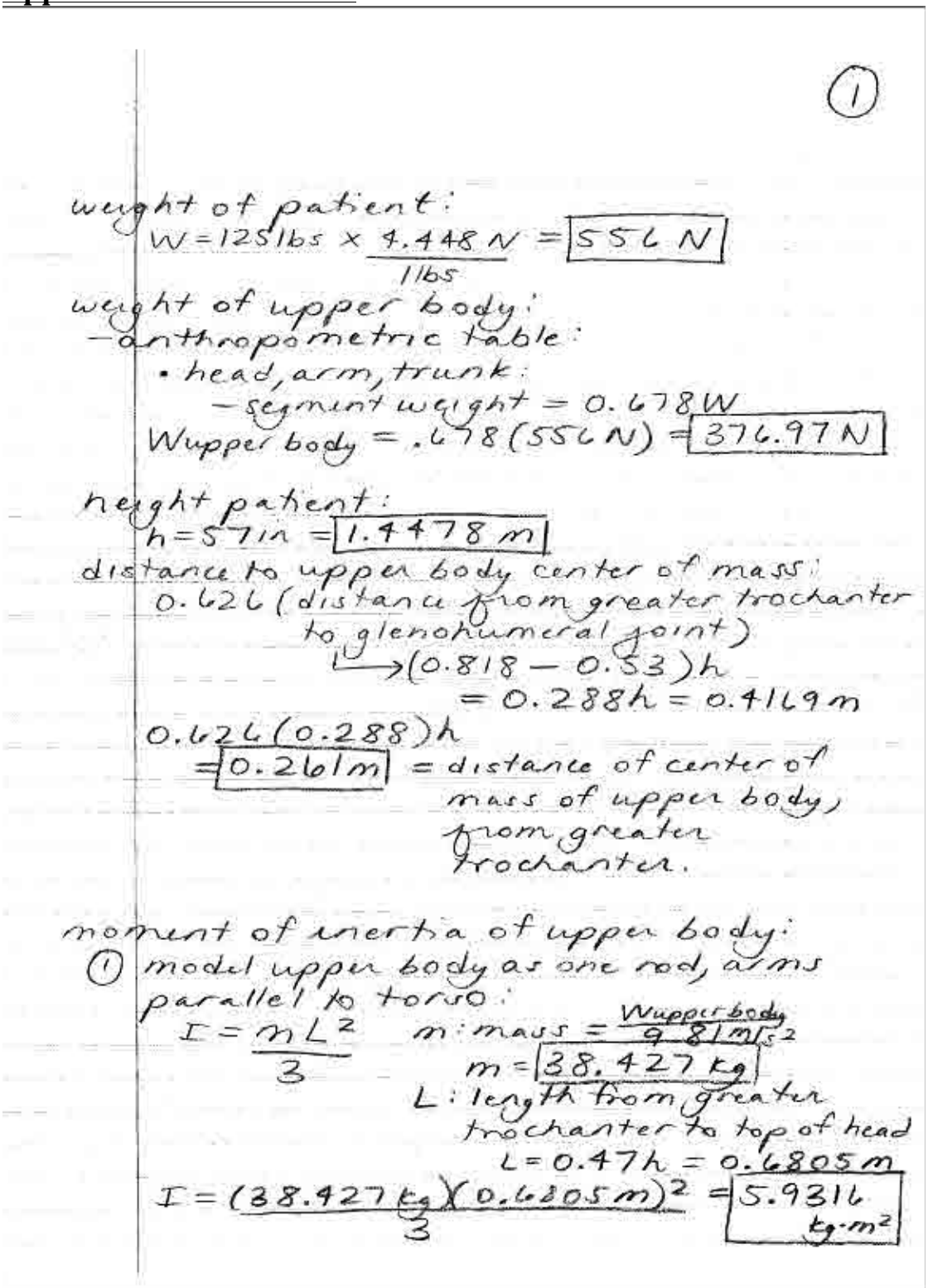
**2. Production Characteristics**

**a.** *Quantity*: One device is needed, two if financial means are available.

**b.** *Target Product Cost*: Yet to be discussed, assumed to be as low-cost as possible, yet still effective. With BME Funding for Rehabilitation Project, a cost of less than $500 was predicted to be realistic**.**

3. **Miscellaneous**
    - **a.** *Standards and Specifications*: Thus far, aware of none. (EC Medical Device Directive)
    - **b.** *Customer*: Utmost, stressed completion. Disappointed multiple times from others pursuing project—including WI orthoist currently in process of designing such braces as a new business venture. Desire function over fashion, but disguisable would be an added bonus.
    - **c.** *Patient-related concerns*: Does not want to be "a robot"—wants to garden and use kitchen, twist and bend.
    - **d.** *Competition*: Mechanical engineering student and outside private orthoist are both working on a device for patient as well. There are surprisingly few articles, patents, and devices aimed towards camptocormia patients, or other patients experiencing trouble straightening and maintaining normal gait.

## Appendix B: Calculations



(1)

weight of patient:

$W = 125\,lbs \times \frac{4.448\,N}{1\,lbs} = \boxed{556\,N}$

weight of upper body:

- anthropometric table:
  - head, arm, trunk:
    - segment weight = 0.678W

$W_{upper\ body} = .678(556\,N) = \boxed{376.97\,N}$

height patient:

$h = 57\,in = \boxed{1.4478\,m}$

distance to upper body center of mass:

0.626 (distance from greater trochanter to glenohumeral joint)

$\rightarrow (0.818 - 0.53)h = 0.288h = 0.4169\,m$

$0.626(0.288)h = \boxed{0.261\,m}$ = distance of center of mass of upper body, from greater trochanter.

moment of inertia of upper body:

(1) model upper body as one rod, arms parallel to torso:

$I = \frac{mL^2}{3}$

$m$: mass $= \frac{W_{upper\ body}}{9.81\,m/s^2}$

$m = \boxed{38.427\,kg}$

$L$: length from greater trochanter to top of head

$L = 0.47h = 0.6805\,m$

$I = \frac{(38.427\,kg)(0.6805\,m)^2}{3} = \boxed{5.9316\ kg \cdot m^2}$

**Figure 1:** Determining locations and magnitudes of forces, with use of anthropometric table, and determining moment of inertia.

(2)

(2) model upper body as one rod, with two rods (arms) perpendicular to body.

$$I = \frac{m_{torso,head} L^2}{3} + 2\left(\frac{m_{arm} l_{arm}^2}{12} + m_{arm} r^2\right)$$

r: distance from hip to arm (⊥)

r = distance from hip to shoulder
= (0.818 − 0.53)h = 0.4169 m
↳ (see page 1)

$m_{arm} = 0.050\,W = \frac{27.8\,N}{9.81\,m/s^2} = 2.834\,kg$

$l_{arm} = (.818 - .377)h = 0.4411h$
$= 0.6385\,m$

$m_{torso,head} = m_{torso,head,arm} - (m_{arm})2$

$= 38.427\,kg - 2(2.834\,kg)$
$= 32.759\,kg$

$$I = \frac{(32.759\,kg)(0.6805\,m)^2}{3} + 2\left(\frac{2.834\,kg(0.6385\,m)^2}{12} + 2.834\,kg(0.4169\,m)^2\right)$$

$= 5.0567 + 2(0.09628 + 0.49256)$
$= \boxed{6.23438\,kg \cdot m^2}$

→ scenario: if an object is picked up, more mass is added to the arm axis, causing an increased moment of inertia

**Figure 2:** Determining the moment of inertia of the upper body.

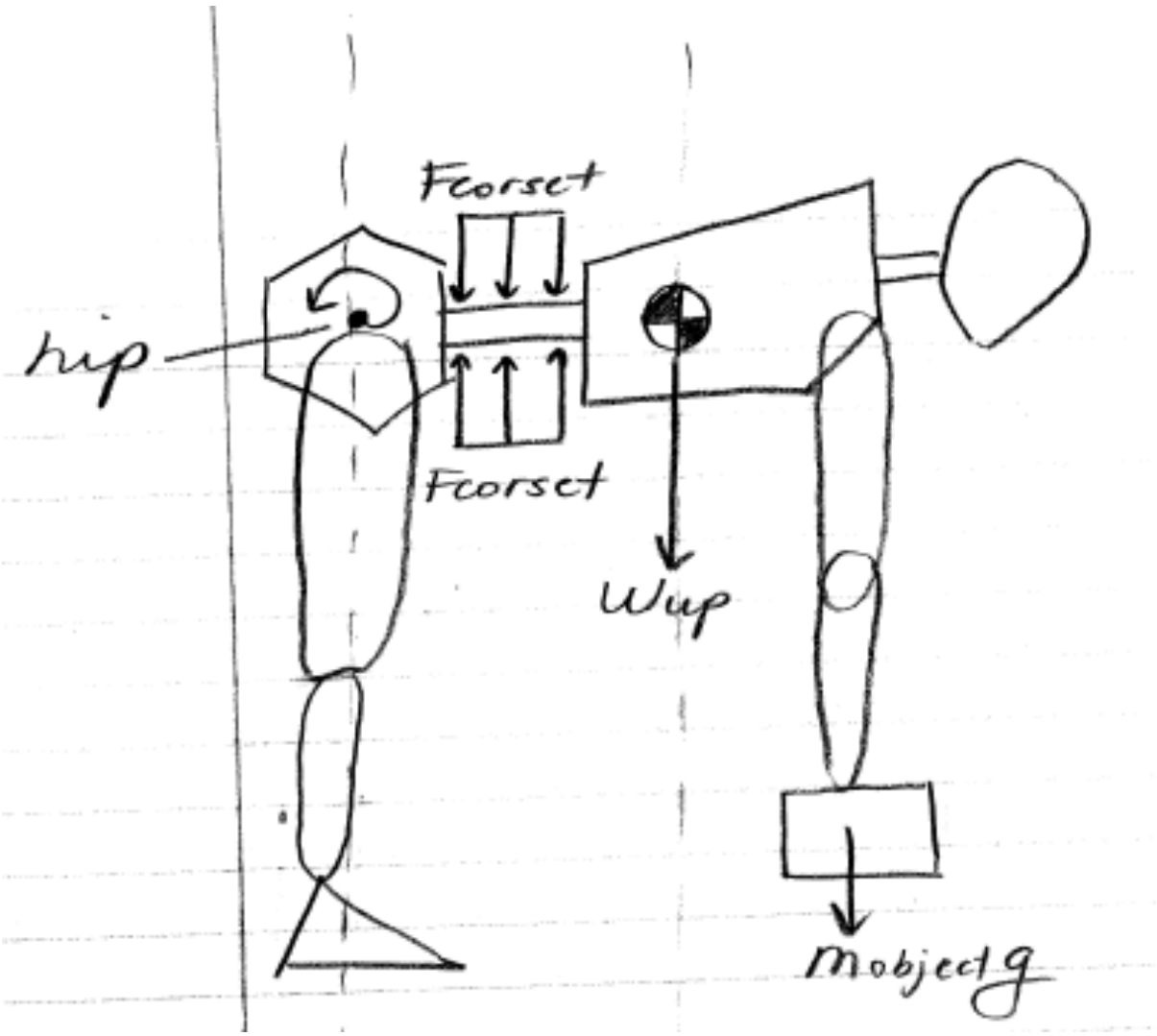



**Figure 3:** Free body diagram of subject, including weight of allowable object to pick up. Corset component is modeled as a distributed force, and cam moment modeled as point moment.

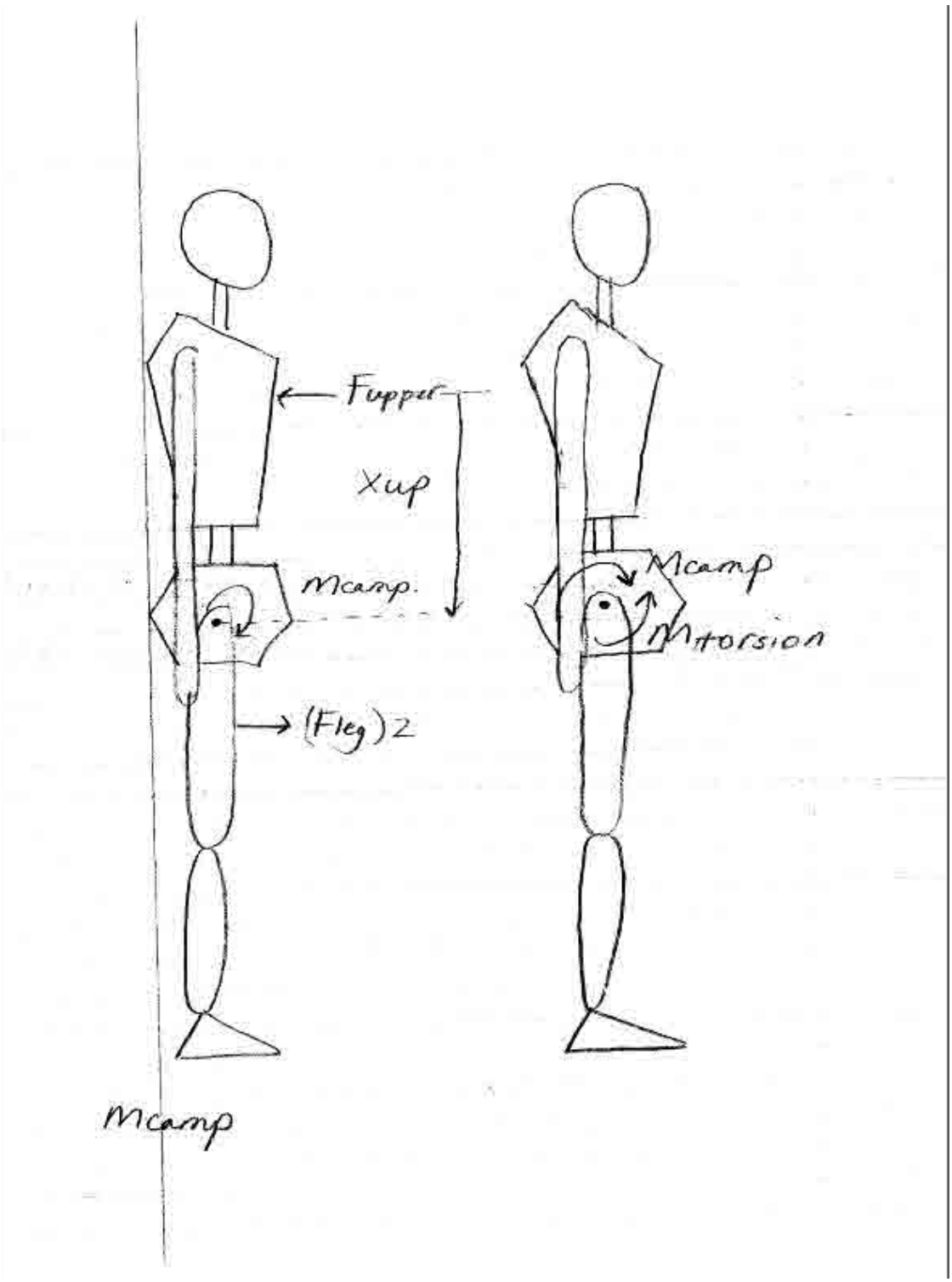



**Figure 4:** Free body diagram of upright patient. Camptocormia condition is modeled as a point moment at hip, and brace is modeled both as a point force opposing the conditions moment, and as a force couple.

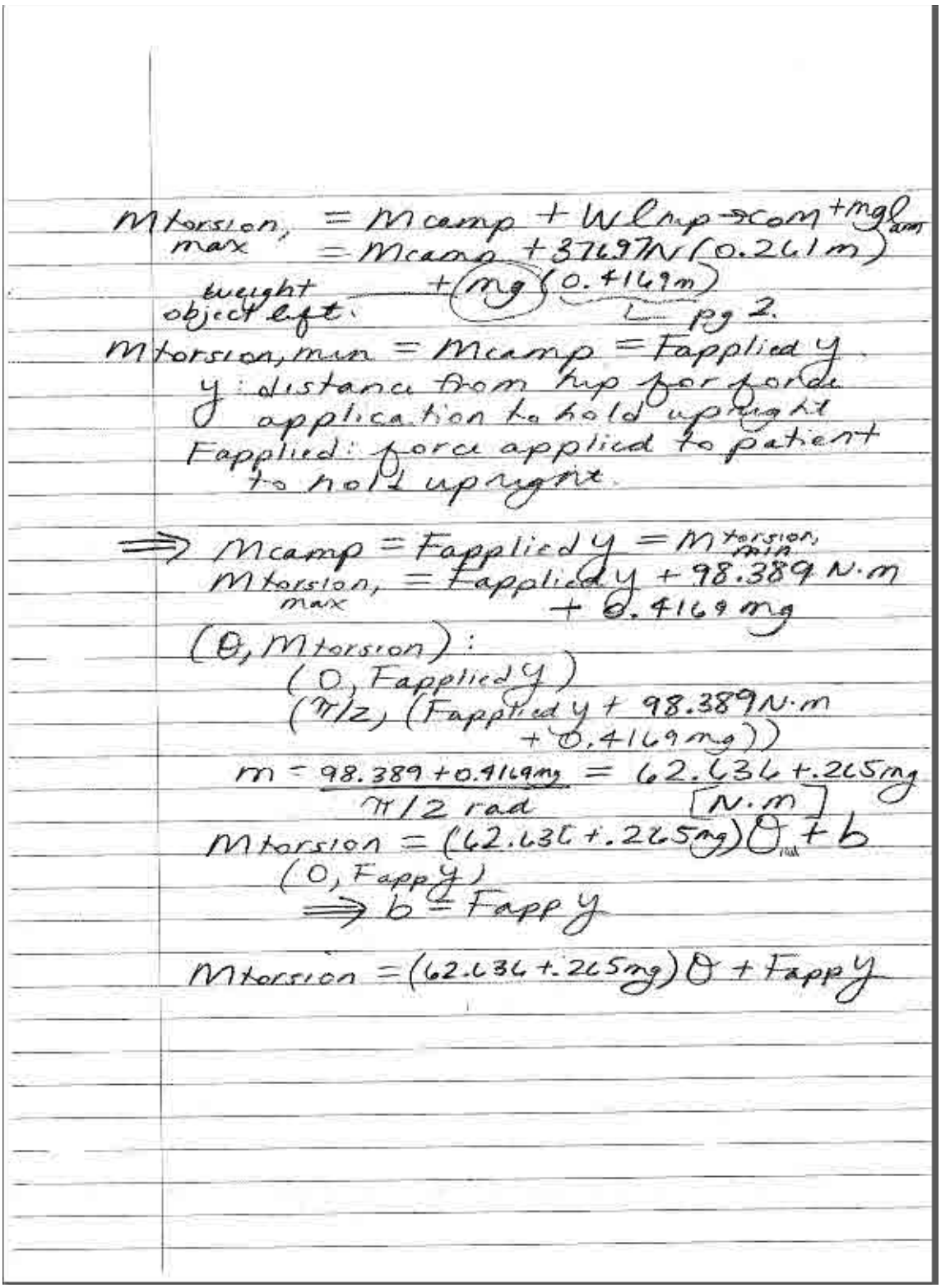



**Figure 5:** Calculations to determine the necessary moment of the cam component, modeled as a function of the angle of the patient relative to the vertical.

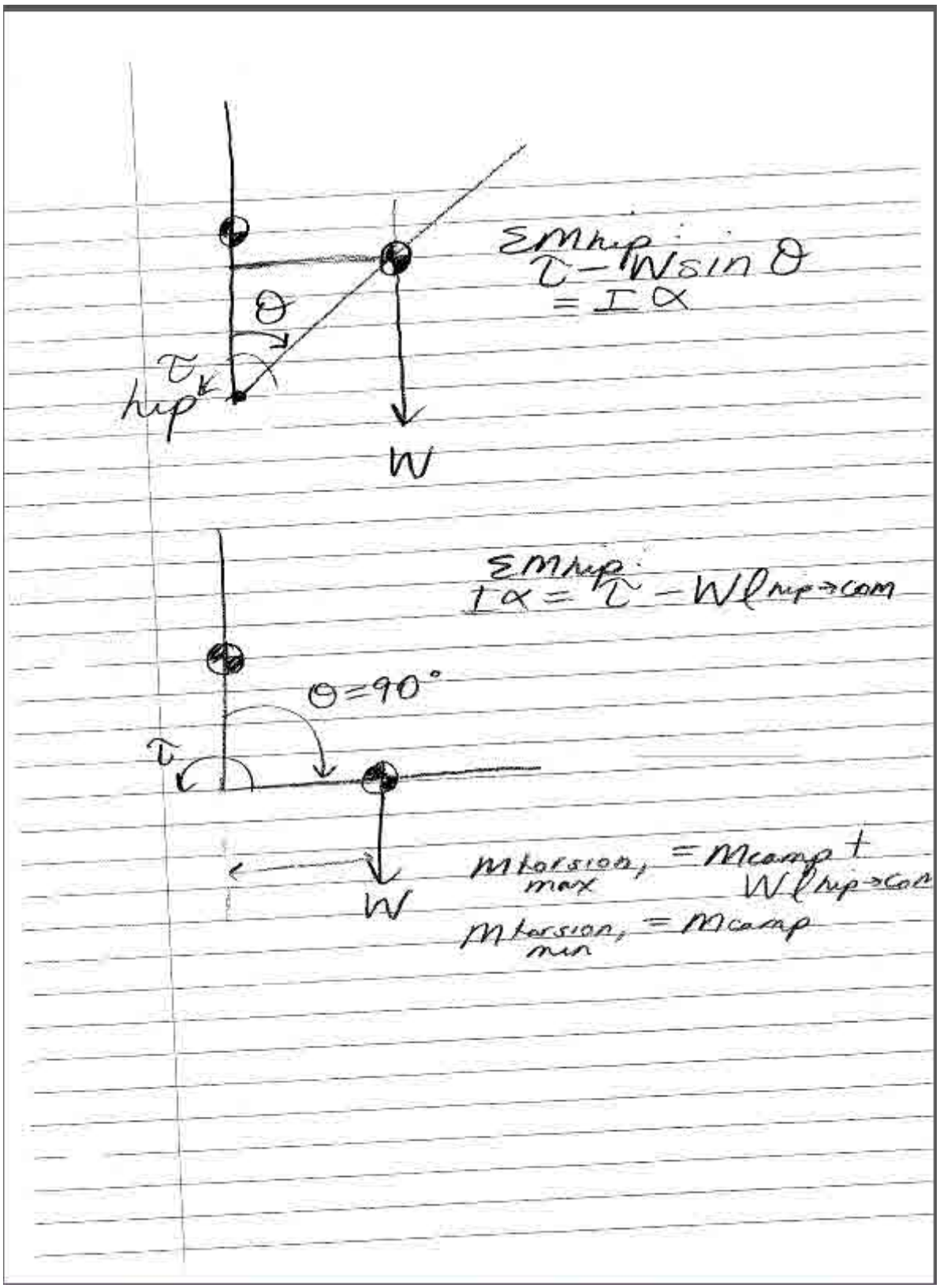



**Figure 6:** Modeling the body and moment diagrams as a function of the angle from vertical.

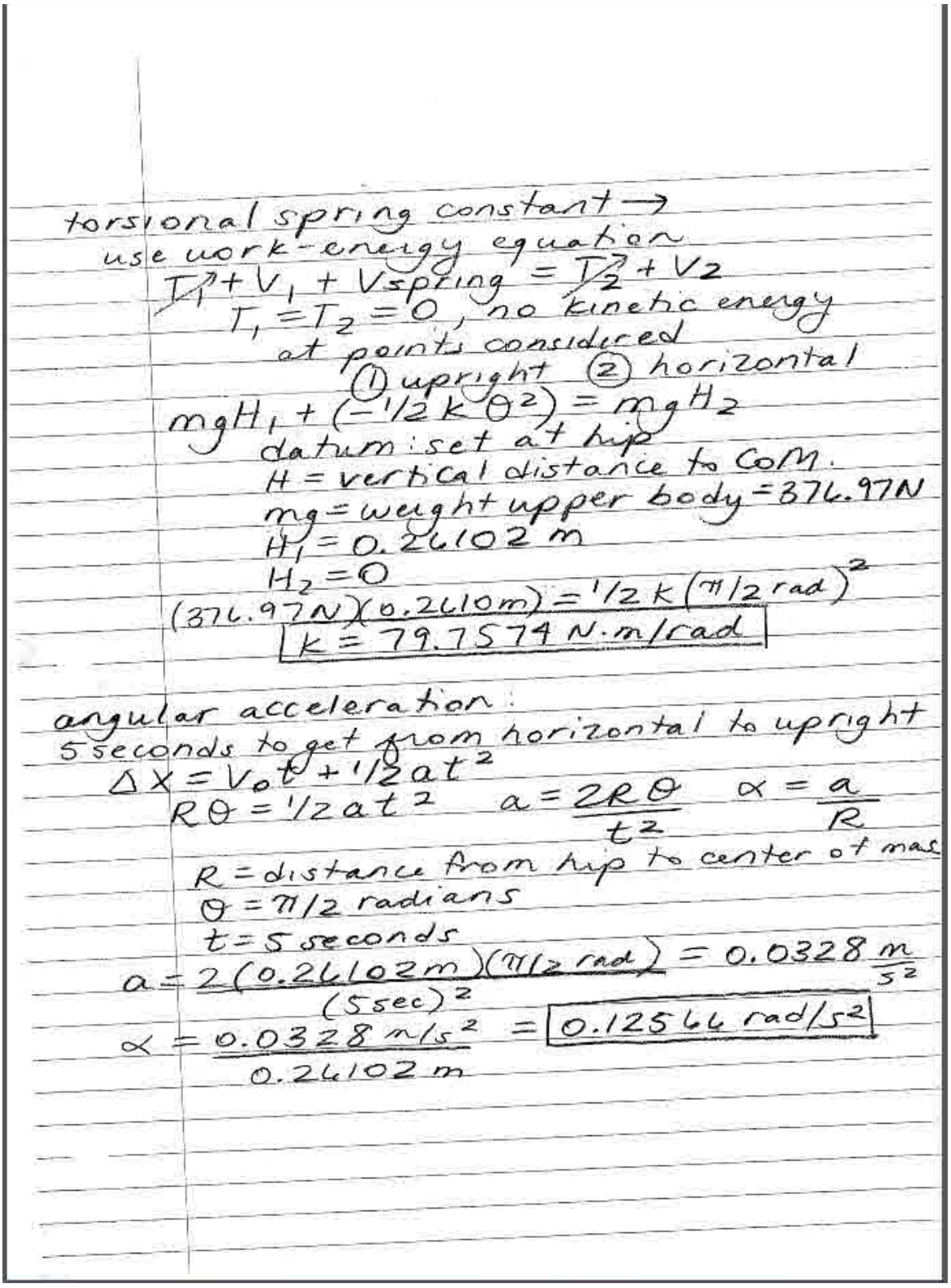



**Figure 7:** Obtaining the torsional spring constant for the cam component with work energy equations. Allowable angular acceleration was determined, from the decision that it should take 5 seconds to move upright from bent position.

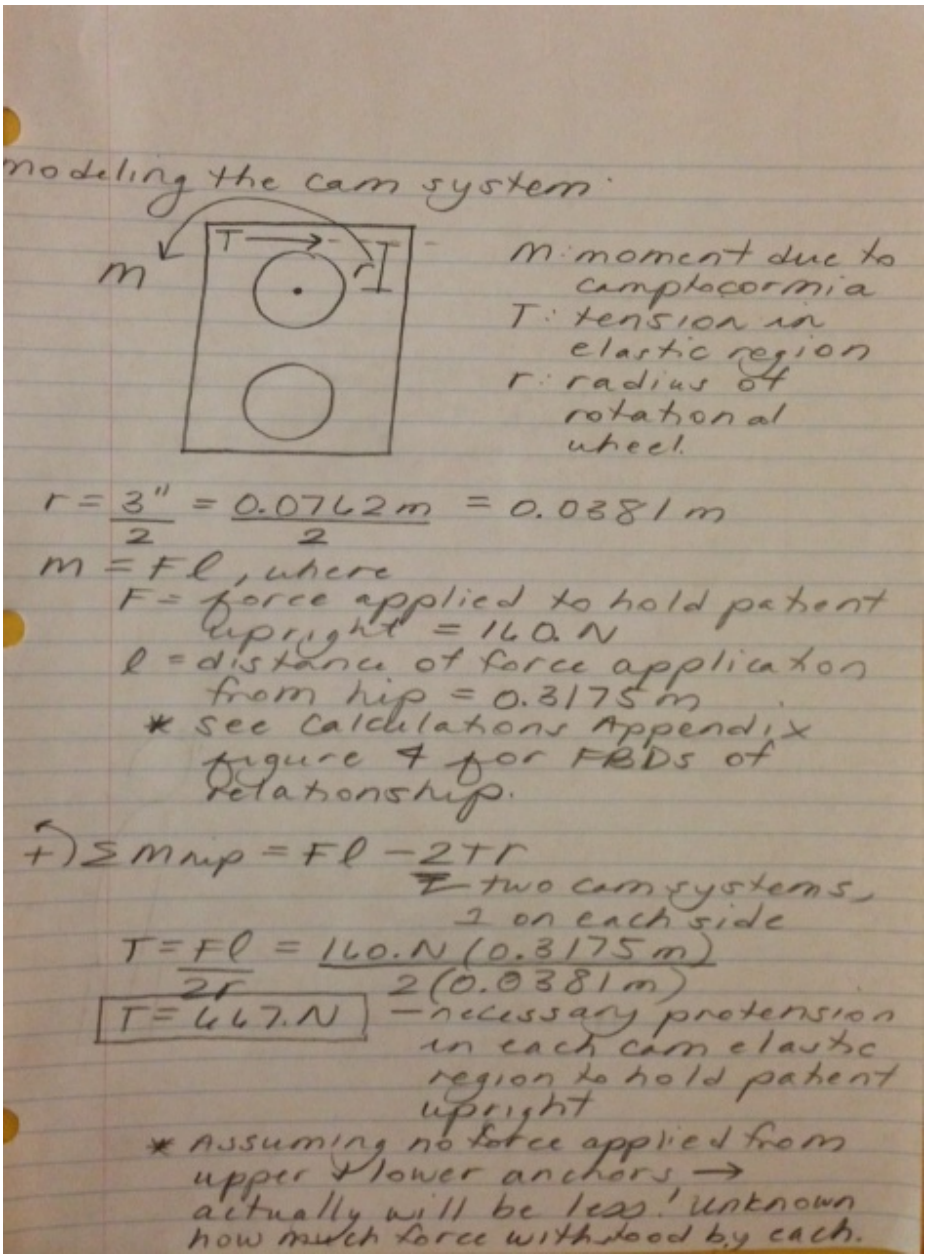



**Figure 8:** With values obtained through patient testing and the chosen radius of the cam wheel, the tension required to hold the patient upright was determined by calculating the moment about the hip. However, because the upper and lower anchoring rings provide a force to resist bending, the true value of elastic tension is actually less than mentioned above. Unfortunately, the force provided at the upper and lower anchoring rings require additional patient force testing.

# Appendix C: SolidWorks Drawings

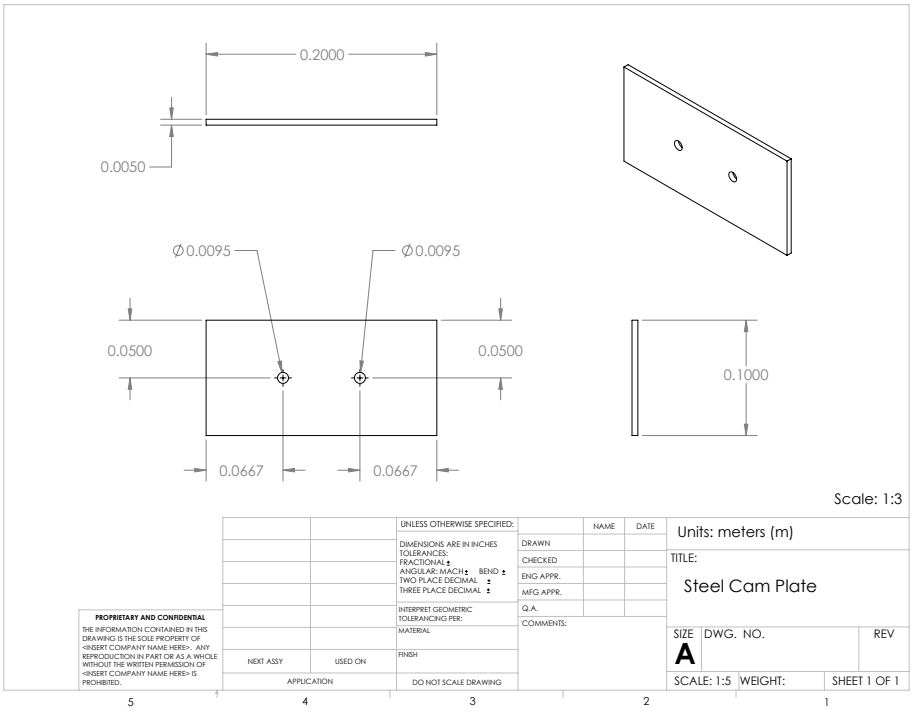



**Figure 1:** A SolidWorks drawing for the steel plate of the cam system.

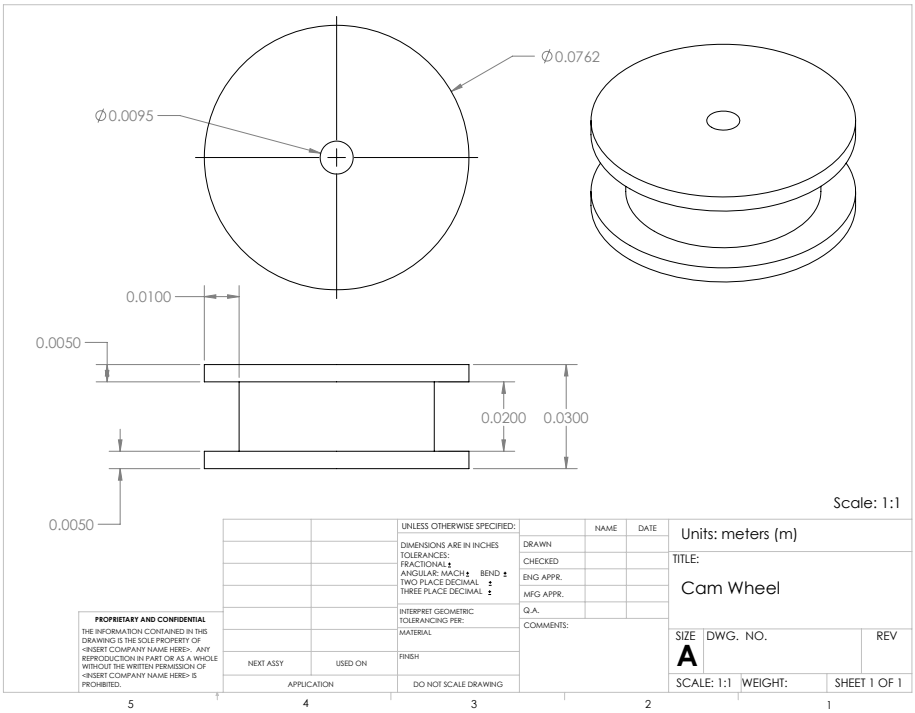



**Figure 2:** The above drawing depicts the cam wheel in SolidWorks.

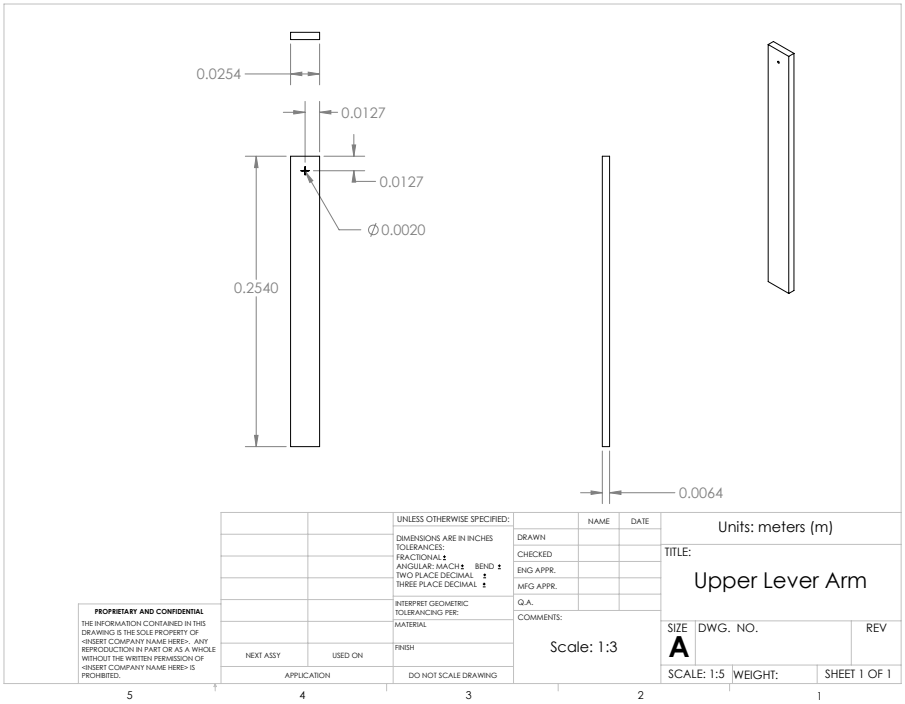



**Figure 3:** A SolidWorks drawing of the upper lever arm.

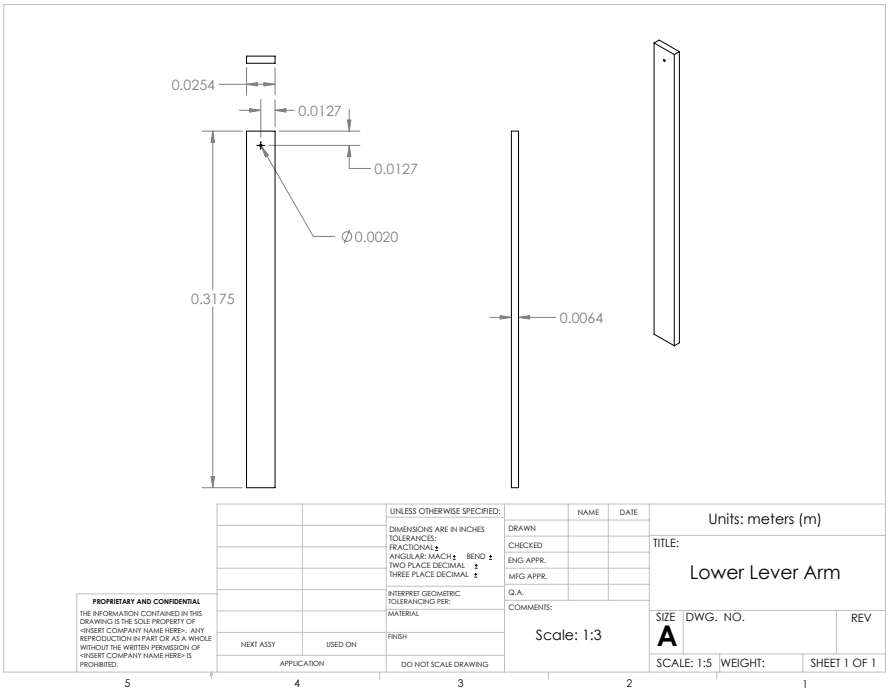



**Figure 4:** A depiction of the lower lever arm in SolidWorks.

## Appendix D: Mobility Brace Design Plan

With a thorough understanding of the design process – client need, problem definition, conceptual design, preliminary design, detailed design, design communication, and fabrication of the final design – the team created a preliminary semester design plan. First, the client need was established and the problem was clearly defined: design, develop, and build a brace or support to aid in holding a person in an upright position when standing or sitting, while also facilitating increased mobility. Three general categories of tasks were initially defined: meetings, deliverables, and project development. The team devised a semester long schedule, as seen in Figure 1, to establish goals and deadlines for progress in all three categories throughout the semester.

It was first necessary to schedule weekly meetings with the client, advisor and team members. The team also considered deadlines of deliverables throughout the semester:

Weekly Progress Reports – due each Thursday
PDS - continuous revisions throughout the semester
Midsemester Presentation – Friday 10/19/12
Midsemester Report and PDS– due Wednesday 10/24/12
Final Report and Final Poster– due Wednesday 12/12/12
Final Presentation – Friday 12/14/12

The project development tasks were defined using the established design process. The team began with research of the problem including understanding of Parkinson's disease and camptocormia, current devices available for treatment, and why the devices do not function effectively for the client. Next, the team began the brainstorming process. Brainstorming was first done individually in order to provide diverse, unbiased ideas for design components and alternative designs. After brainstorming individually, the team came together to share individually brainstormed ideas. From this point, the team discussed the possible design components and determined that the best final design solution would be a combination of ideas presented by the team members. Together the team decided on two separate key components that would function together in the final design: a corset to eliminate curvature of the spine and a rigid frame with a torsion spring or cam component at the hip to hold the client upright and allowing a forward bending motion with the capability of returning to an upright position. Additional ideas that were considered to have potential included a pin system at the hip, I shape versus Y shape rigid frames, and the use of leg bands. A pin system at the hip could be engaged to lock the frame in an upright position and could then be disengaged to allow a forward bending motion. Both I and Y shape frames were considered to determine which style would provide greater support and a greater distribution of force, thus minimizing the force needed to hold the patient upright. Leg bands were considered for added support and to provide an anchor point for the frame. From this point, team hybrid ideas and brainstorming were considered separately by each team member in order to create several hybrid designs from the original independent designs and the additional ideas brainstormed as a team.

The team created three designs and used a design matrix to evaluate the designs with the following categories functionality, self-operability, feasibility, durability, comfort,

cost, and aesthetics. The cam design ranked the highest of the three designs and was chosen as the final design. From this point, the team began calculations to determine the force needed to hold the client upright. Through said calculations the team realized that the 3-5 lb. force needed to hold the client upright originally provided by the client was truly much greater, approximately 377 N, which led to a need for preliminary testing prior to fabrication in order to determine a more accurate force than previously provided. The team was able to meet the client needs for the first force value during preliminary testing. Testing was performed using a handheld force sensor to measure the force needed to hold the upright at angles ranging from 0° to 90°, with 0° corresponding to the upright, or vertical, torso position. The force needed to hold the client upright was determined to be approximately 32-36 lbs., much greater than the 3-5 lbs. initially provided. This was detrimental to the progress of the team as the designed system needed to provide a much greater force than initially expected. During this time the team also worked on assembling the midsemester presentation and report and made revisions to the PDS.

After midsemester, as the final design had been decided, the team began determining final design dimensions and constructing design components in SolidWorks (see Appendix C) as dimensioned design drawings would be needed in order to fabricate the components in the student shop. The team then began ordering materials. As the yield load of bungee cords could not be disclosed by vendors due to liability, the team decided to purchase several sizes and lengths of bungee cords reasonable for the size of the cam component. Accordingly, the team could begin preliminary testing to determine what load magnitude various bungee cords could withstand. The team was told by bungee cord manufacturing companies that bungee cords could safely stretch to a maximum of 1.5 times their length without permanently deforming. Testing determined that a 60 lb. load stretched all bungees purchased to almost double their initial length. The team became doubtful of the ability of bungee cords to support the new 32-36 lb. load needed to hold the patient upright even with a cam system on both sides of the body, but continued with the design nonetheless due to time constraints. A potential solution could have been to use several bungee cords in parallel for each of the two cam systems to support this dramatically increased load, but further testing with a frame prototype would be needed to determine if this strategy would be effective. A second set of preliminary testing was performed on several types of bungee cords. These tests showed that permanent deformation occurred with uniaxial loading of forces much smaller than what the final design would apply to the bungees. The team concluded that in the future, stronger bungee cords would need to be used in order for the design to function effectively.

As the corset component needed to be purchased and was not dependent on the force needed to hold the client upright, the team began investigating possible corset options and realized that the corset component would be the most costly design component. Next, the team created a design matrix to evaluate the four most viable corset options. Categories included self-use, functionality, and cost. The team felt that the corset component was necessary as ideally the corset would assist in holding the client upright by straightening the client's spine and distributing some of the client's upper body weight onto the spinal column to support. Before ordering the chosen corset, the team contacted

both the client and advisor for approval as the component was very expensive, approximately $358. The team experienced great difficulty in communicating with the client during this time and the progress of the project was severely hindered due to the delayed client response. The client decided that the corset component would not be effective and from this point, although the corset component was a fundamental component of the team's design, the team was unable to purchase this component and continued with the frame mechanism, which we believed would not function effectively on its own.

The team then began selecting materials needed for the frame component of the design and purchased the following items: washers, lock nuts, sheet metal screws, carriage bolts, steel sheets, a flat aluminum rod, and a circular aluminum rod. The bolts, washers, and lock nuts would be used to assemble the central rotational axis of the four rotating cam wheels. The sheet metal screws would be used to attach the aluminum upper and lower lever arms to their respective rotating cam wheels. The steel sheets would be used to encase the cam system, the flat aluminum rod to fabricate the lever arms, and the circular aluminum rod to fabricate the cam wheels. After updating the SolidWorks drawings for the parts according to available materials, the team began fabrication of the cam system in the student shop. Upon discussing the project with the shop staff, the team purchased a few additional supplies including longer bolts for the rotating axis of the cam wheels, flathead machine screws to connect the aluminum lever arms to the cam wheels, and eyelets to anchor the bungee cord assembly hooks to the cam wheels. The steel encasing plates of the cam system were cut using a band saw, holes were made using a drill press, and corners were rounded using a metal sander. The cam wheels were fabricated from the aluminum rod stock using a lathe and drop saw. Holes in the cam wheels were made using a lathe for the axis of rotation holes and a drill press for all other holes. The lever arms were cut to length using a band saw, holes were made using a drill press, and corners were rounded using a metal sander. All rough edges and corners on all pieces fabricated in the machine shop were smoothed using a hand file. Meanwhile, bulk straps and buckles were purchased and assembled in a way that would allow the device to be strapped onto the patient's body.

During this time the team also worked on midsemester report revisions, the final report, and the final presentation poster. After complete fabrication of the final design, the team tested the cam system using several bungee cords of various lengths and diameters both individually and in parallel. The testing results showed that much stronger bungees were needed in order to withstand a greater load and deform to a safe length. Upon completion of the prototype and final testing, the team submitted the final prototype, report and poster to the BME department. The team presented their final design to the client, advisor, BME faculty and students at the final poster presentation.

| Tasks | September | | | October | | | | November | | | | December | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 16 | 23 | 30 | 7 | 14 | 19 | 26 | 2 | 8 | 16 | 30 | 2 | 9 | 16 |
| **Meetings (**Client, Advisor, and Team) | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Project Development** | | | | | | | | | | | | | | |
| Research | X | X | X | X | | | | | | | | | | |
| Brainstorming | X | X | X | X | X | X | | | | | | | | |
| Order Materials | | | | | | | X | | X | X | X | | | |
| Design | X | X | X | X | X | X | X | X | X | | X | | | |
| Fabricate Prototype | | | | | | | | | | | X | X | | |
| Testing | | | | | | | | | | | X | X | X | |
| **Deliverables** | | | | | | | | | | | | | | |
| Progress | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| PDS | X | X | X | X | | | | | | | | | | |
| Mid-semester Presentation and Report | | | | X | X | X | X | | | | | | | |
| Final Report | | | | | | | | | | | X | X | X | |
| Final Presentation | | | | | | | | | | | X | X | X | |

**Figure 1:** Longitudinal chart developed at the beginning of semester, and maintained throughout. Planned timing of events are shaded with color, actual events done in a week are denoted with an "X".