# Support System for Fall Protection During Gait Studies

## Final Proposal

**Mark Rubalcava**
**Adrian Rodriguez**
**Jack Olsen**
**Andrew Strelow**

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**Project Sponsor:** Zach Lerner, Ph.D., Director of NAU’s Biomechatronics Lab
**Faculty Advisor:** Dr. Jennifer Wade
**Sponsor Mentor:** Dr. Zach Lerner
**Instructor:** Dr. Jennifer Wade

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# 1 BACKGROUND

## *1.1 Introduction*

In the world of gait study research for patients with neuromuscular deficits such as cerebral palsy or spinal cord injuries, fear of falling is a common problem while undergoing therapy where studies of their gait are performed. Assistive devices to help participants walk have already been commercialized. However, the cost is a large factor for many facilities that study these cases due to the devices being intricate and expensive. The overall goal of this project is to design and engineer a mechanism capable of preventing a patient from falling at a fraction of the cost of the devices already available. It is imperative that this device still meets the same needs and requirements of the researchers and patients themselves.

Our team's sponsor, Dr. Zach Lerner, works within NAU's Human Performance Lab where he researches and studies how people with neuromuscular disorders walk. He is in need of a device that supports individuals participating in the lab's gait studies. Our team has been contracted to produce a system that can attach to a patient while they undergo Dr. Lerner's studies without having a fear of falling with their disorder. The system must allow the patients to walk under their power. However, it must also protect them from falling if they happen to do so. Issues with current systems are that they are expensive, interfere with motion tracking cameras, take up too much space, and can be uncomfortable to the patient. Our objective is to create a system that is user-friendly, conscientious of space, and affordable.

## *1.2 Project Description*

Following is the original project description provided by the sponsor.

> "The Biomechatronics Lab uses robotic exoskeletons to improve walking biomechanics in individuals with neuromuscular disorders. Study participants practice walking with the assistive devices in NAU's Human Performance Lab. Because many of the participants have neuromuscular deficits due to stroke, spinal cord injury, or cerebral palsy, they are predisposed to falling. The goal of this project is to design a fall protection system to use during overground and treadmill gait studies. Commercial systems may be difficult to integrate into the existing lab space and are expensive."

## *1.3 Original System*

This project consists of redesigning existing commercial designs to make them more cost effective and accommodating. In the present market, there are varieties of systems that can complete the task of holding a patient up if they were to fall during a gait study. These systems can either be ground supported or use a track system attached to the ceiling. For a ground support system, the system may be able to be dismantled, allowing it to be transferred from location to location. Another type of ground-supported system is one that is small enough to move around a room but not easily disassembled. An example of this sort of device is the Biodex NxStep Unweighing System. The NxStep allows for movement around a room, variety of patient heights, fitment around a treadmill, and collapses to 32" wide [1]. This is not easily disassembled to move to a different location but can be moved from room to room within the same building.

If the falling protection device is not ground supported, it is frequently mounted to the ceiling with a track system. The systems mounted to the ceiling usually have a higher weight rating allowing them to care for a wider range of patients. Also, as demonstrated by products from

SoloStep, the track shapes can come in a straight line, j-shaped, u-shaped, and an oval [2]. Each different shape has their advantages and disadvantages based on their application. For example, a physical therapy room may be small in size but the therapist's need to have their patients walk for a longer period. In this case, the best ceiling mounted track shape would be the oval, which allows the patient to continuously walk without stopping.

These systems mentioned above have been commercialized and are too expensive to be used in smaller gait study or therapy locations. These locations are in need of a system to keep their patients from falling while they are moving around the room as well as walking on a treadmill at a lower price.

### 1.3.1 Original System Structure

Typical gait study devices come in the form of two styles. The first style localizes itself around a track-mounted system, which is attached to a load-bearing beam above the area where a participant will walk and have their gait tracked. Aretech is a company who produces a device called the Zero G, which is centralized around the track system. The Zero-G incorporates a robotic trolley that automatically tracks patient’s movements up to 6 mph [3]. Parts of the original system include a metal track, trolley, and suspension tether. Additional parts include the patient’s harness, interactive technologies which track gait, and user-interfaces. The second type of system is a mobile frame, which moves along with the patient as they walk. These types of systems are bulky and are formed with metals capable of supporting the patient’s weight. The frames are mounted to a set of wheels that allow the system to move with the patient. An overhead beam built into the frame is usually the place where the patient can be attached via a harness to ensure that they are protected if they happen to fall. Most of the materials of the original system include lightweight metals and durable plastics. These devices are usually housed within therapeutic facilities and research laboratories.

*Figure 1: Biodex NxStep [1]*

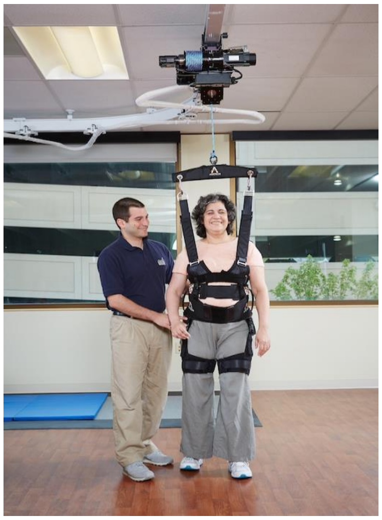


*Figure 2: Aretech [3]*

### 1.3.2 Original System Operation

Another existing fall prevention support system is the Bioness Vector Support in Figure 3. This design has the capability to support up to 500 lbs. of dead weight and can be customized to support a specified amount of weight to relieve from the patient during therapy. The design of the automated motor on the overhead track is unique from others because of the exposed coiled support line on a wheel drum. Other components of the design, which are beyond scope of our project, are onboard-integrated computer system coupled with a hydraulic pump offer precise outputs (such as weight relief) and data collection [4].

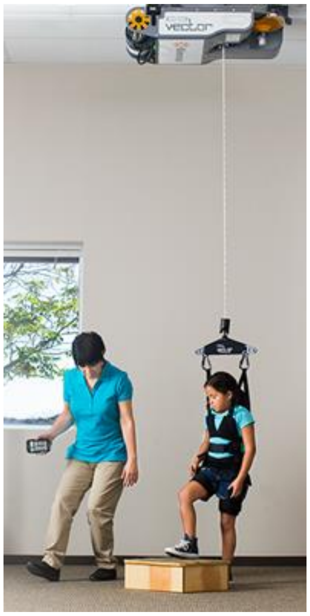


*Figure 3: Bioness Vector Support [4]*

### 1.3.3 Original System Performance

Currently, the overhead supported and ground supported support system performances are functional, safe, and interactive. For these original system variations, catching people before they fall to the ground is the main concern considering performance. To accomplish this first major performance concern, static and dynamic force calculations at the tether connected to the track connected to the user must occur. Data collection and customer requirements help compute these calculations for weight, volume, speed, accuracy, power, and efficiency of the system. The original system can hold a maximum of between 400-500 pounds of static body weight and 10-200 pounds of dynamic body weight [4]. Also, the system can perform at various speeds of user locomotion, typically near a maximum speed of 6 mph. In addition to speed performance, the system is also capable of braking when it exceeds the maximum speed, which contributes to a high safety performance for intensive rehabilitation.

The original overhead supported and ground supported systems also include interactive components to track the movements of the user rapidly (at 2500 times per second) and transfer this data to different software that drives the actuator positioned on a track and displays images of highlighted movement [5]. Phones or tablets may be linked to the patient management software to track patient growth and create/manage care plans. Another interface can link with a mobile device as a remote control for adjusting the system to meet the user needs. The actuator follows the movement of the user while maintaining enough slack in the tether for more comfortable mobility. The actuator simulates freedom of the device for mental awareness strengthening. The slack allows the user to feel free of the device, challenging them, and building their confidence at the same time. Tracking the data and displaying a computer image of movement highlights the areas for the user's mobility improvement and allows for more immediate adjustments that the therapist may direct to the user. Though this interface is not completely relevant to our design problem, it is still relevant to the amount interaction the user has currently with the system and trainer. Our design should strive for a comfortable interaction between the device and users. Overall, the performance of the support system is functional, safe, and interactive.

### 1.3.4 Original System Deficiencies

The main concern with state of the art gait support systems is their cost and interference. With commercialized systems costing upwards of $100,000, they are not feasible for our client's financial situation. Due to this need, our team is focused on designing a system that incorporates similar functions compared to one of the expensive devices, however at a much lower overall sum. Along with cost, another need for our client that is not met by the original system is interference with motion detection cameras. Some designs utilize a frame, which can obstruct the area the cameras need to be focused on to gather accurate data. Due to this problem, our team has decided that the best option for our client is a structural frame with a mounted track system, which only has a tether exposed at the level of the cameras. By only having a tether that suspends the patients to prevent falls, the cameras will have better angles to track the patient's gait and overall provide our client with better data for his research.

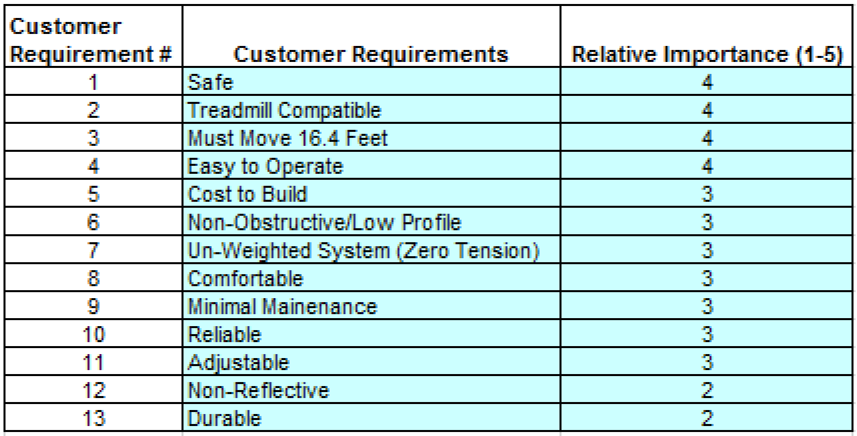
# 2 REQUIREMENTS

The following sections will outline the customer requirements our team has set, the rankings are given to us by our client, and the House of Quality used to determine which customer and engineering requirements to focus on.

## *2.1 Customer Requirements (CRs)*

Below in Table 1 are the requirements articulated by the client and considered for future users of the design.

*Table 1: Customer Requirements*



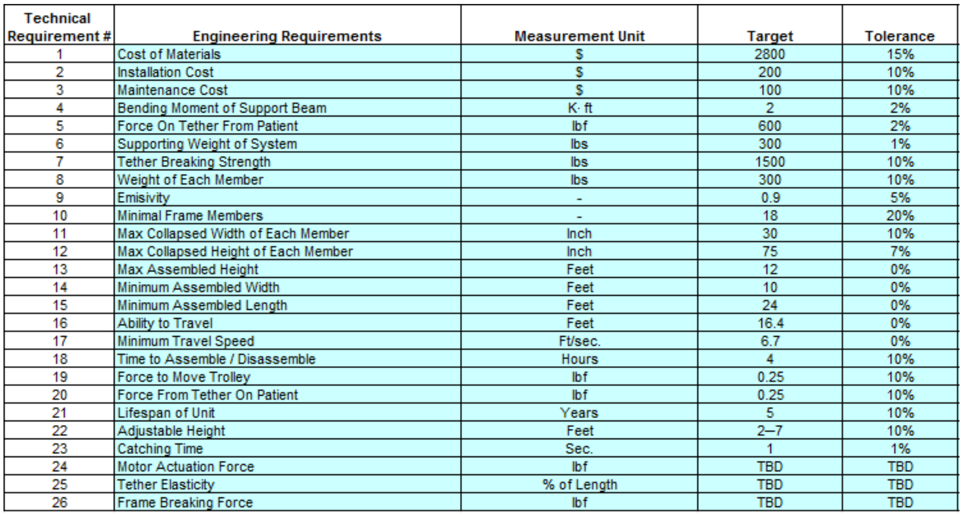
| Customer Requirement # | Customer Requirements | Relative Importance (1-5) |
|---|---|---|
| 1 | Safe | 4 |
| 2 | Treadmill Compatible | 4 |
| 3 | Must Move 16.4 Feet | 4 |
| 4 | Easy to Operate | 4 |
| 5 | Cost to Build | 3 |
| 6 | Non-Obstructive/Low Profile | 3 |
| 7 | Un-Weighted System (Zero Tension) | 3 |
| 8 | Comfortable | 3 |
| 9 | Minimal Mainenance | 3 |
| 10 | Reliable | 3 |
| 11 | Adjustable | 3 |
| 12 | Non-Reflective | 2 |
| 13 | Durable | 2 |

The total cost of the project must abide by the $3,500 budget set by the client. The design needs to incorporate materials that will economically suit the budget. The overall system must safely support a patient's body weight and movements during a fall. The line of sight of the Vicon infrared motion detected cameras must not be restricted. The color/texture of the system cannot interfere with the cameras. The support system allows the patient to use the system when walking on a treadmill. The system must allow the patient to move 16.5 feet in either forward or rearward direction. The tether must not be under tension with the patient attached. The patient must not feel discomfort while operating system to avoid interfering with the gait analysis. The system must be easily operable by both the patient and the therapist. The design needs to have minimal maintenance required over long durations of operation. The system must be able to be operated for long periods. The system must not fail when being used and must catch the patient from falling. The system must be able to be used for small children to elderly adults ranging in heights and weights.

## 2.2 Engineering Requirements (ERs)

The top section of the House of Quality is the engineering requirements section, which outlines what our team needs to focus on in the design process. The engineering requirements are correlated to themselves as well as the customer requirements to determine which ones have the most impact on customer needs. The cost of materials is the engineering requirement that weighs the highest, by over 100 points. The target for the cost of materials is $2800 because the remaining budget must be put toward installation and maintenance costs. Every engineering requirement listed in Table 2 below can link back as an effect to the cost of the materials used. The next important engineering requirement is ensuring the tether supporting the patient has a breaking strength able to withstand the reaction force established by the max patient load during a fall. This engineering requirement is still in the analysis process for calculating but is so critical to providing the safety that it scored second highest in the house of quality point summation. The third place of focus importance is the frame breaking force that ensures the entire system will have enough strength to support consecutive user falls. This focus on the frame breaking force is still under analysis as well because there is not a definite frame design set yet. Once we choose our frame design, we will be able to relate better force equations to return a more accurate target for this requirement.

*Table 2: Engineering Requirements*



| Technical Requirement # | Engineering Requirements | Measurement Unit | Target | Tolerance |
|---|---|---|---|---|
| 1 | Cost of Materials | $ | 2800 | 15% |
| 2 | Installation Cost | $ | 200 | 10% |
| 3 | Maintenance Cost | $ | 100 | 10% |
| 4 | Bending Moment of Support Beam | K· ft | 2 | 2% |
| 5 | Force On Tether From Patient | lbf | 600 | 2% |
| 6 | Supporting Weight of System | lbs | 300 | 1% |
| 7 | Tether Breaking Strength | lbs | 1500 | 10% |
| 8 | Weight of Each Member | lbs | 300 | 10% |
| 9 | Emisivity | - | 0.9 | 5% |
| 10 | Minimal Frame Members | - | 18 | 20% |
| 11 | Max Collapsed Width of Each Member | Inch | 30 | 10% |
| 12 | Max Collapsed Height of Each Member | Inch | 75 | 7% |
| 13 | Max Assembled Height | Feet | 12 | 0% |
| 14 | Minimum Assembled Width | Feet | 10 | 0% |
| 15 | Minimum Assembled Length | Feet | 24 | 0% |
| 16 | Ability to Travel | Feet | 16.4 | 0% |
| 17 | Minimum Travel Speed | Ft/sec. | 6.7 | 0% |
| 18 | Time to Assemble / Disassemble | Hours | 4 | 10% |
| 19 | Force to Move Trolley | lbf | 0.25 | 10% |
| 20 | Force From Tether On Patient | lbf | 0.25 | 10% |
| 21 | Lifespan of Unit | Years | 5 | 10% |
| 22 | Adjustable Height | Feet | 2–7 | 10% |
| 23 | Catching Time | Sec. | 1 | 1% |
| 24 | Motor Actuation Force | lbf | TBD | TBD |
| 25 | Tether Elasticity | % of Length | TBD | TBD |
| 26 | Frame Breaking Force | lbf | TBD | TBD |

## 2.3 Testing Procedures

The testing procedures shown below in Table 3, outlines the steps to be taken to test each engineering requirement to ensure our design meets the engineering requirements. Each testing procedure has a number in the table, which is then placed in the House of Quality.

*Table 3: Testing Procedures*

| Engineering Requirement | Testing Proc. Number | Testing Procedure Description | Data (Include Units) | Initials of Tester, Date, and Time |
|---|---|---|---|---|
| 1-3 | 1 | The overall cost of the system, installation, as well as maintenance costs can be confirmed by compiling a list of all necessary components for the system, fabrication/hired labor, and upkeep and their corresponding prices. With the list, all of the prices can be summed to deliver the costs in each field. | | |
| 4 | 2 | The bending moment on the support beam must not exceed 2.0 K*ft. To verify the reaction force from the patient does not cause a moment higher than 2 k*ft the force can be applied at any location on the beam modeled in Risa. | | |
| 5 | 3 | The force on the tether must not exceed 600 pounds due to the structure being designed around this value. This is the max falling force that the tether will be experiencing. To test to verify the force does not exceed 600 pounds, a force gauge will be used. | | |
| 6 | 4 | To verify the system can support the max patient weight of 300lb, FEA can run to determine the stress within each beam. If the stress in each beam exceeds the fracture stress, then a larger beam size must be used. | | |
| 7 | 5 | To test the breaking strength of the tether, a tensile strength tester can be utilized. The selected material's manufacturer states a breaking strength of 1,790 lb. The breaking strength of the tether must exceed the max patient weight of 300 lb. | | |
| 8 | 6 | The weight of each member will be ordered by foot, therefore the testing will be analysis on the weight per foot our material is, and ensure our members do not surpass this 150 lb weight limitation. | | |
| 9 | 7 | Testing for high emissivity will occur by applying flat black paint to the material, and determine from this the right amount of layers to paint to maximize emissivity. | | |
| 10 | 8 | The testing for minimal frame members will occur in a finite element analysis software. The software will tell us how strong our supports are and from here, we will make alterations to best fit the strength with minimal member ratio. | | |
| 11 | 9 | Testing different collapsing methods will occur first with prototypes to observe the best angle to fold a portion of the assembly that measures to a width no greater than 35 in. | | |
| 12 | 10 | Testing different collapsing methods will occur first with prototypes to observe the best angle to fold a portion of the assembly that measures to a height no greater than 80 in. | | |
| 13 - 16 | 11 | After full assembly of design, use a 25' measuring tape to measure length, width, and height of the design. Measure from edge to edge of the design or floor to top edge of design. Record findings. | | |
| 17 | 12 | A timer and measuring tape will be required to conduct this test. The procedure is as follows:<br>1. Move trolley to one of the ends of the support system.<br>2. Mark a 5' and 15' distance on the ground in front of the trolley path.<br>3. Begin walking forward pulling the trolley and try to hit a constant walking speed before the 5' mark.<br>4. Continue walking at the 5' mark and begin recording time.<br>5. Stop the timer at the 15' mark and record time.<br>6. Calculate velocity by dividing 15' by the recorded time.<br>7. Repeat steps to test the fulfillment of the requirement. | | |
| 18 | 13 | For this procedure a time will be required. When all materials are available begin the timer and construction of the fall protection system. Stop the timer when the structure is completely erected. | | |
| 19 | 14 | With the trolley on the track, this procedure requires a spring inserted into a single open ended tube and a small ruler. Using the spring, apply top of the spring to the side of the trolley to move it down the track. Record the displacement of the spring when the trolley is moving. To find the force use the equation of $F = k*x$, where k is the spring constant and x is the displacement measurement. | | |

| | | | | |
|---|---|---|---|---|
| 20 | 15 | To test the force the attached tether has on the patient, we will attach a force gage to the tether connected to the trolley. The force reading should be less than a pound. If adjustments are necessary additional frictionless bearings will be implemented to the trolley for a less resistive force. | | |
| 21 | 16 | The lifespan of the unit can be tested by using a software to simulate load cycles to see how long it would take for the system to start to fail. Once the center beam eventually deforms where the trolley binds, then the system is no longer able to be used properly. | | |
| 22 | 17 | After the design has been constructed, the length of the tether can be measured using a measuring tape to determine the length. The length of the tether is between two to seven feet long to account for all user sizes. | | |
| 23 | 18 | In order to obtain an accurate time for the system to catch the patient, a teammate will simulate a fall while being connected to the system. Another teammate will record the time from the start of the fall to when the system catches the teammate. A second teammate will also record the fall via video so the team can go back to the video afterwards to obtain an accurate time. | | |
| 24 | 19 | A subsystem of the trolley may include a motor to eliminate any force from the tether onto the trolley. The motor will run along the track keeping the trolley above the patient. The force required to move the motor will be determined by the manufacture of the trolley system. | | |
| 25 | 20 | The elasticity of the tether (E) is a function of the diameter (D), load (W), and construction and material (G). Knowing these values for the tether, we can use the equation:<br>E=WGD2 | | |
| 26 | 21 | The frame breaking force can be determined using a structural analysis software such as RISA to determine the stresses and forces in each beam. We can use the stresses in the beams and compare them to the yield and fracture strength of the material to determine if the beam will elastically deform, plastically deform, or crack and eventually collapse. | | |

## *2.4 Design Links*

The design links for each engineering requirement describes how the proposed design meets the corresponding engineering requirement.

### 2.4.1 Design Link 1: Cost of Materials

For this project, our team set a price limit of $2,800 dollars for the cost of our materials. To meet this objective our system is going to be built using the minimum amount of components while ensuring we are not sacrificing its structural integrity. We want to keep the patient safe most importantly, however we also want the system to be non-obstructive and out of the way when installed. Meeting our goal of $2,800 for materials is attainable, as research has been conducted on the cost of materials necessary to complete the structure as well as the trolley and tether components.

### 2.4.2 Design Link 2: Installation Costs

For our design, we set a maximum cost of $200 towards installation. In order to meet this price our team is going to install the system when all of the components have been purchased. The goal is to have most of the components pre-assembled and fabricated so installation will not take long and rentals of equipment will only be necessary for a few hours. Having a minimal amount of pieces to put together as well as not having to hire additional workers will assist in keeping the cost for installation low.

### 2.4.3 Design Link 3: Maintenance Cost

In order to keep maintenance costs at less than $100 a year our team is going to spend a fair sum of the allotted budget on high quality materials that will be durable and long lasting through use. We plan the $100 per year budget to be used for grease, lubricants, thread locker, stripped bolts/nuts, etc. The bulk of maintenance that will be required for the system will be for keeping the track greased, the bearings on the trolley lubed, and instilling that all of the bolts are properly fastened.

### 2.4.4 Design Link 4: Bending Moment of Support Beam

For our design, it is important that deflection is minimal along the patient support beam. In order to maintain minimal deformation the bending moment established along the beam must also be minimized. With the selection of A992 Wide Flange Structural Steel as the material for the patient beam, structural analysis software has been run to test varying dimensions to compare the moment and deflection results against one another. After testing, it has been found that an A992 W4x13 H-Beam will function properly as the patient support beam. The max bending moment created along the support beam using this size of beam was 1.8 k*ft directly in the center at 12 ft. The elastic deflection inflicted with this bending moment was 0.285 in, which is well within our customer's requirement.

### 2.4.5 Design Link 5: Force on Tether from Patient

The proposed design to our client has included a tether that has a higher breaking strength compared to the actual force being applied to the tether from a falling patient. The tether that has been chosen has a breaking strength of 1790 pounds while the force onto the tether from the patient is going to be a maximum of 600 pounds.

### 2.4.6 Design Link 6: Supporting Weight of System

In order to ensure that the structural support system will not fail under the loading of the patient, high strength materials will be used to maintain structural integrity and rigidity. Our team has chosen to utilize A500 Gr. B steel for the beams and columns of the structure and an A992 H-Beam to run the patient trolley across. The tensile strength of the metals is 50 ksi with a modulus of elasticity of 29,000 ksi. When tested under the max weight of a patient falling 3 ft in structural analysis software, elastic deformation was a mere 0.285 in. When fully assembled the system will be more than capable of supporting a 300 lb patient.

### 2.4.7 Design Link 7: Tether Breaking Strength

For our design, the safety of the patient is the most important priority. In order to ensure this parameter is set, the strength of the tether supporting the patient when they undergo a fall must be capable of handling their body weight and the force they exert. Our system is going to have a max patient weight of 300lbs. When calculated, the force a patient of 300 lb exerts along the beam is 600 lbf. To make sure our tether will not ever fail under the loading of a patient, we are purchasing a tether with a manufacturer breaking strength of 1790 lb.

### 2.4.8 Design Link 8: Weight of Each Member

Our design requires the entire unit to be as lightweight as possible, thus our goal is to make the system comprised of components no more than 300 lb. The necessity for a lightweight design mostly comes from the customer need of mobility. The mobility is more specifically for the patients and for the assemblers. Designing a system that can easily assemble is directly related to the weight of the system and its individual components. If the system and its components were too heavy, the assembly would require more manpower and or machinery, which would increase our budget out of our availability. Having a lightweight system also allows the patient to use the unit with ease free from strenuous resistance attached to the heavy weight.

### 2.4.9 Design Link 9: Emissivity

Low emissivity is necessary for our design to keep the wall mounted infrared cameras away from any interference. An emissivity level greater than 0.90 will ensure the structure will remain clear from sending false signals to the computer software responsible for tracking the motion of the users. Research is reliant on the high emissivity in order to maintain a reliant focus on the most important area of readings, which is a 360 degree view on the lower half of the patient's body.

### 2.4.10 Design Link 10: Minimal Frame Members

Having a minimal amount of frame members links our design to the customer needs in two main ways; ease of assembly and remaining non-obstructive. Less frame members will ensure the assemblers have less to install and in return should mean a faster setup and takedown process. In addition, having less frame members reduces the potential for the unit obstructing the view of the motion sensor cameras

### 2.4.11 Design Link 11: Max Collapsed Width of Each Member

Our design accommodates for the possibility of relocation because the lab space currently given to our client, Dr. Lerner, for his studies may change, so a requirement has been set to have the width collapsible of 35 inches or less. When the day comes to move the unit out of the current space, everything will fit widthwise outside the room through the standard doors. For the overhead support system, none of the members must exceed a width of 35 inches.

### 2.4.12 Design Link 12: Max Height of Each Member

The maximum height of each structural member must be less than 80 inches to ensure the structure members can fit through doorways. In the case where the structure may need to be moved to another laboratory, the height limitation will comply with most standard door sizes.

### 2.4.13 Design Link 13: Max Assembled Height

The maximum assemble height relates to the dimensions (In feet) of the lab and infrared camera levels that the support system will reside in. The height of the ceiling in the room is 11'11 ½", and the infrared cameras have two levels of heights at 7'8" and 9'5 ½". The support system maintains a maximum height at 11'. From this height, the support system is beyond interfering with the camera's line of sight while staying below the ceiling in the room.

### 2.4.14 Design Link 14: Minimum Assembled Width

The minimum assemble width of the design relates to the ability of the support system to encompass a treadmill area in the dimension of 3 ½'X7' and to maintain a width within the area of the lab, 30'X29'4". The outer width between support columns of 10'. The outer width is less than each dimension of the lab area, which allows the system to move, should there be a need to move the support system to the middle or other side of the room completely.

### 2.4.15 Design Link 15: Maximum Assembled Length

The maximum assembly length relates to the dimensions of the room. Though the room is 30'X29'4", the design must maintain a three foot distance from the walls on either side to meet our client's requirement. Due to this an indentation of three feet on either side, we must remove six feet from the full length of the system, thus, the overall length must be 24 feet.

### 2.4.16 Design Link 16: Ability to Travel

The ability to travel 5 meters corresponds to the customer requirement of a travel length of 16' plus the length of a treadmill, 7 ½', making a total length requirement of 22 ½' long. The length of the support system travel track is 24'. The travel length is long enough to cover the length required to test a patient walking 16' plus extra therapy practices that take place on a treadmill. The total length is less than each dimension of the lab room allowing liberty to rotate and move about the lab.

### 2.4.17 Design Link 17: Minimum Travel Speed

The minimum travel speed pertains to the support module that is fixed to a trolley. The support module has the capacity to travel over the interval of speeds 0 ft/sec to 10 ft/sec.

### 2.4.18 Design Link 18: Time to Assemble/ Disassemble

The future of the support system has the potential for the system to be moved to another location. Because of this probability, the support system is capable of being disassembled and moved to the next location. The amount of time to assemble to the system is approximately four hours. The amount of time to disassemble is three and a half hours.

### 2.4.19 Design Link 19: Force to Move Trolley

The force the patient is required to exert on the tether to move the support module on the trolley track. The design of the support module uses wheels that roll on bearings. The force to move the support system is calculated to be ¼ lb.

### 2.4.20 Design Link 20: Force from Tether on Patient

The design requires that the force from the tether acting against the patient as they move across the lab is as minimal as possible. In order to ensure a low force, the design must include a lightweight trolley that will include nearly frictionless bearings to ensure the patient will feel low force from the tether. If the patient were to feel a high force from the tether, the gait analysis being performed will be interrupted due to the patients not walking under their own weight.

### 2.4.21 Design Link 21: Lifespan of Unit

Our team has decided to construct our structure out of steel tubing and a steel H-Beam in the center to support the patient. Since our structure will never be used outside, the material being chosen does not need to have a high corrosion resistance. This allowed us to choose a cheaper steel but still have the structural integrity and durability that is required from our client.

### 2.4.22 Design Link 22: Adjustable Height

The proposed design meets the engineering requirement of having adjustable height by making the tether fit a variety of patients. The tether will be able to retract to the inside of the trolley. The tether at any given time will have a length of two to seven feet.

### 2.4.23 Design Link 23: Catching Time

Our proposed design includes a trolley mechanism that will lock the tether and lock the wheels once a certain force is applied onto the trolley. Once that force is applied, there is a mechanism inside the trolley that will immediately lock the wheels and tether to prevent any injuries to the patient.

### 2.4.24 Design Link 24: Motor Actuation Force

As stated above in design link 23, the trolley will contain a mechanism inside of it that will feel a force from the patient falling, then lock the wheels, and tether. The actual force that will need to be applied as well as the actual mechanism itself is yet to be determined.

### 2.4.25 Design Link 25: Tether Elasticity

Our team has selected a tether that will be made out of polyester to ensure when the tether is locked by the trolley mechanism, it does not injure the patient. The elasticity of the tether has not yet been determined, however, the breaking strength of the tether exceeds the force the patient will be applying to it.

### 2.4.26 Design Link 26: Frame Breaking Force

The overall structure will be made of steel, including the bolts, nuts, and washers being used to fasten the structure. Our team has yet to complete a finite element analysis on the structure to determine the stress in each beam. This process has not been completed because we are still trying to finalize a design with our client. Once the design is finalized, we will complete a full analysis on the structure to ensure the safety and reliability of it.

## *2.5 House of Quality (HoQ)*

The House of Quality in Appendix A: Figure 48 is an engineering tool used to define the relationship between customer requirements and the engineering requirements as well as other products on the market. Currently, our HoQ has the customer requirements with the client rated weight in a number of 1-5, the engineering requirements, and the strength of the relationship between engineering requirement and customer requirement. The compilation of the rankings and relationships yields a product of the absolute technical importance and relative importance.

# 3 EXISTING DESIGNS

Our team has conducted a variety of research to successfully re-engineer a support system for fall protection during gait studies. This type of system already exists in the marketplace, however, are very expensive and can be obstructive to the motion detection cameras.

## *3.1 Design Research*

Our team conducted research on several overall systems and subsystems found in a fall prevention support system. The four overall systems include Bioness Vector Support, SafeGait 360, Aretech Zero-G Gait and Balance Training System, and BioDex NxStep Unweighing System. These four devices range in how they operate, prevent a fall, and study gait. Our team focused mainly on ceiling track-mounted systems for our subsystems. The four subsystems include a stopping mechanism, track system, trolley, and a tether to connect to the patient. The user interface allows for easy operation and collection of gait analysis by the trainer. The trolley is used to catch the patient from falling but move with the patient when they are walking. The trolley will be mounted to the track system, which is then mounted to the ceiling to ensure a sturdy and reliable device. The tether is used to connect the patient to the trolley to prevent a fall. However, after further contact with our client, we were informed to switch from focusing on an overhead mounted system to a ground supported system. This is due to our client relocating to a different laboratory.

Our team did all of our research by utilizing the search engines such as Google. This allowed us to view a number of devices already in the market in a quick amount of time. The manufacturer's websites do not discuss the design portion of the device but rather the applications of their systems. The application details found on their websites helped us develop an idea of how we may want to alter their designs to suit our project needs better. For example, a portable system with many different members may block the view of the infrared motion detected cameras. To solve this, we may re-design it only to have one member connecting to the patient where the cameras are not located to not interfere with the gait studies. The following sections will discuss the four overall systems and four subsystems.

## *3.2 System Level*

To gain a better sense of how our team should design the system, research was conducted on existing systems currently on the market. Through research, we were able to find ideas from designs that could be incorporated into our design. The information below includes data on state of the art systems, which could prove useful in helping the team decide how we would like to construct and engineering our system.

### 3.2.1 Existing Design #1: Bioness Vector Support

The Bioness Vector Support (BVS) system is one of the supports that a physical therapy office might purchase. The BVS meets several of the Customer Requirements (CR) of ease to operate, un-weighted system, adjustable, weight support, and treadmill compatible. The BVS also does not meet highly important customer requirements of cost to build, durability, and minimal maintenance. Beginning with the strengths of the BVS system that meet the CR's is the weight capacity to hold up to 500 lbs. [4]. This model specification supersedes the maximum amount of weight required and could yield information on how our design can incorporate the same engineering designs to hold up to 300 lbs. Another detail of the BVS is the capability that it can be erected to run on an overhead track of five meters or more including over treadmills. The BVS can also adjust the amount of weight to withhold from the patient all with a touch of a button from a smartphone, tablet, and or computer [4]. This specification is useful to our project because of the CR to have zero tension in the tether attached to the harness. The tension in the line would interfere with the patient's ability to perform the therapy exercise correctly. Indirect link to tension is the comfortability of the design on the patient. The BVS system uses the adjustability of the chord length to accommodate the patient's unique body by allowing enough slack in the tether, not to be pulling on the harness, while also maintaining a slight tension to prevent minimal free fall and agile response to a falling patient.

While the Bioness Vector Support has many attributes that meet several of the customer requirements, there is also some design of the BSV that do not meet some of the CR's. The system cost of the BVS is ten times or more than the $2,500 project budget. While the BVS system is of high quality and has minimal maintenance, the support would require maintenance a special technician will be sent to perform the work necessary to repair or maintain the device. The repair could add additional cost to the overall ownership cost for the client. In our design, it will be important to ensure the support system will have less than minimal maintenance, if none at all, and could be maintained by any mechanically experienced personnel rather than a special technician.

*Figure 4: Bioness Vector Support [4]*

### 3.2.2 Existing Design #2: SafeGait 360

The SafeGait 360 is an interactive support system currently on the market that specializes in balance and mobility training. This system is composed of six major components- rail, actuator, harness, closed wireless system, patient management software, and hardware. The rail may be fixed from the ceiling and customized as a straight of full loop configuration, “U” or “J” shaped. This rail design accommodates for the facility space and requirements - such as treadmill accessibility. An actuator attached to the railing is “a stealth, state of the art support and tracking device that moves with the patient” [5]. Though an actuated patient tracking system is not necessary for our design, utilizing this type of technology will reduce the frictional resistance caused by the patient's connected movement, which is a customer requirement. Acceleration of the user matches the motion of the actuator, which helps the user keep balance and have the illusion of walking freely with confidence. The harness design was generated from therapists to maximize the patient’s comfort by introducing counter-uplifting forces with leg cuffs and straps around the torso. Next, the support system interacts within a closed wireless system that provides security, privacy, and connectivity. The closed wireless system ensures no other wireless signals will interfere with the rehabilitation device, minimizing the source of error. Another system component is the patient management software that uses a smart and user-friendly interface to manage patient statistical data and customize a care plan. Data gathered from the therapy sessions can detail summary of progress and export this progress in a chart format into the patient health records. Lastly, the hardware connects with this software with a mobile device, such as a phone or tablet for flexible control options.

Since safety is the ultimate goal for this system, four major device components are implemented - dynamic fall prevention (DFP), falling length limits, body weight support, and a horizontal lock.

Two of these functions are requirements for our design: falling length limits, body weight support. The dynamic fall prevention is software that can distinguish between a user's intentional movement downwards and when they are experiencing a fall. This software can adjust sensitivity levels of the patient at varying independence stages - low, medium, and high. The backup fall protection feature is a decent limiter that sets a maximum downward travel distance based on the patient's position and height. Having a backup fall preventing device is something to consider for the design of our support system to ensure safety. Another safety feature is the body weight support, which can adjust to unload the patient up to 50% of their weight at a 175-pound maximum. The final major safety feature is the horizontal lock that allows for vertical travel as desired for a steady place to anchor onto a treadmill or for push/pull training. In all, this system is an exemplary device that facilitates valuable patient/ therapist interaction in a modern, safe, and efficient environment.

*Figure 5: Safe Gait Support System [5]*

### 3.2.3 Existing Design #3: Aretech Zero-G Gait & Balance Training System

There are a handful of current commercial gait training systems on the market today. One of these systems is Aretech's Zero-G, displayed in Figures 6 and 7, which is a ceiling mounted track system that suspends the patient from an overhead robotic trolley. The technology integrated into this design is advanced in that it has an interactive data analysis system, which tracks a patient's gait and is displayed on an interface that both the patient and therapist can view. The Zero-G offers a wide range of patient diagnosis from spinal cord injury to cerebral palsy and has a weight range of 20-400lbs [3]. The Zero-G allows a variety of functionality allowing a patient to practice walking, balance-activities, postural tasks, sit-to-stand exercises, stair walking, and getting up off of the floor. The robotic trolley allows tracking of a patient at up to 6 mph and is offered in track sizes of up to 85 feet [3]. Tracks can be configured in straight, J-curved, U-curved, or customized options to permit installation in most facilities [3].

*Figure 6: Zero-G V.2 [3]*

*Figure 7: Zero-G V.2 [3]*

The Zero-G is a well-renowned system that incorporates requirements important to implement into our design. The overhead track system is of particular interest to our team, as our client wants to conserve as much space as possible within his research laboratory. A track configuration allows the system to keep up and out of the way of the floor space when not in use. Another component that the Zero-G includes which we are also considering incorporating in our design is a frictionless trolley, which lets the patient move freely wherever the track allows them too. Wide range patient compatibility is another important need of our client that the Zero-G utilizes in its design. The ability to offer a size range from child to adult is essential as research can be conducted on virtually any patient. Our client also requires that our design will have the ability to be used on a treadmill. Having an overhead suspension system like the Zero-G is vital because the tether in which the patient is strapped to can be retracted to allow for obstacles like stairs or a treadmill to be inserted under them. After conducting a thorough investigation into Aretech's Zero-G, there are multitudes of ideas our team may utilize in our design.

### 3.2.4 Existing Design #4: BioDex NxStep Unweighing System

Another design our team is interested in is the BioDex NxStep Unweighing System, which utilizes a mobile system to prevent patients from falling. This device can be used for patients who have had a spinal cord injury, stroke or traumatic brain injury, Parkinson's disease, older adults, amputation of a lower extremity, orthopedic patients, and much more [1]. This system allows for the user or therapist to select the amount of weight to take away from the patient and to raise or lower the height bar depending and the height of the patient. The weight load variation can be very useful because if someone has a very hard time holding their weight, this system can take up to 400 pounds to help the person start to walk with less weight on their legs [1]. The overhead bar is connected to the harness to allow for distribution of forces the patient may feel if they were to fall. The overhead bar is then connected to a tether at a single point. This system can be used with a treadmill to allow gait studies to occur without having the patient be constantly moving around the room. In this case, the patient can be in one place but still have movement. As a bonus, the system does come with two different therapist seats; one on either side of the system to allow for a comfortable working environment for the therapist while the patient is on the treadmill [1].

This system is a very important system to us for several reasons. First, the system can fit around a treadmill which is one constraint given to us by our client. Secondly, the system does not fill a lot of space within the room to hold the patient up in the event of a fall. A concern from our client was that if we were to build a mobile system, then it would interfere with the motion tracking cameras that are set up. The NxStep has very low interference with the motion-detected cameras due to the minimal number of members that make up the frame. Lastly, the system can hold a patient weighs up to 400 pounds. The weight limit we have been given is around 250-300 pounds to withstand. It would be in our best interests to break down this system and see exactly how it can withstand 400 pounds safely and how we can utilize that within our designs to hold 250-300 pounds.

## *3.3 Subsystem Level*

At a subsystem level, the general, existing designs can be decomposed into User Interface, Brake and Motor, Track, and Tether. Each of the subsystems is critical components that existing designs on the market apply different engineering designs. In this section is the result of research from the existing subsystems that could influence the future concept generation process. Along with the research is an analysis of the existing subsystems fulfillment of the customer requirements.

### 3.3.1 Functional Model

The functional model below in Figure 8 is a decomposition of the important functions our design must meet. The purpose of the model is to help the design team to understand as well as clearly display the complexity within the system that will be designed. The first function of the system is to bring in some source of electricity to supply to a motor. Our team decided that it would be important to include a motor to move the weight of the support system rather than the patient moving the support system. The benefit of having a motor would be that the comfort of the patient would increase as well as the compatibility to move 16.5 feet. The next function is the “Actuate Elect.” function. This function drives the system forward without requiring effort from the patient. It also sends a signal to the mechanism used to stop the patient from falling. The final important function is when the input of the human is when the patient is falling. In the event the patient falls, there are a function input and output to prevent this motion from continuing. This function is a motor or servo used to stop the patient from falling. The entire functional model is critical to the success of our team's design as it helps to direct integral functions of the design that need to meet the customer requirements.

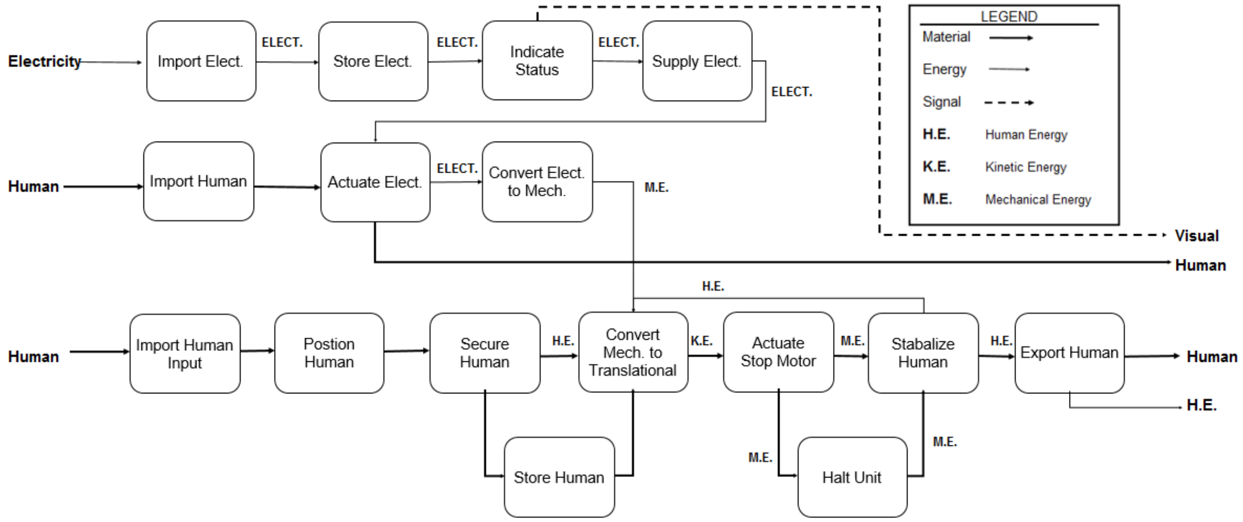


*Figure 8: Functional Model*

### 3.3.2 Subsystem #1: Stopping Mechanism

One of the most critical components of the system is the ability to stop a patient from falling. The stopping mechanism needs to satisfy the safety, reliability, durability, and cost customer requirements. Each of these requirements will help to ensure that the research of the human interfaces will contribute to future engineering concepts and design.

#### *3.3.2.1 Existing Design #1: Centrifugal Clutch Seat Belt System*

A common method used to bring a human body to a halt is the seat belt mechanism found in automobiles. This system is seen in Figure 9, works by a rotating ratchet gear with a clutch lever fastened to the outer edge that when a specific rotational velocity is achieved the clutch extends outward past the edge of the ratchet. When the clutch is extended this far, it catches a cam which actuates the pawl. The pawl is forced into the rotating ratchet, which then stops the rotation of the ratchet. The ratchet is attached to the spool from which the tether is unwound [6]. The strength of this system is in the reliability to stop a body in motion. The seat belt mechanism is also cost in a range from $100 - $200 range. The weakness of the system is that it will require some changes to use with children. Though the patients using the device will not be traveling as fast as those in vehicles, the centrifugal clutch system will still be a design from which our team can stem future ideas.

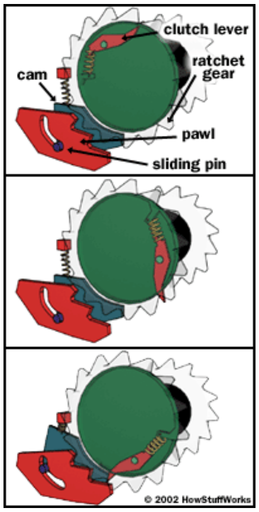


*Figure 9: Centrifugal Clutch [6]*

#### 3.3.2.2 Existing Design #2: Shock Absorber

An unconventional subsystem that can be used is a shock absorber. The shock absorber system seen in Figure 10 is a design used to reduced vibrations in vehicles or any mechanical system. How our team could use this system is by utilizing the shock absorbers ability to take kinetic energy and convert it into heat energy through compression of the hydraulic fluid in an extension cycle (system in tension) [7]. Rather than stopping the patient abruptly in a fall like in the previous centrifugal clutch subsystem, the shock absorber would slow the patients falling speed to a gradual velocity of around a few inches per second. The passive falling speed would allow the patient and or the accompanying therapist to catch or help the patient to avoid the high risk of falling injury. Hydraulic shocks can cost around $50 – $150 each, which would not be a burden on the project budget.

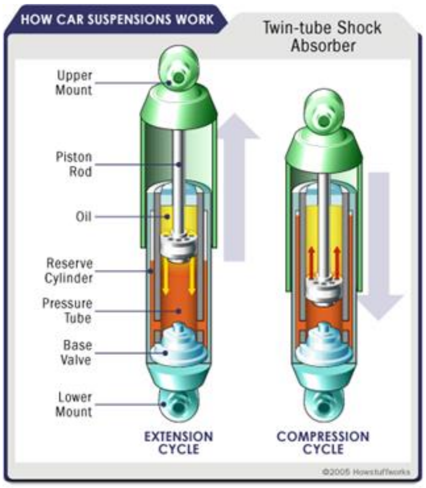


*Figure 10: Shock Absorber [7]*

#### 3.3.2.3 Existing Design #3: Spring Shock Absorber

A similar subsystem to the hydraulic shock absorber is the spring shock absorber. The spring shock works by the tension of each end of the shock, which then causes a compressive force on the spring. This system would slow a patient fall and bring them to a stopped position completely. The spring in the shock would also provide some relief to the patient bearing their weight after they have fallen, making it easier for the patient to regain their balance. Because of the simplicity of the shock absorber design, minimal maintenance would be required. Additionally, the shock absorber would be durable enough to handle the cycling of the patient weight. While the spring shock would not be adjustable, the project design would have to ensure that the shock could be interchangeable to work with varying weights. The reason it must be interchangeable is due to the spring being too stiff for lighter weights and would make it very uncomfortable for the patient when they fall.

*Figure 11: Spring Shock Absorber [8]*

### 3.3.3 Subsystem #2: Trolley

Using a track system requires a trolley to attach on the track, move smoothly along with a user's motion, and hold the weight of a person up to 500 pounds. There are three different trolley options to meet the needs of our system - geared, motorized, and push trolleys.

#### *3.3.3.1 Existing Design #1: Gear Trolley*

This type of trolley helps provide positive load positioning along the total beam that will fit most S-, W-, and I-Beams. The geared trolley is designed with baked enamel paint for protection and precision ball bearing wheels. A benefit to this all-steel construction with hardened axles and lubricated wheel design is its durability and wear resistance. The extra durability will help keep the system safe. Additionally, the geared trolley has an easy installation to hoists. Another benefit of this design is the precision provided by the hand chain gear system. This precision would help guide the user with confidence for the purpose of our system by manual adjustments made by the professional physical therapist. The hand gear system is also good because it does not require power equipment to do the work over straight or curved tracks. In all this is a reliable and efficient device to use for the trolley component [9].

*Figure 12: Geared Trolley [9]*

### 3.3.3.2 Existing Design #2: Motorized Trolley

The motorized trolley is described as durable, reliable, and powerful. This design has larger wheels than similar models, to maintain and withstand severe use at or near rated capacities. Additionally, this trolley is easily adjustable for a range of different beam widths big or small. The trolley is powered by TENV (Totally Enclosed, Not Ventilated) motor that is designed to ventilate but also prevents liquids and solids from entering the machine. This type of motor is also compatible with a remote control to hoist and move loads with a push of a button. Lastly, the motorized trolley can have added on features that will increase brake and gearbox life as well as reduce power consumption. This will be a good option for our design because of the adjustability and durability factors [10].

*Figure 13: Motorized Trolley [10]*

### 3.3.3.3 Existing Design #3: Push Trolley

The push trolley is the last option for the system, capable of 1/4 to 3-ton capacities. Included with the device are lifetime lubricated precision ball bearings that ensure minimal manual effort and limited maintenance. A specific push trolley from the company Chester Hoist is equipped with “eight duo-sealed Timken tapered roller bearings that absorb the radial and thrust loads exerted in [the] heavier sizes” [11]. This means a greater surface area of contact for the bearings and track that helps create a fluid motion with minimal friction. The stability and rigidity for the trolley come from the shaped heavy rolled steel side plates that extend beyond the wheels to behave as bumpers. Steel equalizing pins that provide smooth operation and load equalization connect the two halves of the trolley. The wheels of the trolley are long, made of cast iron, and have machined threads for extra smoothness for rolling motion. The axles in the side frame are made of steel for rigid support; also steel trolley blocks reinforce the side plates as well as equalize the pin. A push trolley design is beneficial to our system because it is free from a power source, has low friction, and a high weight capacity.

*Figure 14: Push Trolley [11]*

### 3.3.4 Subsystem #3: Track Configuration

In this subsystem, the track is one of the parts that has infinite designs and options. From rails to beams, the selection of the right track is critical to meeting requirements of cost, durability, safety, reliability, and minimal maintenance. The research of existing designs shows tracks that are found in industrial applications to support systems.

#### *3.3.4.1 Existing Design #1: Rollon Linear Rail Systems*

Rollon Linear Evolution’s compact rail systems are track configurations available in T, K, and U profiles made from 100Cr6-hardened steel [12]. These tracks, seen in Figures 15-16, are designed for applications in aerospace, medical, railways, automation, industrial machinery, and logistics. The tracks consist of induction hardened raceways and high precision radial ball bearing sliders that are affordable and easy to install on all types of surfaces including non-machined surfaces. They have two slider types: N-series aluminum die-cast bodies and C-series with steel bodies. The sliders are resistant to dirt and other forms of debris and include lubricated-for-life bearings. Technical features include max operating speed of 9 m/s, max acceleration of 20 $m/s^2$, and a max radial load capacity of 15,000 N (337 lbs.) [12]. These track systems also allow for adjustable preload.

Figure 15: Rollon Track [12]

Figure 16: Rollon Slider [12]

### 3.3.4.2 Existing Design #2: I – Beam

Another form of track structure that may be suitable for our design is an I-beam. I-beams are available in a wide range of sizes and materials such as aluminum and steel. An I-beam can be a simple solution for a track to mount a trolley on as they are capable of supporting heavy loads and can be machined for a close to the frictionless surface for wheels or roller bearings to move along. Although there is a tendency for I-beams to be expensive, they are capable of meeting our client's need of being able to support a max patient weight of 300lbs.

Figure 17: I - Beam [13]

### 3.3.4.3 Existing Design #3: Box Sliding Rail

Real Sliding Hardware is a company that produces industrial grade sliding hardware. Their typical system consists of a rail trolley that moves inside of a box rail track. Real Sliding Hardware, found in Figure 18, has designed their box rails to be used in exterior or interior applications and are formed out of galvanized or stainless steel that can be powder-coated to customer specifications. If a personalized order is requested, Real Sliding Hardware can be manufactured to custom track lengths and applications. Kit sizes are available in a range of 6-50 feet with their strongest box rail being capable of supporting 800 lbs. [14].

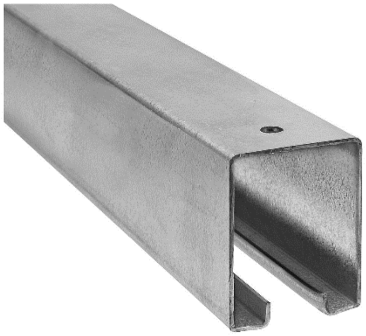


Figure 18: Box Rail [15]

A box rail track could function as a useful design to base our trolley mechanism off within our system. With steel as a structural base for supporting the patient, the integrity of a box rail track will meet our client's requirements of safe and reliable. The ability for application customization may also be helpful in fulfilling our client's requirement of a low profile and non-reflective track system.

### 3.3.5 Subsystem #4: Tether Material

Support systems, such as Bioness, or Areteck, use a different material to secure the patient to the support system overhead. The selection of material is important because of the repeated stress that will be put on the tether during normal use. Existing tether uses to support patient's o from synthetic polymers to metallic cables. The tether is also an important part of meeting the safety, reliability, and durability requirements.

#### *3.3.5.1 Existing Design #1: Double Braided Nylon Rope*

There are several materials one can use to keep a person from falling. One of these materials is a double braided nylon rope that can come in a variety of sizes to withstand a range of tensile strengths. For example, a size of ¼-inch thick double braided nylon rope has a tensile strength of 2,200 pounds on average [16]. For our project, we will first need to calculate the max amount of force that will be exerted by the patient onto the tether to know what thickness our tether will need to be. The double braided nylon rope distributed by Knot and Rope Supply come in thickness from ¼ inch to 1 inch where the one inch has a tensile strength of 26,000 pounds on average [16].

#### *3.3.5.2 Existing Design #2: 7x19 Grade 304 Vinyl Coated Stainless Steel Cable*

Another option for a material being used as a tether would be a stainless-steel cable coated with vinyl. This type of cable will be able to support on average from 350-1800 pounds depending on the thickness of the cable [17]. The vinyl coated stainless steel cable will provide less friction on the trolley making it easier for the patient to walk with the tether attached. If the tether cable were to have a high frictional force going against the patient, the patient will have a harder time walking and will affect the gait analysis. The stainless-steel cable in Figure 19 also has high flexibility, corrosion resistance, and abrasion resistance. The flexibility will become very useful in our design, as we do not want a tether that is extremely tight on the patient because if the patient were to fall, the force from the cable onto the patient would be enormous, possibly causing injury. The image below is an example of 5/16 inch, 7x19 Grade 304 Vinyl Coated Stainless Steel Cable.

*Figure 19: Vinyl Coated Stainless Steel Cable [17]*

#### *3.3.5.3 Existing Design #2: Antenna Support Rope*

Antenna support rope manufactured from Synthetic Textile Industries is a cheaper, yet very strong material a tether. The diameter of the rope is 5/16 inches with a breaking strength of approximately 1,790 pounds [18]. Antenna support rope is made from double braided polyester rope to ensure the reliability and durability of the system. This rope is distributed from DX Engineering and costs about $25 for 100 feet, which is more than enough for our application [18].

*Figure 20: Antenna Rope [18]*

# 4 Designs Considered

This section covers eleven different designs created and considered by the team to best fulfill the customer requirements. Each design also divides to its subsystems for a functional decomposition. These considerations provide assistance in further analysis for deciding advantages and disadvantages of the overall system.

## 4.1 Design #1: Ground Supported Vehicle Suspension

The vehicle suspension is a collaboration of a vehicle suspension design and a bio frame design from a tree. From the bio-inspired side, the support frame in Figure 21, which looks like a large “Y,” is mimicking a tree from the base to the main branches. At the ends of the branches is where the vehicular inspired design is introduced by the suspension system. The suspensions system is based on an interchangeable spring shock suspension that is compressed when under tension. This would allow a patient to fall, but at a steadily declining rate until reaching zero velocity. The patient would not be allowed to fall to the ground, but only to free fall a short distance to reduce whiplash. The system also has lasers located near the wheels. These lasers are sensors to detect when the patient's feet have crossed the front of the system (Indicated by the dotted line in Figure 21, which then actuates the motor (powered from the onboard battery) and moves the system forward half a foot. This operation is intended to remove the weight of the system being carried by the patient. The design also includes a remote for the therapist to control the speed of the motor manually so that the design can move around the room with or without the patient.

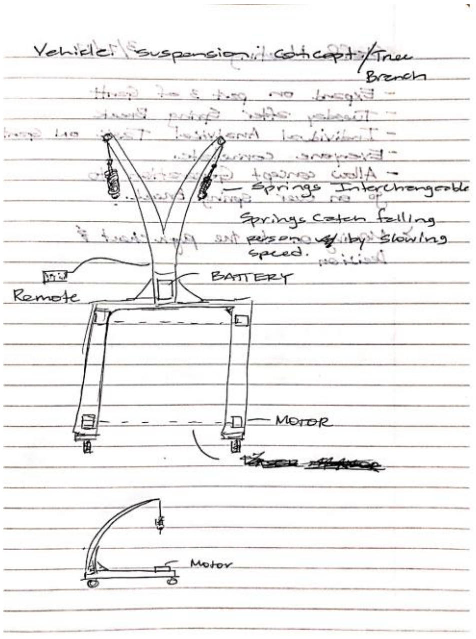


*Figure 21: Ground Supported Vehicle Suspension*

*Table 4: Ground Supported Vehicle Suspension*

| Advantages | Disadvantages |
|---|---|
| System moves its weight rather than relying on patient to move | Higher cost of motor, suspension, and sensors |
| Adjustable motor speeds | Requires charging |
| Interchangeable shocks | Higher maintenance from motor suspension |

## 4.2 Design #2: Ground Support Hanging Fruit

Another bio-inspired design is the hanging fruit design based on how a tree supports a fruit, such as an apple, orange, and lemons. These kinds of fruits that hang from the branches are hanging from thin stems that lead to the major supporting branches. The design uses this technique of nature by using a single stem or supporting beam seen in Figure 22. The design uses a motor, powered by an onboard battery, to provide the necessary length of the tether. Attached to the motor is a ratchet gear that stops when in contact with a key. A spring sensor at the top of the support frame actuates the key. When the spring is compressed too far, from the weight of the patient falling, it triggers the sensor and then actuates the key to stop the ratchet to prevent the spool from unwinding. When the spool is prevented from rotating the patients fall is stopped in a short distance and time. The design also uses a pulley system with a hydraulic press to adjust the tension in the tether. Lastly, the hanging fruit design uses sensors at the front of the ground portion of the frame to actuate the motors on the wheels to move forward the desired distance according to the patient's speed.

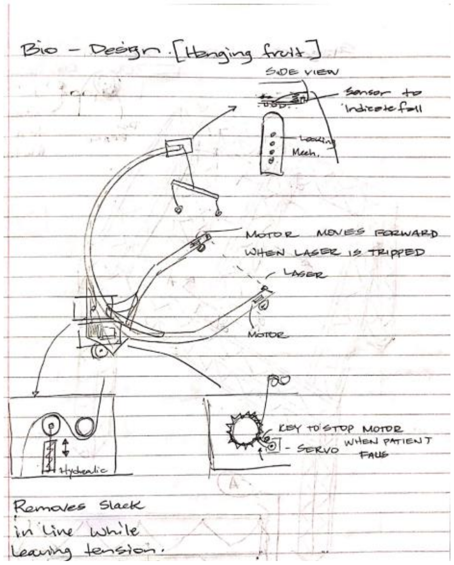


*Figure 22: Ground Support Hanging Fruit*

*Table 5: Ground Support Hanging Fruit*

| Advantages | Disadvantages |
|---|---|
| Cost to build is feasible under the current budget | Maintenance for motor, hydraulic, and sensors |
| System moves its weight rather than relying on patient to move | Requires charging for battery |
| Adjustable speed and tether length | |
| Safety stopping mechanism | |

## 4.3 Design #3: Overhead Aluminum Truss

The aluminum truss design in Figure 23 is based on event staging. This type of overhead track system allows the client to collapse the entire structure to make the unit mobile to another location. The aluminum trusses are similar to building blocks and can be customized to a new room with different dimensions. The center overhead truss also can move on rollers across a track allowing the client to maximize use around the room. Underneath the center truss is the track on which the support system rolls freely (seen in lower half of Figure 23). This setup allows the user the capability to move in an x - y plane. Within the support system is a motor used to retract and loosen the length of the tether. Another motor is used to drive the support system along the track. The buildings AC Voltage supply power each motor. The tether coming off the spool runs over a pressure spring sensor which if compressed too far actuates a disc brake attached to the spool and preventing the patient from falling.

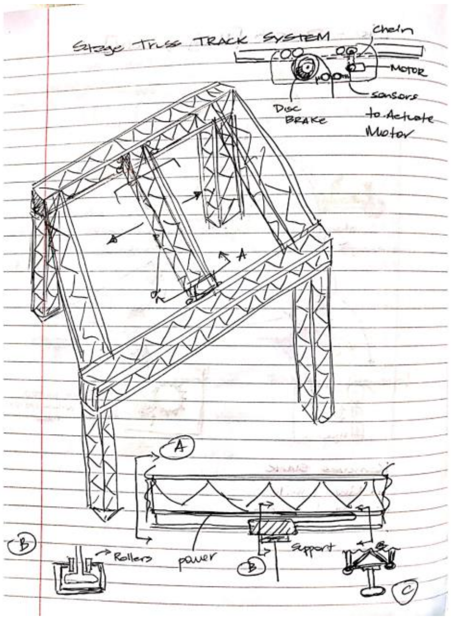


*Figure 23: Overhead Aluminum Truss*

*Table 6: Overhead Aluminum Truss*

| Advantages | Disadvantages |
|---|---|
| Maximizes use of space in a room | Requires power from local source |
| Ability to be collapsed and reconstructed | Higher maintenance |
| System moves its weight rather than relying on patient to move | Higher cost because of extra materials |

## 4.4 Design #4: Mobile Overhead Arches

This design incorporates arches to support a mobile track system. The first considered subsystem is the arch structure attached to the center I-beam that allows for a sturdy system that allows movable clearance to station over a treadmill. The arches are designed in a truss manner and the material considered is some aluminum or steel to ensure stability. The I-beam is a minimum length of five meters, so the user has this amount of length to move at a minimum. A push trolley is attached to the overhead I-beam with frictionless bearings that allow the user to have effortless fluid motion. The trolley is equipped with long cast iron wheels with machined threads as well for extra smooth rolling motion. A harness attaches to the trolley with a tether to the fall protection device that sets a falling length on the size of the user. The tether will have an elastic quality to better brace the fall as well. The last subsystem includes the rollers that the entire system rests on that allows mobility around the room. The roller tracks are designed to run parallel with the support I-beam, and wide enough to fit over a range of treadmills while retaining mobility. Once the structure is in its desired position, the rollers are lockable to keep the entire structure set in position. Listed below are the advantages and disadvantages of this mobile arch design concept.

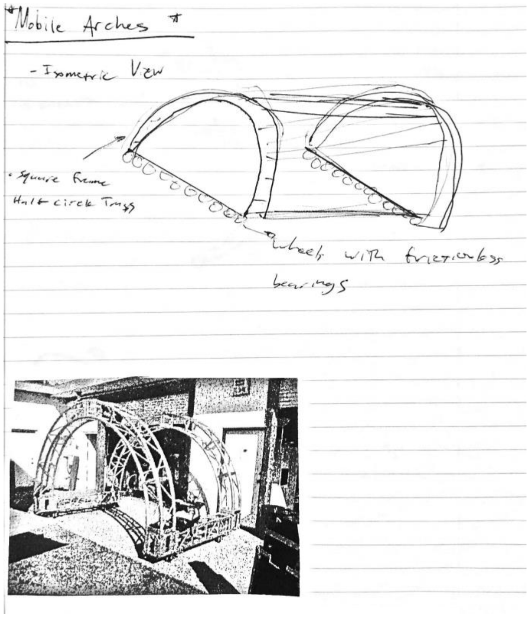


Figure 24: Mobile Overhead Arches

Table 7: Mobile Overhead Arches

| Advantages | Disadvantages |
|---|---|
| Easy to operate | Reliability |
| High safety | Tension on patient |
|  | One direction user mobility |

## 4.5 Design #5: Triangle Beam

The triangle beam is a design concept that contains an overhead support built on wheels for mobility. The system structure incorporates square truss supports in the shape of triangles at each end that connects a triangle truss beam for the overhead support. The overhead cable track is a minimum length of five meters and attaches to the overhead triangle truss beam with tension rods. Having a single cable for the track helps reduce the friction created by the user's movement because of its lightweight. The user will connect to the overhead support simply with a harness connected to a fall protection tether device. This fall protection device is set at a fall height adjustable to the user's size, and the tether is made with an elastic ratio to help brace the fall. The system rests on top of low friction, lockable, low profile wheels tracked to run horizontally with the cable track, and the width of these tracks is large enough to fit over the desired treadmill. The low profile wheels can lock with a flip of a switch that can be kicked or tapped by a foot to activate.

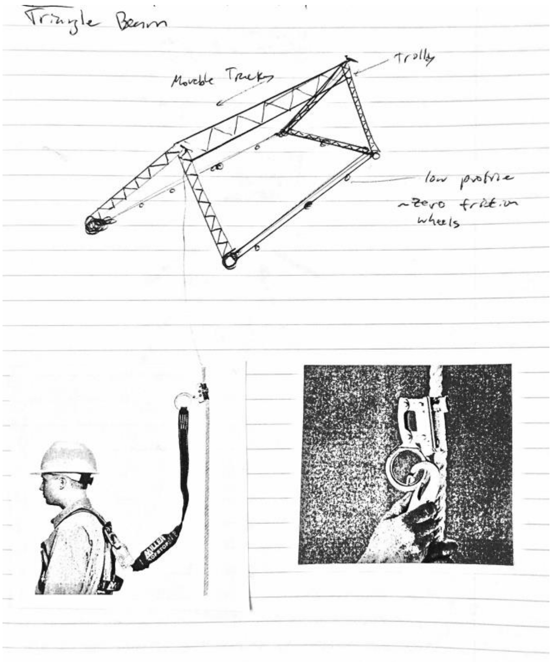


*Figure 25: Triangle Beam*

*Table 8: Triangle Beam*

| Advantages | Disadvantages |
|---|---|
| Low cost to build | Obstructive |
| Minimal tension | Durability |
| Mobility | |

## 4.6 Design #6: Semicircle Base Support

This considered design has a semicircle as a base inspired by a boxing bag holder. The first subsystem to consider is the semi circle base that must be wide enough to fit the designated treadmill and sturdy enough to have three bending supports that link the overhead support. Three supports attach to the base; one directly in the middle of the semi circle base and the other two to the left and right. These supports are designed to be flexible enough to bend with a user's fall to help brace the fall impact. All three of these supports rise vertically then curve to meet in one place overhead that creates a junction to attach the hanging fall protection device. The fall protection device is a simple tether system that can adjust to the size of the user, and the tether is chosen to have an elastic value to help brace the fall for comfortability purposes. The whole structure rests on low profile wheels that allow a wide range of motion as well as capable of locking in place if necessary. Overall, this design has minimal parts, which will help keep the cost low.

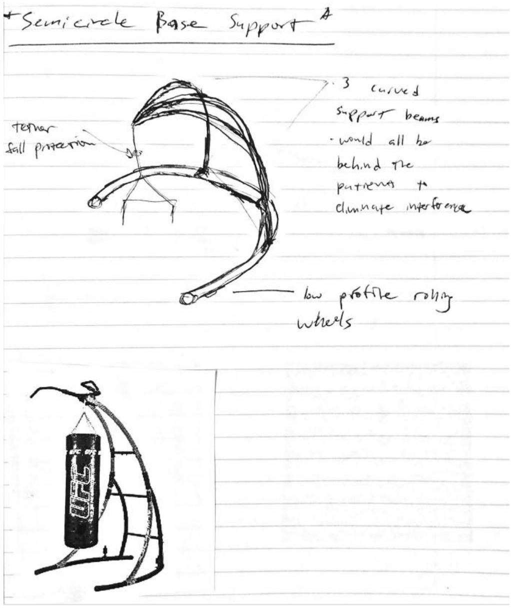


*Figure 26: Semicircle Base Support*

*Table 9: Semicircle Base Support*

| Advantages | Disadvantages |
|---|---|
| Low cost to build | Durability |
| Mobility | Tension on the user |
| Safety | |

## 4.7 Design #7: Ground Supported Mobile Frame Type 1

To meet our client's requirement of a portable system our team came up with several different concepts of ground supported mobile frame. This particular design consists of steel tubing once again to form the frame itself; however, the orientation of this system differs from design seven in that it has more components. The frame will have two base pieces of the same dimensions to create a heavier system. The extra weight will provide better resistance against the force from the patient during a fall. This is a key component, as the system will not tip over during a fall ensuring the safety of the patient. This system will utilize a vertical support column with a horizontal beam to hoist the tether just like design seven. The benefits of this style of the system are that it is on wheels so it can be rolled to wherever it is needed within the lab, it is durable and long lasting, and most of all it is very safe regarding fall protection. These benefits outweigh the disadvantages and meet nearly all of our client's requirements.

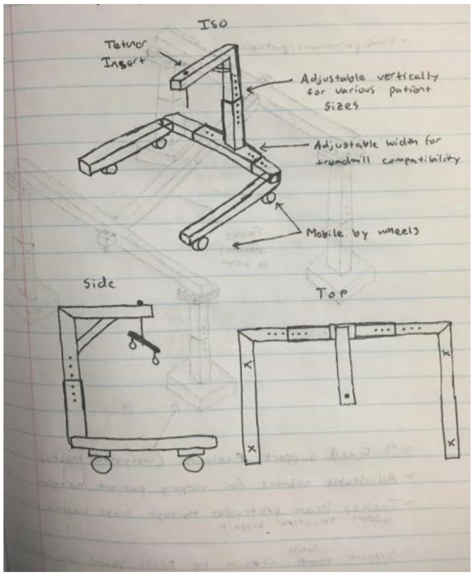


*Figure 27: Ground Supported Mobile Frame Type 1*

*Table 10: Ground Supported Mobile Frame Type 2*

| **Advantages** | **Disadvantages** |
|---|---|
| Safe system | Requires force from patient |
| Mobile/portable | Will exceed allotted budget |
| Treadmill compatible | Obstructive to motion detection cameras |
| Vertically adjustable | Bulky |

## 4.8 Design #8: Column Supported Overhead Track System

Another form of design our team will possibly pursue is an overhead track mounted system. Within this design, the goal is to utilize the entire laboratory our client has available to mount an overhead beam to suspend the patient. Having a beam mounted overhead allows the system to be out of the way of the motion detection cameras our client needs to track the gait of his participants. The track will be the main component of the system as it allows for the use of a trolley in which the patient can be hoisted. This system will have four vertical columns located in each corner of the laboratory. Fastened to the vertical columns will be two beams that span the length of the facility. These beams will support the cross member that houses the track component of the system. Attached to the track will be a trolley that will control how much tether needs be extended to allow for a multitude of patient sizes and will be designed to halt if a patient happens to fall. The trolley is a mobile component that will move along with the patient as they practice their gait within the lab. Having an overhead track makes it easy for the system to be compatible with a treadmill. Our client requires that our fall protection system is capable of being mobile, can allow varying patient sizes, and most importantly protects the patients from injuring themselves when practicing their gait. The column supported overhead track system meets all of these requirements.

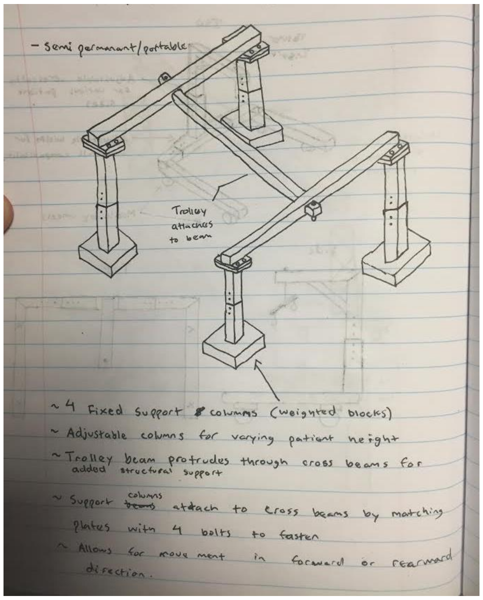


*Figure 28: Column Supported Overhead Track System*

*Table 11: Column Supported Overhead Track System*

| Advantages | Disadvantages |
|---|---|
| Non-obstructive to motion detection cameras | Will exceed the allotted budget |
| Treadmill compatible | Requires long assembly time |
| Allows for varying patient sizes | Centered in middle of laboratory |
| Ability to traverse over 5m | Not very portable |

## 4.9 Design #9: Ground Supported Mobile Frame Type 2

To meet as many of our client's requirements, our team developed multiple ground-supported systems. One of these is a ground supported mobile frame, which utilizes steel tubing formed into a U-shaped base with a vertical column that supports a beam at the top end to hoist the patient. The base incorporates wheels designed to be as frictionless as possible to provide the least amount of resistance from the patient to initiate its movement. Having a beam that expands horizontally from the top of a vertical column allows the patient to be suspended from a tether attached to it. In the case of a fall, the force the patient exerts on the tether will be driven through the horizontal beam into the rest of the frame. The frame will be designed to counteract the force from a fall and keep the patient safe from injury. The ground supported mobile frame will have adjustable legs horizontally and vertically to allow varying patient sizes as well as the ability to fit through a doorway while still being compatible with a variety of treadmill sizes. This adjustability, as well as the ability to be portable and mobile, are all requirements of our client.

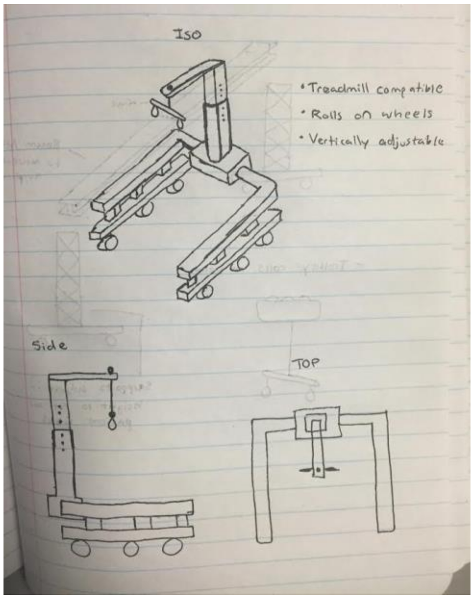


*Figure 29: Ground Supported Mobile Frame Type 2*

*Table 12: Ground Supported Mobile Frame*

| Advantages | Disadvantages |
|---|---|
| Treadmill compatible | Force required from patient to move |
| Ability to travel at least 5m | May exceed budget allotted |
| Vertically/Horizontally adjustable | Will take up space within facility |
| Portable system | Possibly obstructive to motion detection cameras |

## 4.10 Design #10: Frame Ground Support

The frame ground support design includes a frame around the patient. The system will include a set of locking wheels, sturdy frame construction, and a tether mechanism above the patient. The locking wheels allow for movement of the system around the room as the patient is walking but will lock up when the patient exerts a certain force on the system if they were to fall. If the patient were to fall, the system would not continue to roll potentially causing further injury to the patient. The two side members of the frame will extend vertically from the center of the bottom members with four ribs to prevent bending of the vertical members. The top member will then connect to the vertical members and will house the tether mechanism. The tether mechanism will act similar to the locking wheels by locking the tether when the patient exerts a certain force on the system.

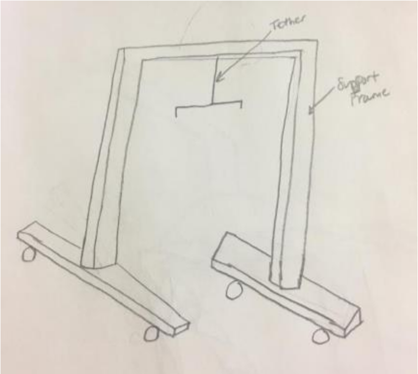


*Figure 30: Frame Ground Support*

*Table 13: Frame Ground Support*

| Advantages | Disadvantages |
|---|---|
| Portable | No Vertical/Horizontal Adjustments |
| Treadmill Compatible | Obstructive to side cameras |

## 4.11 Design #11: Adjustable Ground Support

This design is a ground-supported system, which includes a weighted back end to resist the moment on the support arm if the patient falls. It has the same locking wheels mechanism as described in the previous concept, however, due to the weight, there will be more wheels below the horizontal members to distribute the force from the weight better. The legs of the system below the weight and the member above the weight where the support arm connects will be vertically adjustable to make the system fit a variety of heights. The support arm will extend outwards from the vertical members with the tether mechanism attached at the end. The tether will then protract from the mechanism down to the patient and will connect to the patient’s harness.

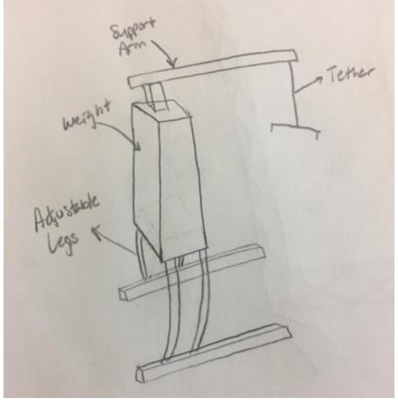


*Figure 31: Adjustable Ground Support*

*Table 14: Adjustable Ground Support*

| Advantages | Disadvantages |
|---|---|
| Portable | Obstructive to rear cameras |
| Treadmill Compatible | More weight on patient |
| Vertically Adjustable | Heavy |
| Resists Moment on Support Arm | |

# 5 Design Selected

The purpose of this section is to highlight the highest rated design generated through the completion of decision matrices and Pugh matrices conducted by the team.

## *5.1 Rationale for Design Selection*

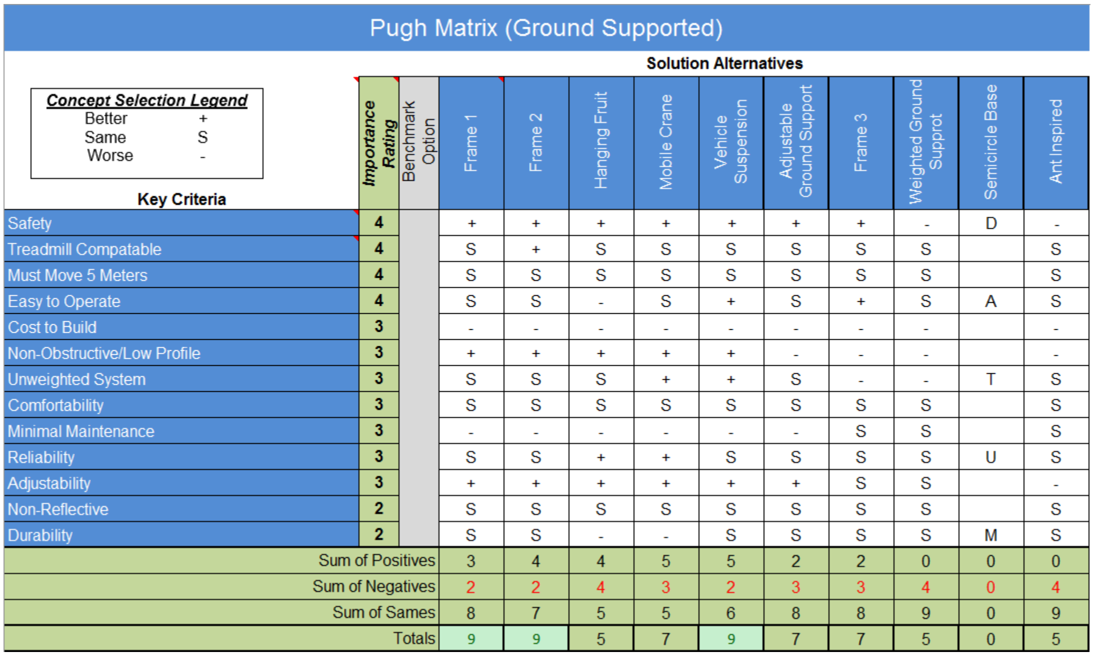
Through arduous execution of decision and Pugh matrices of our various concepts, we initially agreed that we would pursue design seven, the ground supported mobile frame. Our selection of design seven came from its high scores within our tests against the other options. The ground supported mobile frame has appealing attributes such as its adjustability, mobile configuration, as well as high level of safety. This fall protection device meets, and in certain circumstances, exceeds our customer's requirements. This device is capable of moving at least 5 meters, can function with multiple types of treadmills, and is capable of supporting varying patient types. However, after presenting these concepts with our client, he decided to combine multiple concepts. Our client is interested in an overhead support system that can span across the laboratory and that can be rolled to different locations. The concepts we have combined are concepts 7 and 8. The system will also include more structural braces to ensure the safety and reliability of the overall system. Using metal for the majority of parts is going to make this device strong and long lasting under continual use.

### 5.1.1 Pugh Matrices

The following sections outline the matrices used to narrow down the concepts to one ground supported system and one overhead system. Our team decided to decide on one of each type of system due to not knowing if our client will be relocating in the future.

### 5.1.1.1 *Ground Supported Systems*

Figure 32 shown below, displays the Pugh matrix for our ground supported design concepts. The datum for the matrix is the semi circle base for which all other designs were correlated against on a plus, same, or minus scale. If the design got a plus, then that design performs better in that category than the datum. If it got a same, then it performed the same in that category. If the design got a minus, then the design performs worse than the datum design. The top three designs that rated the highest are Frame 1, Frame 2, and the Vehicle Suspension. These designs were then put into a decision matrix to obtain the best design.



Pugh Matrix (Ground Supported)

***Concept Selection Legend***

| | |
|---|---|
| Better | + |
| Same | S |
| Worse | - |

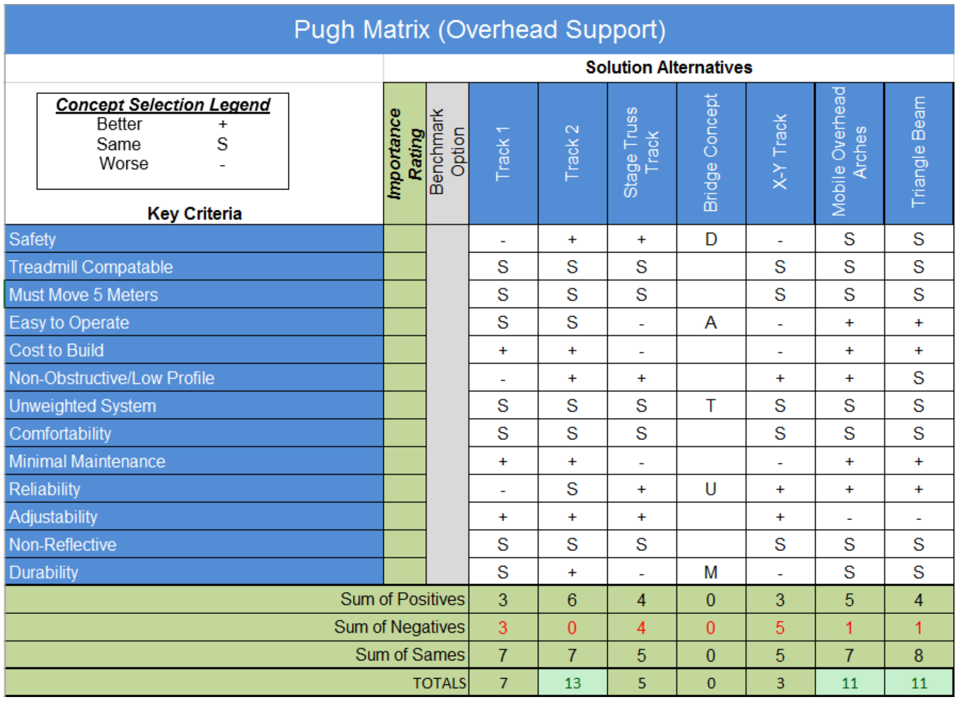
Solution Alternatives

| Key Criteria | ***Importance Rating*** | Benchmark Option | Frame 1 | Frame 2 | Hanging Fruit | Mobile Crane | Vehicle Suspension | Adjustable Ground Support | Frame 3 | Weighted Ground Supprot | Semicircle Base | Ant Inspired |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Safety | **4** | | + | + | + | + | + | + | + | - | D | - |
| Treadmill Compatable | **4** | | S | + | S | S | S | S | S | S | | S |
| Must Move 5 Meters | **4** | | S | S | S | S | S | S | S | S | | S |
| Easy to Operate | **4** | | S | S | - | S | + | S | + | S | A | S |
| Cost to Build | **3** | | - | - | - | - | - | - | - | - | | - |
| Non-Obstructive/Low Profile | **3** | | + | + | + | + | + | - | - | - | | - |
| Unweighted System | **3** | | S | S | S | + | + | S | - | - | T | S |
| Comfortability | **3** | | S | S | S | S | S | S | S | S | | S |
| Minimal Maintenance | **3** | | - | - | - | - | - | - | S | S | | S |
| Reliability | **3** | | S | S | + | + | S | S | S | S | U | S |
| Adjustability | **3** | | + | + | + | + | + | + | S | S | | - |
| Non-Reflective | **2** | | S | S | S | S | S | S | S | S | | S |
| Durability | **2** | | S | S | - | - | S | S | S | S | M | S |
| Sum of Positives | | | 3 | 4 | 4 | 5 | 5 | 2 | 2 | 0 | 0 | 0 |
| Sum of Negatives | | | 2 | 2 | 4 | 3 | 2 | 3 | 3 | 4 | 0 | 4 |
| Sum of Sames | | | 8 | 7 | 5 | 5 | 6 | 8 | 8 | 9 | 0 | 9 |
| Totals | | | 9 | 9 | 5 | 7 | 9 | 7 | 7 | 5 | 0 | 5 |

*Figure 32: Ground Support Pugh Matrix*

### 5.1.1.2 *Overhead Systems*

The Pugh matrix for the overhead support systems is shown below in Figure 33. The datum of the matrix is the Bridge Concept. The other six designs were rated based off this design on a plus, same, or minus scale. The top three overhead support systems from the Pugh matrix are Track 2, Mobile Overhead Arches, and Triangle Beam. These three designs were then put into a decision matrix to determine the best overall overhead system.



Pugh Matrix (Overhead Support)

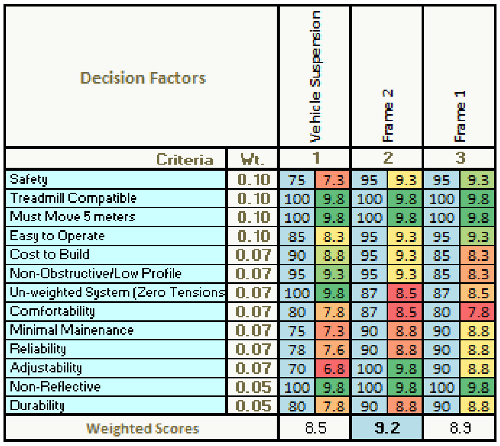
***Concept Selection Legend***
Better +
Same S
Worse -

| Key Criteria | Importance Rating | Benchmark Option | Track 1 | Track 2 | Stage Truss Track | Bridge Concept | X-Y Track | Mobile Overhead Arches | Triangle Beam |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Solution Alternatives** | | | | | | |
| Safety | | | - | + | + | D | - | S | S |
| Treadmill Compatable | | | S | S | S | | S | S | S |
| Must Move 5 Meters | | | S | S | S | | S | S | S |
| Easy to Operate | | | S | S | - | A | - | + | + |
| Cost to Build | | | + | + | - | | - | + | + |
| Non-Obstructive/Low Profile | | | - | + | + | | + | + | S |
| Unweighted System | | | S | S | S | T | S | S | S |
| Comfortability | | | S | S | S | | S | S | S |
| Minimal Maintenance | | | + | + | - | | - | + | + |
| Reliability | | | - | S | + | U | + | + | + |
| Adjustability | | | + | + | + | | + | - | - |
| Non-Reflective | | | S | S | S | | S | S | S |
| Durability | | | S | + | - | M | - | S | S |
| Sum of Positives | | | 3 | 6 | 4 | 0 | 3 | 5 | 4 |
| Sum of Negatives | | | 3 | 0 | 4 | 0 | 5 | 1 | 1 |
| Sum of Sames | | | 7 | 7 | 5 | 0 | 5 | 7 | 8 |
| TOTALS | | | 7 | 13 | 5 | 0 | 3 | 11 | 11 |

*Figure 33: Overhead Support Pugh Matrix*

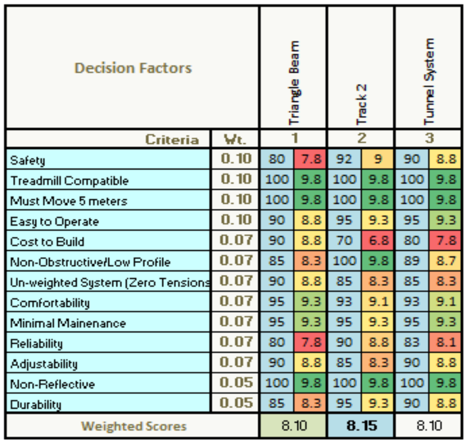
### 5.1.2 Decision Matrices

With our top three design concepts generated from our Pugh Carts our team then conducted a decision matrix to clarify the top design for both the ground supported (Figure 34) and overhead track systems (Figure 35). To construct a decision matrix, our team took our customer requirements and ranked them against each of the concepts from 1-100. A score of 100 means that the concept perfectly supports the requirements and a score of one means that the concept fails to support the requirement. Weights of importance relating to the customer requirements were then generated to multiply by the rankings. The final weighted scores were the determining factors in which design we selected to pursue for our project. To make the matrices easier to follow, our team color coordinated the answers. Green means that the concept ranked high in its ability to work with the customer requirements and red means the concept did not rank well regarding the requirements. For Frame 2 in the ground supported decision matrix, our team has decided to redesign the trolley/tether mechanism to reduce the force put onto the patient to better meet the requirement of un-weighted system. For the Track 2 concept in our overhead decision matrix, our team has found the materials needed to construct this system from other suppliers to decrease the cost of the overall system. For the ground-supported system, our top ranked design concept was Frame Design 2: Ground Supported Mobile Frame Type 2. For the overhead track system, our top ranked design concept was Track 2: Column Supported Overhead Track System.



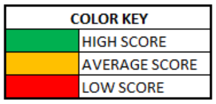
| Decision Factors | | Vehicle Suspension | | Frame 2 | | Frame 1 | |
|---|---|---|---|---|---|---|---|
| Criteria | Wt. | 1 | | 2 | | 3 | |
| Safety | 0.10 | 75 | 7.3 | 95 | 9.3 | 95 | 9.3 |
| Treadmill Compatible | 0.10 | 100 | 9.8 | 100 | 9.8 | 100 | 9.8 |
| Must Move 5 meters | 0.10 | 100 | 9.8 | 100 | 9.8 | 100 | 9.8 |
| Easy to Operate | 0.10 | 85 | 8.3 | 95 | 9.3 | 95 | 9.3 |
| Cost to Build | 0.07 | 90 | 8.8 | 95 | 9.3 | 85 | 8.3 |
| Non-Obstructive/Low Profile | 0.07 | 95 | 9.3 | 95 | 9.3 | 85 | 8.3 |
| Un-weighted System (Zero Tensions | 0.07 | 100 | 9.8 | 87 | 8.5 | 87 | 8.5 |
| Comfortability | 0.07 | 80 | 7.8 | 87 | 8.5 | 80 | 7.8 |
| Minimal Mainenance | 0.07 | 75 | 7.3 | 90 | 8.8 | 90 | 8.8 |
| Reliability | 0.07 | 78 | 7.6 | 90 | 8.8 | 90 | 8.8 |
| Adjustability | 0.07 | 70 | 6.8 | 100 | 9.8 | 90 | 8.8 |
| Non-Reflective | 0.05 | 100 | 9.8 | 100 | 9.8 | 100 | 9.8 |
| Durability | 0.05 | 80 | 7.8 | 90 | 8.8 | 90 | 8.8 |
| Weighted Scores | | 8.5 | | **9.2** | | 8.9 | |

*Figure 34: Ground Supported Decision Matrix*



| Decision Factors | | Triangle Beam | | Track 2 | | Tunnel System | |
|---|---|---|---|---|---|---|---|
| Criteria | Wt. | 1 | | 2 | | 3 | |
| Safety | 0.10 | 80 | 7.8 | 92 | 9 | 90 | 8.8 |
| Treadmill Compatible | 0.10 | 100 | 9.8 | 100 | 9.8 | 100 | 9.8 |
| Must Move 5 meters | 0.10 | 100 | 9.8 | 100 | 9.8 | 100 | 9.8 |
| Easy to Operate | 0.10 | 90 | 8.8 | 95 | 9.3 | 95 | 9.3 |
| Cost to Build | 0.07 | 90 | 8.8 | 70 | 6.8 | 80 | 7.8 |
| Non-Obstructive/Low Profile | 0.07 | 85 | 8.3 | 100 | 9.8 | 89 | 8.7 |
| Un-weighted System (Zero Tensions | 0.07 | 90 | 8.8 | 85 | 8.3 | 85 | 8.3 |
| Comfortability | 0.07 | 95 | 9.3 | 93 | 9.1 | 93 | 9.1 |
| Minimal Mainenance | 0.07 | 95 | 9.3 | 95 | 9.3 | 95 | 9.3 |
| Reliability | 0.07 | 80 | 7.8 | 90 | 8.8 | 83 | 8.1 |
| Adjustability | 0.07 | 90 | 8.8 | 85 | 8.3 | 90 | 8.8 |
| Non-Reflective | 0.05 | 100 | 9.8 | 100 | 9.8 | 100 | 9.8 |
| Durability | 0.05 | 85 | 8.3 | 95 | 9.3 | 90 | 8.8 |
| Weighted Scores | | 8.10 | | **8.15** | | 8.10 | |

*Figure 35: Overhead System Decision Matrix*



| COLOR KEY | |
|---|---|
| 🟩 | HIGH SCORE |
| 🟨 | AVERAGE SCORE |
| 🟥 | LOW SCORE |

## 5.2 *Design Description*

The proposed design will include a steel structure, trolley, and tether. The steel structure will be composed of support columns, crossbeams, and a centralized track beam. The support columns and cross beams will be constructed out of A500 Grade B Steel square tubing while the track beam will be composed of an A992 Structural Steel H-Beam. To join the crossbeams and columns together, there will be structural trusses to decrease deformation in the track beam. The trolley will be attached to the track beam and will move freely across via nearly frictionless bearings. The tether will be retractable inside the trolley to account for a variety of patient heights.

### 5.2.1 Facility Layout

In the layout of the room, there are eight infrared cameras located around the edges of the room at varying heights. The door and large openings on the right of the trimetric view lead to additional lab and office space. The door on the left opens to the main computer lobby of Building 61 SLC (Student Learning Center). The door connecting the lobby and the lab will be the entrance from which materials for constructing the support will be transferred through.

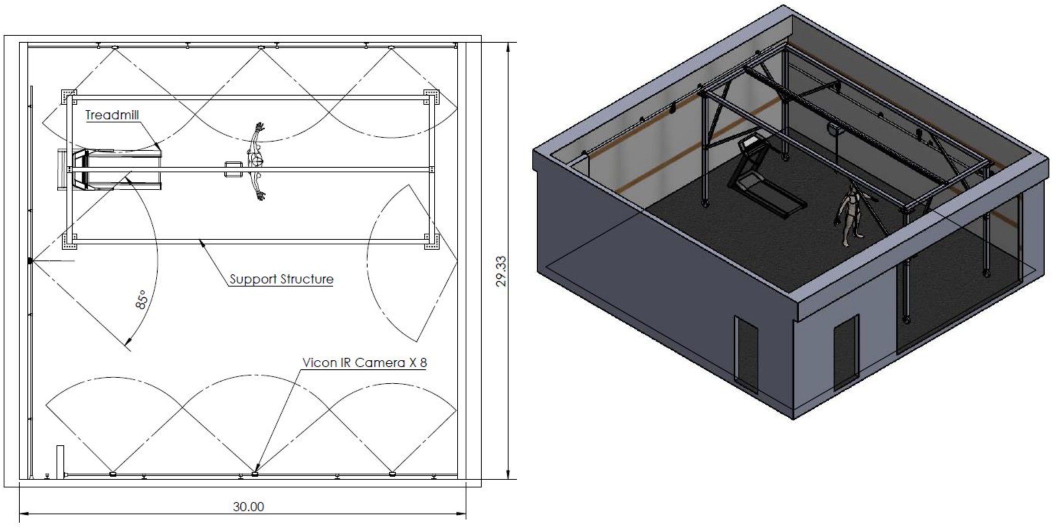


*Figure 36: Facility Layout*

### 5.2.2 Solidworks Models

In order to view the system in a three dimensional space, we have created a SolidWorks assembly of the overall design which is shown in Figure 37. The individual trolley mechanism with the tether is shown in Figure 38. The assembly includes the columns, supporting beams, center H-Beam, mounting plates, locking wheels, trolley and tether. The columns and supporting beams are constructed out of A500 Grade B Steel tubing of size 4”x4”x3/16”. The supporting trusses connecting the columns to the overhead beams are made of the same material but have a sizing of 2”x2”x11GA. The center beam is a W4x13 H-Beam made of A992 Steel.

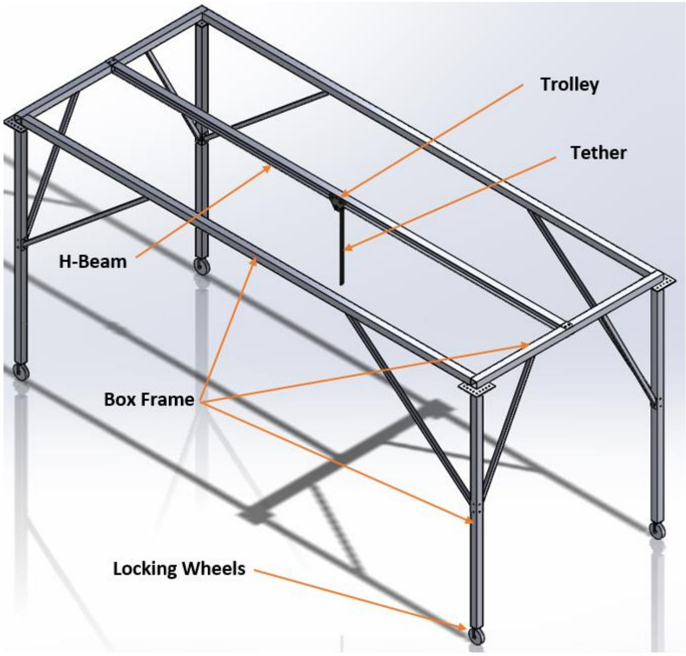


*Figure 37: SolidWorks Assembly*

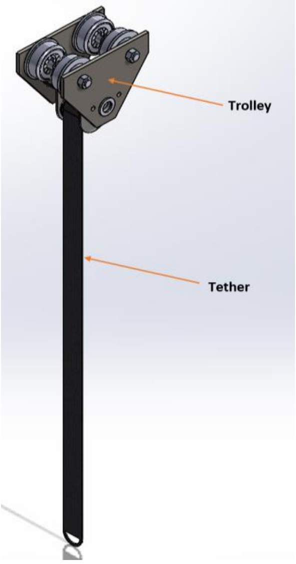


*Figure 38: Trolley and Tether Components*

The above assembly was converted into a SolidWorks drawing, shown in Figure 39, to display a variety of views and dimensions of the structure. The dimensions include the height of the columns, lengths of the beams, thickness sizing of the mounting plates, as well as where the bolts will be in each plate. The views shown in the drawing are isometric, front, left, and top. The SolidWorks drawing of the structure is more informational than the assembly and was taken to the client to demonstrate how the structure would look fully assembled.

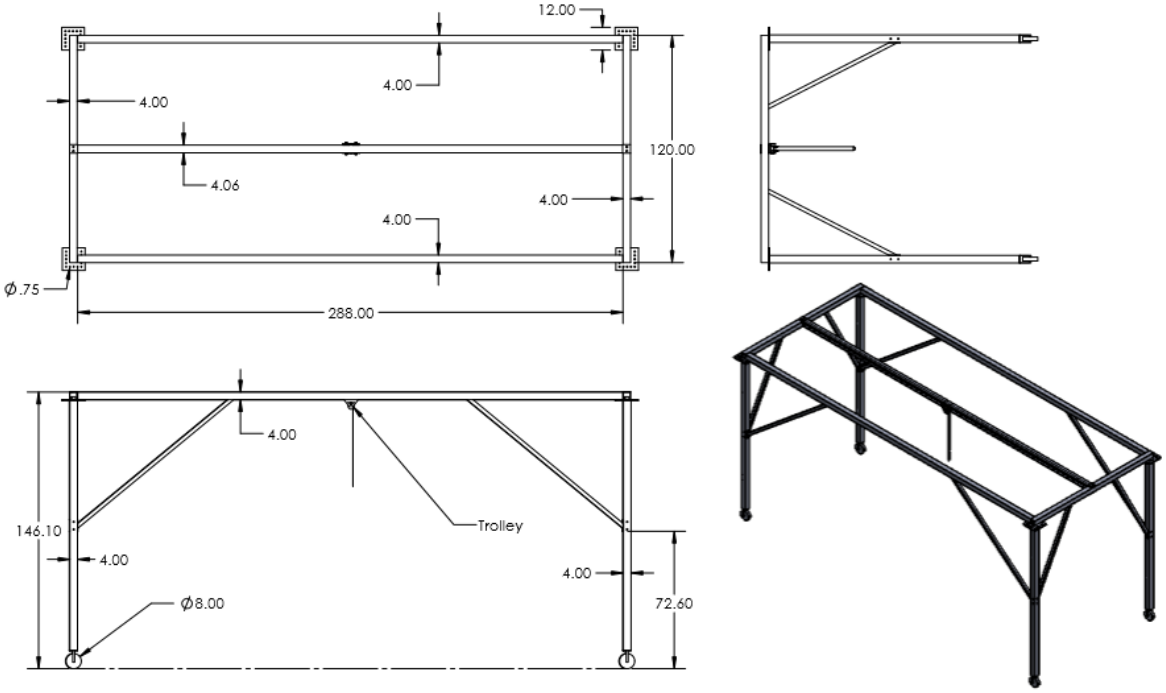


*Figure 39: Engineering Drawing*

### 5.2.3 Patient Support Beam Reaction Force Analysis

This section outlines the steps taken in order to find the force from a patient falling onto the tether that will be connected to their harness. Patients varying in weights and heights will use the system but the weight of each patient will not exceed 300 pounds or 136 kilograms. Using the maximum weight of the patient, the maximum force that will be applied onto the tether can be obtained. The maximum distance of the fall is estimated to be about three feet due to it being half the height of a six-foot tall patient.

The first calculation performed is the velocity of the patient falling zero to three meters. The velocity is a function of acceleration and the distance of the fall. The second calculation is the time it takes a patient to fall an equivalent distance. The formulas used for each are found in Equation 1 and Equation 2 [19] .Following these equations are MATLAB plots to display how the velocity and time vary with different fall distances. The impact force from the patient onto the tether can be found in Equation 3 [19]. The velocities and time used in the equation are from a fall distance of three feet.

$$V = \sqrt{2gd} = \sqrt{2(9.81\frac{m}{s^2})(0.9144\,meters)} = 4.23563\frac{m}{s} = 13.896\frac{ft}{s}$$

Equation 1

V =Velocity of Patient
g = gravity = 9.81 meters per square second
d =max distance of the fall = 3 feet = 0.9144 meters

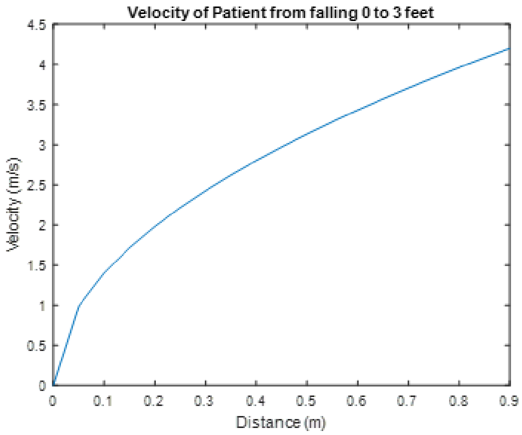


*Figure 40: Velocity of Patient from Falling 0 to 3 ft*

$$t = \sqrt{\frac{2d}{g}} = \sqrt{\frac{2(0.9144\ m)}{9.81\frac{m}{s}}} = 0.431766\ s$$ Equation 2

t = time for patient to fall 3 feet
d = distance of fall = 3 feet = 0.9144 meters
g = gravity = 9.81 meters per square second

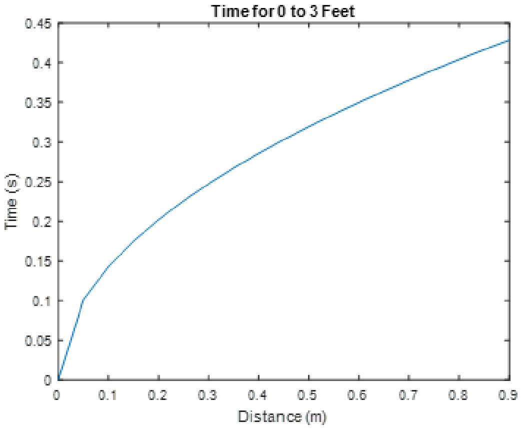


*Figure 41: Time for 0 to 3 ft*

$$F = \frac{2mV}{t} = \frac{2(136.078\ kg)(4.23563\frac{m}{s})}{0.431766\ s} = 2669.85\ N = 600.208\ lbf$$ Equation 3

F = Falling Force from Patient onto Tether
m = Mass of Patient = 136.078 kg=300 lb

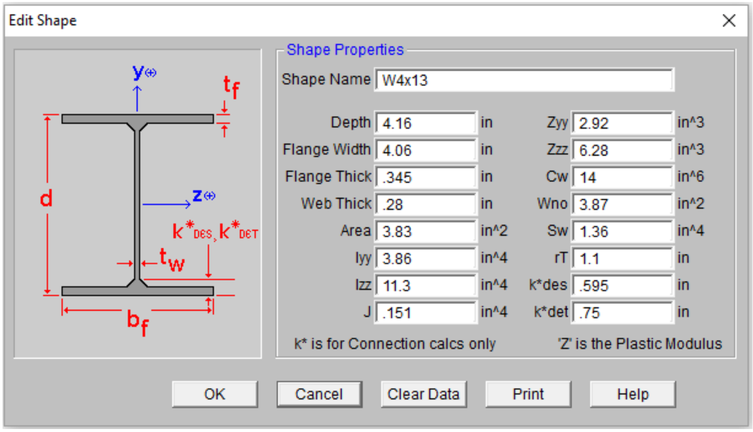
V = Velocity of Patient Falling 3 feet
t = Time it takes patient to fall 3 feet

The results from the calculations are shown above in each equation. The velocity of a patient weighing 300 pounds falling from 3 feet is about 4.24 meters per second. The time it takes for a patient weighing and falling the same amount is about 0.432 seconds. Knowing these two values, the impact force from a 300-pound patient falling 3 feet is 600.208 pound-force. The impact force can be used to determine the total moment and deflection in the center beam of the structure. This will also allow our team to find the force in the beams supporting the center beam. Once we know this information, we can determine what extra support beams our system needs or what can be taken away from the system.

### 5.2.4 Patient Support Beam Bending Moment and Deflection Analysis

If a patient is to fall undergoing gait training, a bending moment will establish along the support beam. An analysis was computed to find the reaction force against the fall of a patient, the resulting bending moment, as well as the deflection that will occur on the support beam. The information below highlights the bending moment caused by the max patient weight along the center of the beam. A focus of the bending moment occurring directly in the center of the beam is due to it being the largest in this location.

Calculations of the bending moments and resulting deflections along the length of the support beam were performed using a structural analysis software called RISA 2D.  To quantify answers, appropriate material specifications including the type of steel, geometry and dimensions were entered within the software. Below in Figure 42, is a display of the properties important to the calculation of the bending moment acting on the support beam under a fall. The properties needed to calculate a bending moment within the software include the cross-section geometry, type of material, thickness of the material, and cross-section dimensions. With these properties entered, results of the area, moment of inertia, and polar moment of inertia are generated.



Shape Name W4x13

| | | | | | |
|---|---|---|---|---|---|
| Depth | 4.16 | in | Zyy | 2.92 | in^3 |
| Flange Width | 4.06 | in | Zzz | 6.28 | in^3 |
| Flange Thick | .345 | in | Cw | 14 | in^6 |
| Web Thick | .28 | in | Wno | 3.87 | in^2 |
| Area | 3.83 | in^2 | Sw | 1.36 | in^4 |
| Iyy | 3.86 | in^4 | rT | 1.1 | in |
| Izz | 11.3 | in^4 | k*des | .595 | in |
| J | .151 | in^4 | k*det | .75 | in |

k* is for Connection calcs only 'Z' is the Plastic Modulus

*Figure 42: Shape Properties for W4x13*

In this analysis, an A992 H-Beam W4x13 was evaluated. The values of the calculations on this size of H-Beam will assist in the decision of what size of cross section and thickness should be used on the structure.

RISA has all of the equations listed below integrated within the software to make calculations fast. However, to check the accuracy of the software, calculations of the area, moment of inertia and the polar moment of inertia can be performed quickly using the following equations from a Mechanics of Materials textbook [20].

Cross Section of H-Beam

<u>Area:</u>

$A_c$ = Cross-Sectional Area
$b_f$ = Flange Width = 4.06 in
$t_f$ = Flange Thickness = 0.345 in
$t_w$ = Web Thickness = 0.28 in
d = Depth = 4.16 in

$$A_c = 2\left(b_f * t_f\right) + \left(t_W * \left(d - 2t_f\right)\right)$$

Equation 4

<u>Moment of Inertia:</u>

$I_x, I_y$ = Moment of Inertia
$b_f$ = Flange Width = 4.06 in
$t_f$ = Flange Thickness = 0.345 in
$t_w$ = Web Thickness = 0.28 in
d = Depth = 4.16

$$I_{xx} = \frac{t_W^3 * \left(d - 2t_f\right)}{12} + 2\left[\left(\frac{t_f * b_f}{12}\right) + \frac{\left(t_f * b_f\right)\left(\left(d - 2t_f\right) + t_f\right)^2}{4}\right]$$

Equation 5

$$I_{yy} = \left(\frac{b_f\left(d - 2t_f\right)}{12}\right) + \left(2 * \frac{\left(b_f^3 * t_f\right)}{12}\right)$$

Equation 6

<u>Polar Moment of Inertia:</u>

$J_z$ = Polar Moment of Inertia
$b_f$ = Flange Width = 4.06 in
$t_f$ = Flange Thickness = 0.345 in

$$J_z = I_{xx} + I_{yy}$$

Equation 7

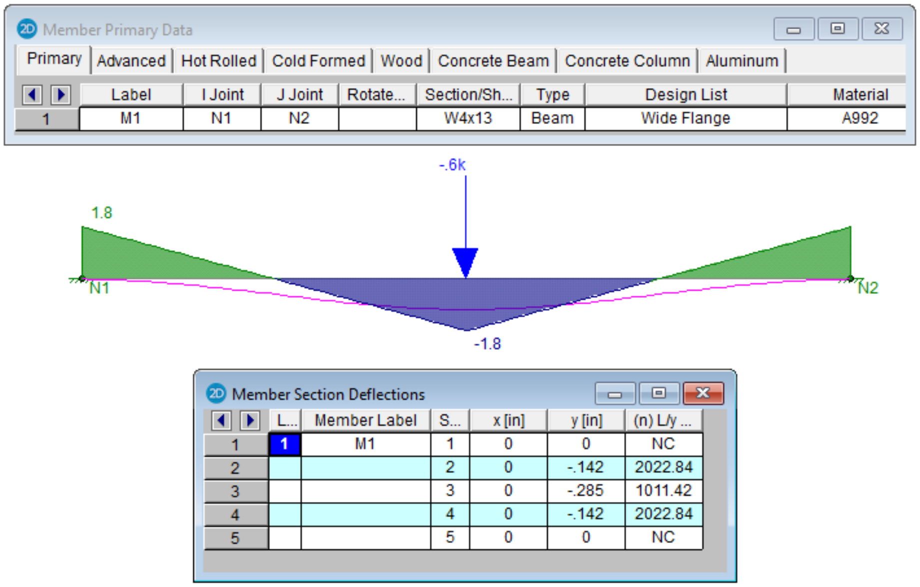
$$J_z = \left[\frac{t_W^3 * \left(d - 2t_f\right)}{12} + 2\left(\left(\frac{t_f * b_f}{12}\right) + \frac{\left(t_f * b_f\right)\left(\left(d - 2t_f\right) + t_f\right)^2}{4}\right) + \left(\frac{b_f\left(d - 2t_f\right)}{12}\right) + \left(2 * \frac{\left(b_f^3 * t_f\right)}{12}\right)\right]$$

Equation 8

$t_w$ = Web Thickness = 0.28
d = Depth = 4.16

In order to designate the correct size of support beam for the structure, the moment and deformation that will be imposed on it during a fall had to be analyzed. Looking at the results of the moment and deflection occurring in the center are the most important because this location is where they will be greatest. When comparing the results of different sized beams to the size selected, using a W6x12 would work however cost more than the smaller W4x13 that also works. The client has required a deflection of no more than an inch as it would cause the trolley to bind. The smallest H-Beam offering from the distributor being sought after to purchase materials from is a W4x13. Since the W4x13 is within the client's tolerance deflection, it has been chosen to save in the overall cost of the system. To ensure the safety of the patients, the choice of a support beam capable of handling a load greater than the max patient weight is wanted. Using RISA to calculate the moments and deformations for varying sizes allowed for the decision of the correct dimensions for the support beam. The finalized choice for the fall protection system is a steel A992 W4x13 H-Beam as it can support the reaction force from a fall under the max patient weight with minimal deflection and is more affordable than the larger beams that would have also worked.

Displayed below in Figure 43, is the simulation of a 600lb-force (Patient Force) acting on the selected H-Beam type. The green shading within the pictures highlight the positive moment occurring while the purple highlight the negative moment occurring. The pink line represents the deflected shape of the beam undergoing the loading of the reaction force. The table under the picture displays the amount of deflection in inches along the length of the beam, with number three being in the direct center.



| | Label | I Joint | J Joint | Rotate... | Section/Sh... | Type | Design List | Material |
|---|---|---|---|---|---|---|---|---|
| 1 | M1 | N1 | N2 | | W4x13 | Beam | Wide Flange | A992 |

| | L... | Member Label | S... | x [in] | y [in] | (n) L/y ... |
|---|---|---|---|---|---|---|
| 1 | 1 | M1 | 1 | 0 | 0 | NC |
| 2 | | | 2 | 0 | -.142 | 2022.84 |
| 3 | | | 3 | 0 | -.285 | 1011.42 |
| 4 | | | 4 | 0 | -.142 | 2022.84 |
| 5 | | | 5 | 0 | 0 | NC |

*Figure 43: Bending Moment and Deflection on W4x13*

### 5.2.5 Structural Frame Deflection Analysis

An analysis of the deflections, thickness of beam, length of beam L (Feet), varying load W (lbf), and possible material to apply to the overhead track Lerner Support System. This analysis calculates the deflection of the sub-frame beams shown in red in Figure 44. The main material under evaluation is the A500 Steel.

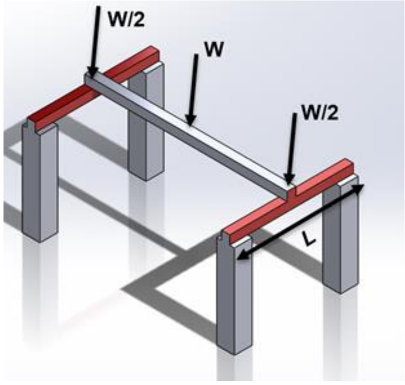


*Figure 45: Load Distribution*

*Figure 44: Square Tubing [21]*

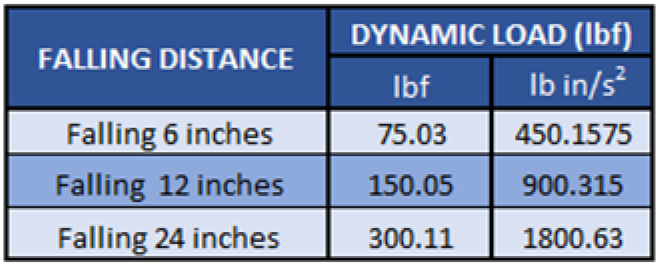
To perform this analysis initial calculations of pound-force in inches/sec$^2$, moment of inertia of the cross section of the frame, and deflection and the midsection of the beam. The final calculation of the deflection of the beam will be most important because it directly relates to the integrity of the frame as a whole. If the side supporting beams have high deflection than it will be likely the entire frame will be flexible - given the center and side support beams composed of the same material and dimensions. The engineering requirement allows for deflection up to two inches. Should a patient fall, the design of the frame should be rigid enough that the frame will not have a spring like reaction to the force from the patients fall.

Before the first calculations were done initial parameters were set that outline the inputs for the load, length of beam, and thickness of box or cylinder tubes. In Table 15 is listed all of the defined inputs that are used in the proceeding formulas. The load is set by the customer requirement of the support to limit the use for patients of 300 lbs or less. The three lengths are set by the minimum treadmill width of 4.5 feet plus additional room for infrared cameras for a total of ten feet, which the support must fit over, and the dimension of the 30 FT X 30 FT room. The intermediate length is middle length to analyze a middle between the boundaries. The thickness relates to the wall thickness of the box frame and cylinder frame.

*Table 16: Parameters*

| SET PARAMETERS | |
|---|---|
| Max Static Load (lbf) | 300 |
| Short Beam Length (Ft) | 10 |
| Medium Beam Length (Ft.) | 20 |
| Large Beam Length (Ft) | 30 |
| Small Thickness (inch) | 3/16 |
| Medium Thickness (inch) | 1/4 |
| Large Thickness (inch) | 3/8 |

*Table 15: Falling Distance*



| FALLING DISTANCE | DYNAMIC LOAD (lbf) | |
|---|---|---|
| | lbf | lb in/s$^2$ |
| Falling 6 inches | 75.03 | 450.1575 |
| Falling 12 inches | 150.05 | 900.315 |
| Falling 24 inches | 300.11 | 1800.63 |

The next step in the process involves calculating the Moment of Inertia (MOI). To do this is required to have the modulus of elasticity of the material as well as the dimension s of the cross section. In this analysis, the dimensions of the cross sections of wall thickness and overall diameter of tube base of the box will vary, so as to find the dimensions that will meet the engineering requirements. The following equations 9 and 10 [22] are for the moment of inertial and listed variables.

$$Tube\ Frame\ MOI,\quad I\,(in^4) = \frac{\pi({r_o}^2 - {r_i}^2)}{64}$$ Equation 9

$$Box\ Frame\ MOI,\quad I\,(in^4) = \frac{a^4 - b^4}{12}$$

$r_o = Outside\ Radius$

$r_i = Inside\ Radius$ Equation 10

$a = Outside\ Square\ Dimension$

$b = Inside\ Square\ Dimension$

The final calculation involves finding the amount of deflection at the center of the beam. Similar to equations 9 and 10, the deflection formula will also be dependent upon inputs that vary. The only input that will not change is the modulus of elasticity seen below in Table 17 [23]. The other inputs that vary are the load, length, and moment of inertia.

*Table 17: Modulus of Elasticity*

| BEAM MATERIAL | MODULUS OF ELASTICITY (PSI) |
|---|---|
| A500 STEEL BOX | 2.90E+07 |

Below is the single formula, equation 11 used to find the deflection at the center of the beam using the collective values found from the previous calculations and tables.

$$\delta = \frac{Wl^3}{192EI}$$

*Where,*

$W = Load\ (lb)$

$l = Length\ (in)$

$E = Modulus\ of\ Elasticity\ (psi)$

$I = Moment\ of\ Inertia\ (in^4)$

Equation 11

The calculation of deflection was done by holding tube thickness and falling distance constant while varying the length. The process repeats as an iteration moving the thickness and falling distance to the proceeding defined values, found in Tables 15 and 16, and held constant while the length of the beam varies. A total of nine iterations are performed for the material. In Figure 46 are the results from the described calculations to find deflection. Each of the calculated deflections is displayed on the figures as well as a red dash line to indicate the limitation of the deflection to stay beneath two inches.

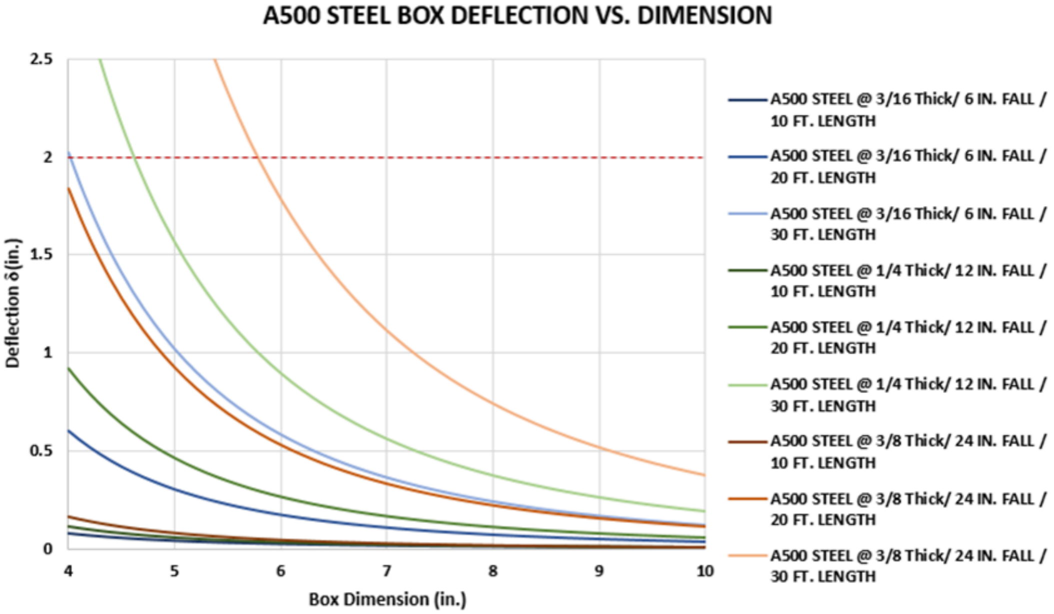


*Figure 46: A500 Steel Box Deflection vs. Dimension*

The analysis of the A500 Steel Box yielded numerous options to select a material dimension. The enlarged Figure 46 displays the results of the same calculation process. Figure 46 is enlarged since many of the data lines are closely trending to one another. From the analysis, all nine calculations of differing wall thickness, falling distance, and length yielding nine results to select from that meet the engineering requirement of less than two inches of deflection. The option of all nine design conditions offers the flexibility for our design to accommodate the changing project requirements. Of the nine design options, the top three choices are listed below.

1. 3/8” Thick Wall / 24” Fall / 20’ Length, When Square Dimension is 4"a9"
2. 3/16” Thick Wall / 6” Fall / 30’ Length, When Square Dimension is 4"<a9"
3. ¼” Thick Wall / 12” Fall / 10’ Length, When Square Dimension is 4"a9"

# 6 Proposed Design

## *6.1 Implementation of Design*

To successfully implement our design, our team will construct a prototype to visually see the design. Once a physical model is constructed, inconsistencies in the design can be noticed and any changes necessary will be made. Additionally, a three dimensional analysis will be performed using a structural analysis software to highlights areas with large deflections. With the results of the analysis, decisions on specified materials may be altered in order to increase the integrity of the structure.

## *6.2 Prototype*

For the support design prototype, our team will be using a 3D printer to print out the fully assembled design to a smaller scale. In addition to the model, there will be a printed treadmill and human being that will aid in helping our design team to gain a visual perspective of the smaller scaled design. The material to be used in the print will be ABS (Acrylonitrile butadiene styrene). This plastic is much stronger which will be needed for our print that will consist of skinny beam members because of the scale.

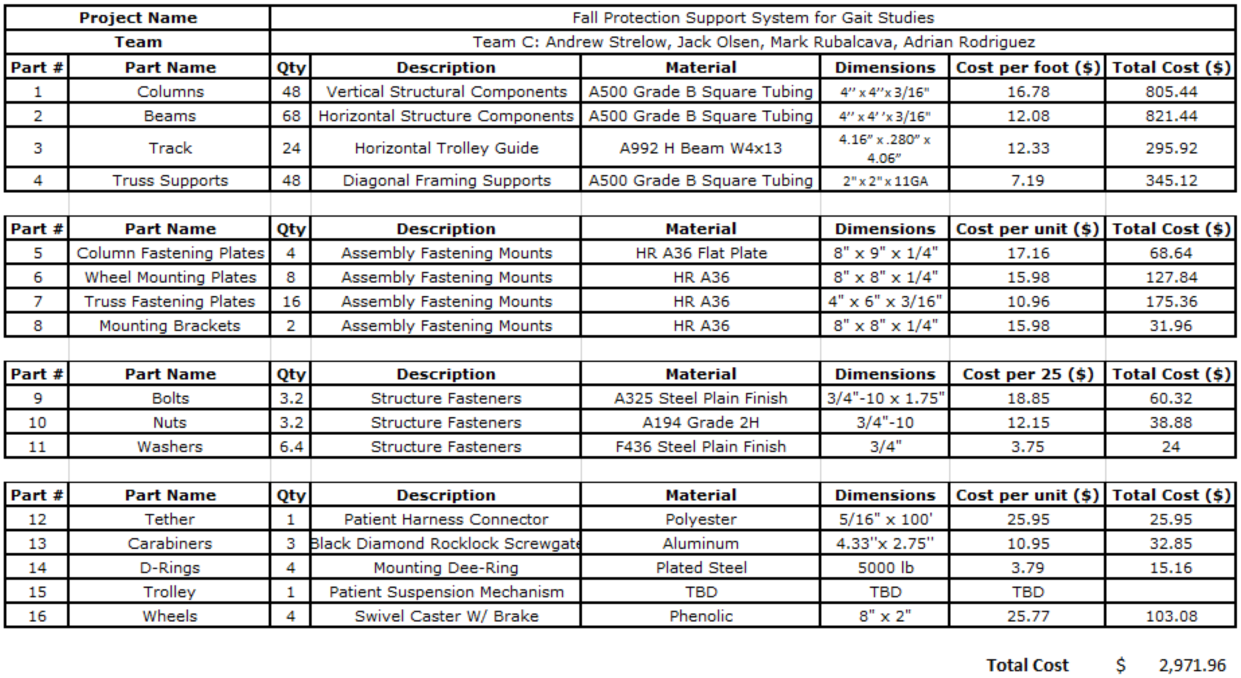
## *6.3 Resources Needed*

The team will install the design by themselves in the laboratory. In order to raise the members to their desired locations, the team will lift the beams into place and align the plates together. To join the plates together, the team will use standard tools to fasten the bolts and nuts on the plates. Having the team install the structure will reduce the costs of the installation and allow more of the budget to be allocated to materials and shipping. However, if the team is not able to install the design, outside help will be required.

## 6.4 Bill of Materials

Table 18, below displays the proposed costs of all of the components needed to fully assemble the fall protection system. Included in the list are the individual prices for the beams, columns, and truss supports, which make up the support structure. Also, listed are the prices for all of the hardware needed to assemble the structure, including the nuts, bolts, and washers [24, 25]. Finally, the prices for the tether components and patient support connections are included as well.

*Table 18: Bill of Materials*



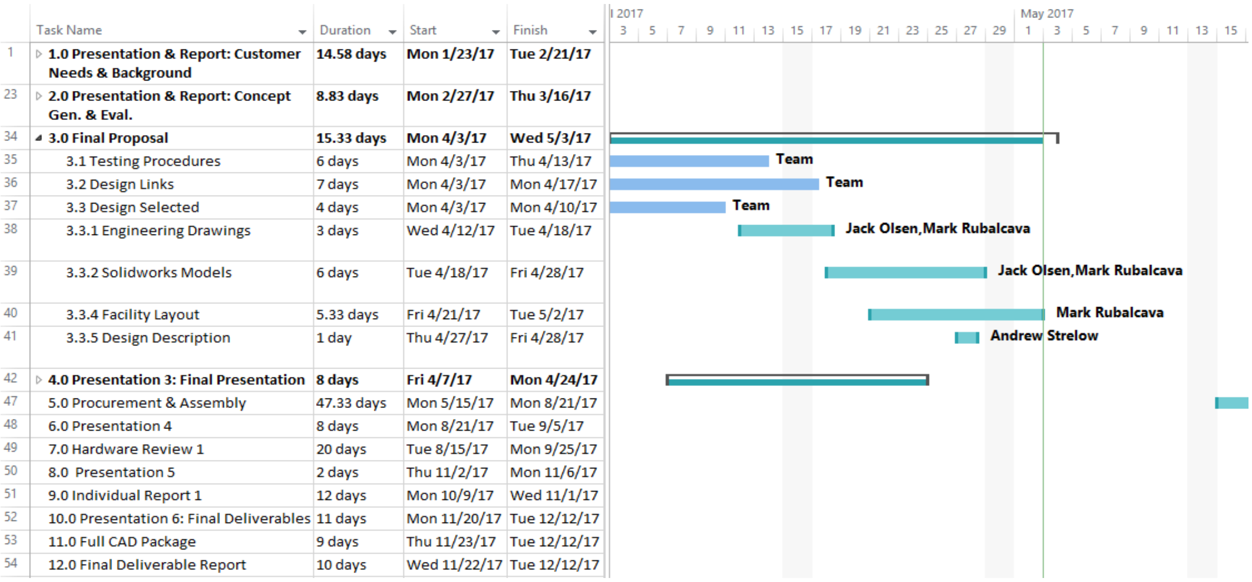
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Project Name** | | Fall Protection Support System for Gait Studies | | | | | |
| **Team** | | Team C: Andrew Strelow, Jack Olsen, Mark Rubalcava, Adrian Rodriguez | | | | | |
| **Part #** | **Part Name** | **Qty** | **Description** | **Material** | **Dimensions** | **Cost per foot ($)** | **Total Cost ($)** |
| 1 | Columns | 48 | Vertical Structural Components | A500 Grade B Square Tubing | 4'' x 4''x 3/16" | 16.78 | 805.44 |
| 2 | Beams | 68 | Horizontal Structure Components | A500 Grade B Square Tubing | 4'' x 4' 'x 3/16" | 12.08 | 821.44 |
| 3 | Track | 24 | Horizontal Trolley Guide | A992 H Beam W4x13 | 4.16" x .280" x 4.06" | 12.33 | 295.92 |
| 4 | Truss Supports | 48 | Diagonal Framing Supports | A500 Grade B Square Tubing | 2" x 2" x 11GA | 7.19 | 345.12 |
| | | | | | | | |
| **Part #** | **Part Name** | **Qty** | **Description** | **Material** | **Dimensions** | **Cost per unit ($)** | **Total Cost ($)** |
| 5 | Column Fastening Plates | 4 | Assembly Fastening Mounts | HR A36 Flat Plate | 8" x 9" x 1/4" | 17.16 | 68.64 |
| 6 | Wheel Mounting Plates | 8 | Assembly Fastening Mounts | HR A36 | 8" x 8" x 1/4" | 15.98 | 127.84 |
| 7 | Truss Fastening Plates | 16 | Assembly Fastening Mounts | HR A36 | 4" x 6" x 3/16" | 10.96 | 175.36 |
| 8 | Mounting Brackets | 2 | Assembly Fastening Mounts | HR A36 | 8" x 8" x 1/4" | 15.98 | 31.96 |
| | | | | | | | |
| **Part #** | **Part Name** | **Qty** | **Description** | **Material** | **Dimensions** | **Cost per 25 ($)** | **Total Cost ($)** |
| 9 | Bolts | 3.2 | Structure Fasteners | A325 Steel Plain Finish | 3/4"-10 x 1.75" | 18.85 | 60.32 |
| 10 | Nuts | 3.2 | Structure Fasteners | A194 Grade 2H | 3/4"-10 | 12.15 | 38.88 |
| 11 | Washers | 6.4 | Structure Fasteners | F436 Steel Plain Finish | 3/4" | 3.75 | 24 |
| | | | | | | | |
| **Part #** | **Part Name** | **Qty** | **Description** | **Material** | **Dimensions** | **Cost per unit ($)** | **Total Cost ($)** |
| 12 | Tether | 1 | Patient Harness Connector | Polyester | 5/16" x 100' | 25.95 | 25.95 |
| 13 | Carabiners | 3 | Black Diamond Rocklock Screwgate | Aluminum | 4.33''x 2.75'' | 10.95 | 32.85 |
| 14 | D-Rings | 4 | Mounting Dee-Ring | Plated Steel | 5000 lb | 3.79 | 15.16 |
| 15 | Trolley | 1 | Patient Suspension Mechanism | TBD | TBD | TBD | |
| 16 | Wheels | 4 | Swivel Caster W/ Brake | Phenolic | 8" x 2" | 25.77 | 103.08 |
| | | | | | | | |
| | | | | | | **Total Cost** | $ 2,971.96 |

## 6.5 Costs and Budget

The original budget set by the client for the overall system was $2,500. However, after extensive conversation with the client and a proposed design brought forth, our client has raised our budget to approximately $3,500. This budget includes the purchasing and shipping of all materials as well as the installation of the structure. To date, the team has yet to purchase any materials but plans to start purchasing over the summer.

## 6.6 Schedule

In the next week, our team plans to finalize a design that will be accepted by the client as the solution for the fall protection system. The proceeding actions after will be to procure materials and begin assembly of the design. From the beginning of September 2017, the design team will begin testing procedures on the fully assembled design to continue improving any and vetting any flaws in the support structure and fall protection device.



| | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | **1.0 Presentation & Report: Customer Needs & Background** | **14.58 days** | **Mon 1/23/17** | **Tue 2/21/17** |
| 23 | **2.0 Presentation & Report: Concept Gen. & Eval.** | **8.83 days** | **Mon 2/27/17** | **Thu 3/16/17** |
| 34 | **3.0 Final Proposal** | **15.33 days** | **Mon 4/3/17** | **Wed 5/3/17** |
| 35 | 3.1 Testing Procedures | 6 days | Mon 4/3/17 | Thu 4/13/17 |
| 36 | 3.2 Design Links | 7 days | Mon 4/3/17 | Mon 4/17/17 |
| 37 | 3.3 Design Selected | 4 days | Mon 4/3/17 | Mon 4/10/17 |
| 38 | 3.3.1 Engineering Drawings | 3 days | Wed 4/12/17 | Tue 4/18/17 |
| 39 | 3.3.2 Solidworks Models | 6 days | Tue 4/18/17 | Fri 4/28/17 |
| 40 | 3.3.4 Facility Layout | 5.33 days | Fri 4/21/17 | Tue 5/2/17 |
| 41 | 3.3.5 Design Description | 1 day | Thu 4/27/17 | Fri 4/28/17 |
| 42 | **4.0 Presentation 3: Final Presentation** | **8 days** | **Fri 4/7/17** | **Mon 4/24/17** |
| 47 | 5.0 Procurement & Assembly | 47.33 days | Mon 5/15/17 | Mon 8/21/17 |
| 48 | 6.0 Presentation 4 | 8 days | Mon 8/21/17 | Tue 9/5/17 |
| 49 | 7.0 Hardware Review 1 | 20 days | Tue 8/15/17 | Mon 9/25/17 |
| 50 | 8.0 Presentation 5 | 2 days | Thu 11/2/17 | Mon 11/6/17 |
| 51 | 9.0 Individual Report 1 | 12 days | Mon 10/9/17 | Wed 11/1/17 |
| 52 | 10.0 Presentation 6: Final Deliverables | 11 days | Mon 11/20/17 | Tue 12/12/17 |
| 53 | 11.0 Full CAD Package | 9 days | Thu 11/23/17 | Tue 12/12/17 |
| 54 | 12.0 Final Deliverable Report | 10 days | Wed 11/22/17 | Tue 12/12/17 |

*Figure 47: Schedule*

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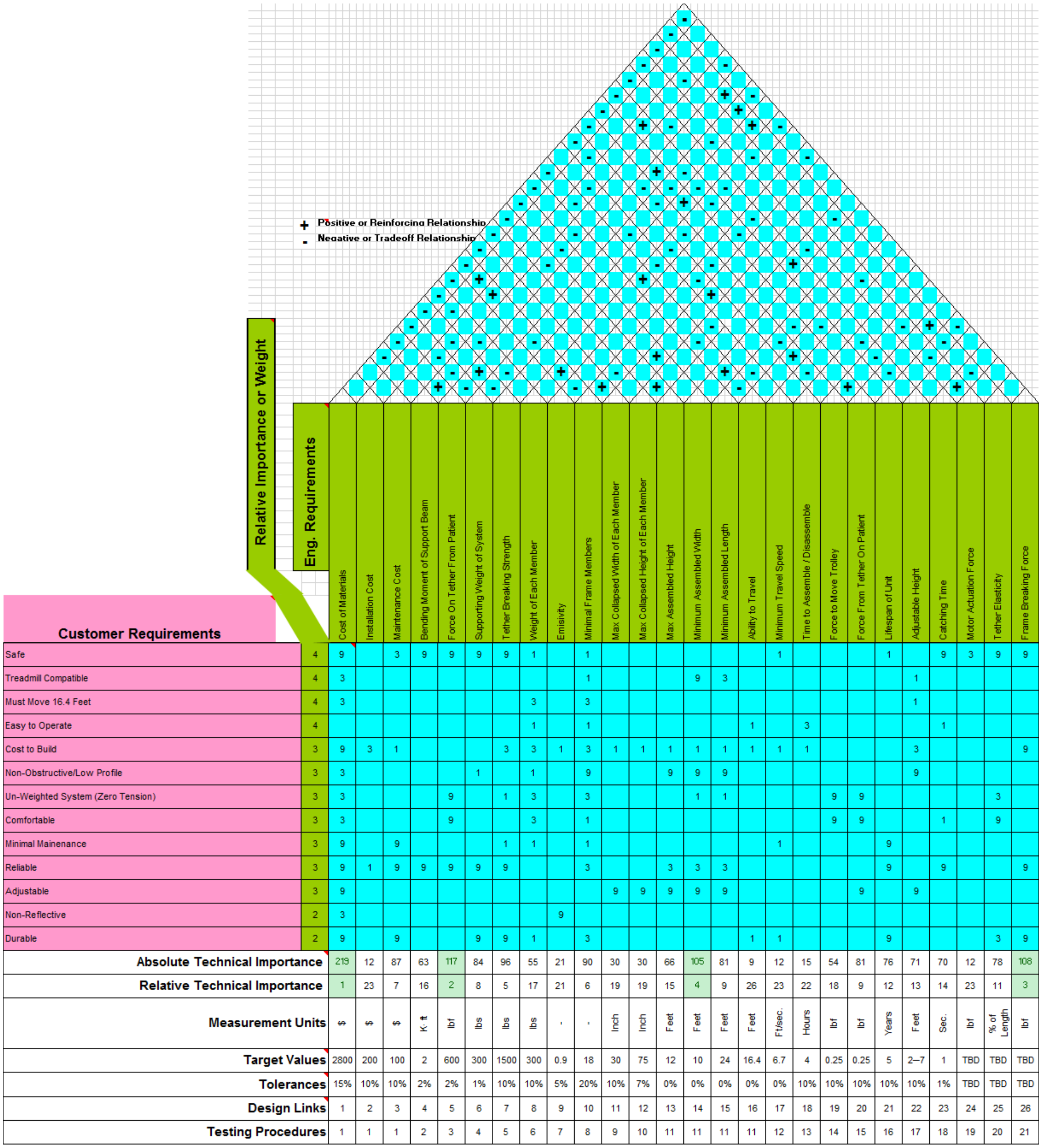
# APPENDIX A: House of Quality



| Customer Requirements | Relative Importance or Weight | Cost of Materials | Installation Cost | Maintenance Cost | Bending Moment of Support Beam | Force On Tether From Patient | Supporting Weight of System | Tether Breaking Strength | Weight of Each Member | Emisivity | Minimal Frame Members | Max Collapsed Width of Each Member | Max Collapsed Height of Each Member | Max Assembled Height | Minimum Assembled Width | Minimum Assembled Length | Ability to Travel | Minimum Travel Speed | Time to Assemble / Disassemble | Force to Move Trolley | Force From Tether On Patient | Lifespan of Unit | Adjustable Height | Catching Time | Motor Actuation Force | Tether Elasticity | Frame Breaking Force |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Safe | 4 | 9 |  | 3 | 9 | 9 | 9 | 9 | 1 |  | 1 |  |  |  |  |  |  | 1 |  |  |  | 1 |  | 9 | 3 | 9 | 9 |
| Treadmill Compatible | 4 | 3 |  |  |  |  |  |  |  |  | 1 |  |  |  | 9 | 3 |  |  |  |  |  |  | 1 |  |  |  |  |
| Must Move 16.4 Feet | 4 | 3 |  |  |  |  |  |  | 3 |  | 3 |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |
| Easy to Operate | 4 |  |  |  |  |  |  |  | 1 |  | 1 |  |  |  |  |  | 1 |  | 3 |  |  |  |  | 1 |  |  |  |
| Cost to Build | 3 | 9 | 3 | 1 |  |  |  | 3 | 3 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |  |  |  | 3 |  |  |  | 9 |
| Non-Obstructive/Low Profile | 3 | 3 |  |  |  |  | 1 |  | 1 |  | 9 |  |  | 9 | 9 | 9 |  |  |  |  |  |  | 9 |  |  |  |  |
| Un-Weighted System (Zero Tension) | 3 | 3 |  |  |  | 9 |  | 1 | 3 |  | 3 |  |  |  | 1 | 1 |  |  |  | 9 | 9 |  |  |  |  | 3 |  |
| Comfortable | 3 | 3 |  |  |  | 9 |  |  | 3 |  | 1 |  |  |  |  |  |  |  |  | 9 | 9 |  |  | 1 |  | 9 |  |
| Minimal Mainenance | 3 | 9 |  | 9 |  |  |  | 1 | 1 |  | 1 |  |  |  |  |  |  | 1 |  |  |  | 9 |  |  |  |  |  |
| Reliable | 3 | 9 | 1 | 9 | 9 | 9 | 9 | 9 |  |  | 3 |  |  | 3 | 3 | 3 |  |  |  |  |  | 9 |  | 9 |  |  | 9 |
| Adjustable | 3 | 9 |  |  |  |  |  |  |  |  |  | 9 | 9 | 9 | 9 | 9 |  |  |  |  | 9 |  | 9 |  |  |  |  |
| Non-Reflective | 2 | 3 |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Durable | 2 | 9 |  | 9 |  |  | 9 | 9 | 1 |  | 3 |  |  |  |  |  | 1 | 1 |  |  |  | 9 |  |  |  | 3 | 9 |
| **Absolute Technical Importance** |  | 219 | 12 | 87 | 63 | 117 | 84 | 96 | 55 | 21 | 90 | 30 | 30 | 66 | 105 | 81 | 9 | 12 | 15 | 54 | 81 | 76 | 71 | 70 | 12 | 78 | 108 |
| **Relative Technical Importance** |  | 1 | 23 | 7 | 16 | 2 | 8 | 5 | 17 | 21 | 6 | 19 | 19 | 15 | 4 | 9 | 26 | 23 | 22 | 18 | 9 | 12 | 13 | 14 | 23 | 11 | 3 |
| **Measurement Units** |  | $ | $ | $ | K ft | lbf | lbs | lbs | lbs | - | - | Inch | Inch | Feet | Feet | Feet | Feet | Ft/sec. | Hours | lbf | lbf | Years | Feet | Sec. | lbf | % of Length | lbf |
| **Target Values** |  | 2800 | 200 | 100 | 2 | 600 | 300 | 1500 | 300 | 0.9 | 18 | 30 | 75 | 12 | 10 | 24 | 16.4 | 6.7 | 4 | 0.25 | 0.25 | 5 | 2–7 | 1 | TBD | TBD | TBD |
| **Tolerances** |  | 15% | 10% | 10% | 2% | 2% | 1% | 10% | 10% | 5% | 20% | 10% | 7% | 0% | 0% | 0% | 0% | 0% | 10% | 10% | 10% | 10% | 10% | 1% | TBD | TBD | TBD |
| **Design Links** |  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| **Testing Procedures** |  | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 11 | 11 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |

*Figure 48: House of Quality*