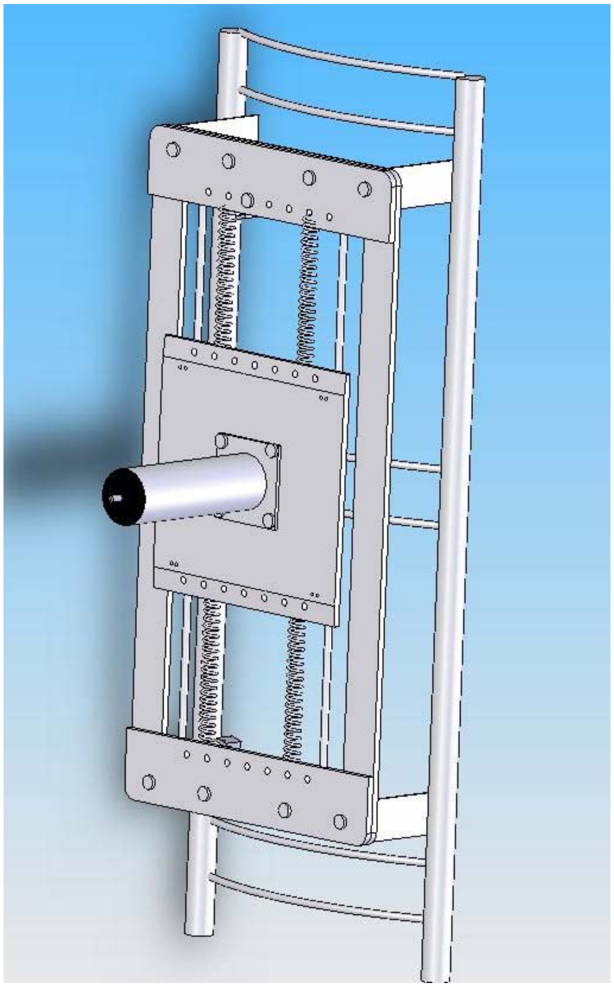
Mechanical Engineering 450: Winter 2006

Suspended Load Backpack

Final Report



Team 5: Matthew Esper, Melinda Sedon, Matthew Vanderpool, Megan Van Wieren
Professor R. Brent Gillespie
April 18, 2006

EXECUTIVE SUMMARY

Early last year, the first suspended load backpack was created by Larry Rome of the University of Pennsylvania. Analysis from this prototype shows its ability to simultaneously (1) generate electrical energy and (2) carry a load at lower metabolic costs than would be needed to generate the same electrical energy and carry the backpack separately. However, little is known about the reason for this phenomenon as well as the dynamics of this system. Our client, Professor Art Kuo of the University of Michigan Department of Mechanical Engineering and Biomedical Engineering, asked our team to build a suspended-load backpack to further his research of metabolic savings and walking dynamics.

Our team generated customer requirements with our client and shaped them into engineering specifications. From there we also created a Quality Function Deployment Chart to relate these requirements and specifications. We reviewed much of the literature pertaining to the motion of walking, carrying loads, metabolic efficiency, as well as suspended load systems. We were also able to gain valuable knowledge from experts such as Professor Kuo and Professor Rome.

The concept generation phase of this project was stimulated through brainstorming within our team and with the valuable input from our classmates. Major categories of concepts were generated to guide the design of our prototype: (1) variable springs (2) variable damping (3) frictionless vertical motion path (4) attachment of system components to the pack frame and (5) locked position.

Our team expanded the five major categories and then began concept selection, taking care to consider function, along with manufacturability and assembly. We created three Alpha prototypes, each showcasing a different type of vertical motion system. From this trial and error process we were able to select components and methods of assembly for our Beta design. This design included variable springs, variable damping, and a low-friction vertical path. To ensure our tolerances, it made use of a jig plate that also functioned as a frame for attaching system components. The load was varied using standard free weights and clamps to secure them to the load plate.

To improve this design for the creation of our final prototype, we added more secure hip and shoulder straps, variable damping through a motor and capstan system, and an accelerometer and radial encoder to measure the dynamics of the system. With the finalization of the motor placement and measurement devices, we were able to manufacture a suspended-load backpack able to fulfill the requirements necessary to accurately study the dynamics of suspended-load walking. This prototype was delivered in time and under-budget while exceeding all the final customer requirements.

Improvements could be made to extend the range of the damping system. Possible improvements include the use of a gear box, similar to the one used on Larry Rome's pack, or negative resistance damping.

TABLE OF CONTENTS

INTRODUCTION

ABSTRACT

Earlier last year Larry Rome of the University of Pennsylvania invented what is called the 'suspended-load backpack'. Tests on this pack show that the user can simultaneously carry a load and generate energy at lower metabolic costs than doing these tasks separately. Little is known about the dynamics of this system or the reason for the metabolic energy savings. From these initial findings it suggests that walking with a suspended-load could be more efficient than walking with a rigid load.

Our client, Professor Art Kuo of the University of Michigan Department of Mechanical Engineering and Biomedical Engineering, would like to study the dynamics of the suspended-load backpack. He hopes this will help explain why less metabolic energy is required for walking with a suspended-load backpack rather than a rigid backpack. Professor Kuo has requested that our team undergo the task of building a suspended-load backpack for his use. Our plan is to develop a pack that can be used to study the dynamics of this system by using a design with variable system parameters: stiffness, damping, and mass.

RESEARCH RESULTS

Our team gathered information on our project before meeting with our client, Professor Kuo. We read the papers published by Larry Rome and Art Kuo in Science magazine to become familiar with the current model of the ‘suspended-load backpack’ and to begin to learn about its shortcomings. After our initial meeting with Professor Kuo we also did internet research that focused on the energy efficiency of carry loads. This included articles on Nepalese Porters, obese women, and even the rhinoceros beetle.

Our team was able to gain valuable first hand knowledge from experts in areas pertaining to the motion of walking with a load and its expenditure of energy. Professor Kuo was able to give our team an overview of the current research that has been done and where the next steps should be taken. We were also able to contact Larry Rome through Professor Kuo, although little new information was acquired because his research on the suspended-load backpack is currently active.

CUSTOMER REQUIREMENTS & ENGINEERING SPECIFICATIONS

To produce a final prototype that will make Professor Kuo’s system dynamics research possible, our team first discussed the prototype requirements with our client. The most important requirements were: (1) the pack had two load options: suspended load that could be locked in a fixed position or locked and (2) the damping and spring stiffness of the pack could be changed. The customer requirements are located in Table 1 on page 5.

Customer Requirements
Variable damping
Variable spring stiffness
Light weight
Low friction
Ability to lock load from moving
Fits multiple sized people
Minimize frame to body motion
Comfortable enough to wear for long periods of time
Durable enough for multiple uses
Does not interfere with normal walking motions
Allows for variable weight loads
Easy to use
Ability to collect data on the dynamics of the pack

Table 1: Suspended-load customer requirements

It was then our task to take these requirements and develop engineering specifications. Our results are in Table 2. The specifications will guide the design of our prototype and be used to develop a specific project plan.

The relation between our customer requirements and the project engineering specifications can be seen in the Quality Function Deployment (QFD) Chart, Appendix A. We will use our QFD chart to determine on which engineering specifications we should spend the most design time. This will help to maximize the number of customer requirements met. This chart is also a very useful tool when determining which design parameters will affect our customer requirements in a positive way and which will affect our customer requirements in negative way. Because this product has never been produced with the same intent of use in the past, we do not have any existing models to compare in our QFD. Thus, the primary use of this chart is to evaluate the importance and relationship of engineering specifications and customer requirements.

Engineering Specifications
Ability to control system stiffness
Ability to control system damping
Frame weight not to exceed 20% of maximum load
Pack will have 2 load options- locked and suspended
Zero motion between the load and the frame when in locked position
Frame motion not to exceed 1 cm relative to the body, measured at the hips and shoulders
Frame can withstand 375 N in the vertical direction, 1.5 x Max Load
Change time for stiffness or damping of system is less than 1 minute
Pack should last for 50 trials before replacing parts
Parts failing after 50 trials must be easy to find and replace
Parts that are difficult to find or replace must last for 200 trials
Pack should fit hip sizes 30 inches to 45 inches
Comfortable to wear for 2 hours
Ability to measure and record vertical motion of load relative to pack
Ability to measure and record motion vertical of the frame

Table 2: Engineering specifications created from customer requirements.

CONCEPT GENERATION

To being our concept generation we conducted a brainstorming session with our design team. During this session we first used blank paper and large markers to draw our individual ideas. Next we had a show-and-tell session within the group to explain our design ideas. This session brought forward the major categories of concepts that would be generated before prototyping our final pack. The major categories of concept generation that our team would focus on include (1) variable springs (2) variable damping (3) frictionless vertical motion path (4) attachment of system components to the pack frame and (5) locked position. We expanded these major categories as described through additional brainstorming within our team and also valuable input from our classmates. We then converged into choices for our initial rapid prototype. Drawings and models of concept design can be seen in Appendix B.

Variable damping: Our first brainstorming sessions provided few creative damping ideas. The only idea was to simply use dampers to provide damping to the system. After doing additional research and brainstorming outside of our group, we add two other ideas. One was to use magnets that would produce eddie currents. The magnets would provide damping, but we were unsure that it would be enough for our use. We were also uneasy about the tight tolerance that is needed to produce the damping current. The second idea was to use a motor for the damping. This concept posed the problem of converting circular motion into linear motion, which would include a high friction transmission. There was also some concern about the amount of weight this would add to the pack.

Variable springs: Our first idea was to vary the spring stiffness by simply adding spring in parallel to the system. This would be accomplished by including multiple holes on the load plate and corresponding holes that would attach to the frame. We also come up with the idea of using the same number of springs, but changing sets when a different stiffness was to be tested. The downfall here would be keeping track of many sets of springs, all with different stiffness. Another idea was to use the concept of a leaf spring. This would allow for varying stiffness with the use of one spring instead of many. We were not sure about the loads this spring could handle or about the attaching options. A fourth idea was to vary the stiffness by changing the length of each spring by screwing some object into or out of the spring. This would allow the length and therefore the stiffness to change without physically changing springs. However, it would be much harder to calculate the stiffness of these springs.

Vertical motion path: It is very important to our project that the motion of our pack follows a vertical path. After our initial brainstorming session we had produced three main ideas. The first idea was to use strong wire as guides that the pack load would attach to and follow. This concept provided the low friction required and would also be very easy to test in a rough prototype. The second idea was to use rods that would allow for exclusive vertical motion. It was suggested to use wood dowel rods that could be found at any hardware, however there was some question as to the friction that the wood would create. We decided metal rods would be ideal for low friction and durability, but the drawback was in attaching the metal rods for an initial rapid prototype. The third idea was proposed during one of our class-wide brainstorming sessions; to use drawer slides as the framework for vertical motion. These would be low friction and easily found at any local hardware, making them quickly testable.

Attachment of Components to frame: The attachment of the components of our dynamic system to the frame brought about many creative ideas. The first idea was to attach the springs, damping mechanism, and load directly to the pack frame. This was the most obvious first choice, however there were many questions about drilling into the metal frame or if the motion would be vertical due to the curvature of the pack frame. Second, we thought about using some sort of heavy duty Velcro that would allow different system component to be added on in varying positions. The third idea was to attach a strip of metal to the top and bottom of the frame that would create separation between the original frame and the components. This would allow us to be sure the motion is vertical by overcoming the hurdle proposed by the curvature of the pack frame. Through class-wide brainstorming another idea was brought forward: to machine a rectangle out of metal that would have with the middle milled out. This would give us a template for attaching our system components and would overcome the difficulty in achieving vertical motion. The template will also allow us to tolerance the pack.

Locked Position: Developing a locked position for our pack is the last major category that our team would focus on. This is because we must first have categories (1) – (4) roughly in place before a locking mechanism can be decided upon. Our team has come up with multiple concepts for this function. One idea, assuming rods were used, was to simply clamp above and below the attachment location of the load to the rods. This idea would cause some scraping to the rods, which may cause permanent damage and ultimately increasing the amount of friction. Another idea was to use an expandable device. This would be placed between the load and the metal bar both above and below the load, securing it in place. The next idea was to secure the load by attaching the

CONCEPT SELECTION

When choosing a design, we had to consider more than what would work theoretically best. Manufacturability and assembly have to be taken into account as well. We created three Alpha prototypes. Each showcased a different type of vertical motion system. From these prototypes we were able to select components and methods of assembly.

***Variable spring selection*:** We have decided to use extension springs in parallel for several reasons. First of all, it is very easy to compute the spring stiffness. Also, through design, we will be able to change the spring stiffness easily through addition and subtraction of the springs. Leaf springs do not allow for the range of motion that we expect to see. However, extension springs come in variable lengths and stiffness thus enabling us to select springs that allow for large motion ranges.

Variable damping selection: After careful consideration, we have decided to use a motor with active damping. This will make controlling the damping very simple as it can be manipulated electronically with a computer. Using this system is advantageous because it does not require the user to change the number of dampers. And, unlike the eddie current system, it does not require as tight of physical tolerances. The motor will also be able to handle the weight that will be applied to the system.

Vertical motion system selection: We learned a great deal about the vertical motion systems from our prototypes. First we found that using a wire system could not withstand the forces placed on it by the weights. Also, friction was quite high. The second solution we came up with used the idea of drawer slides. Although friction can be quite low if assembled correctly, it is very hard to meet all of the tolerances. The slides require the sides to not only be parallel, but also perfectly in line with not tilting. This proved to be quite a challenge. Using a rail system subtracts one of these dimensions because they are cylindrical. We were also able to find bearings to fit these rods and found that there was very little friction. Thus, we have decided to go with the rail system.

CONCEPT DESCRIPTION

Our final design evolved a great deal from our initial brainstorming session, as described in the Concept Selection section. Along with the concepts already discussed, this section will provide a more detailed description of our next prototype.

Attachment of Components to Frame: For the final design we will use a jig to attach the system components to the existing external frame. This plate will also be used to ensure that the rails are parallel, allowing for exclusive vertical motion, along with ensuring that tolearance is kept. We will machine a rectangular frame, our jig, out of aluminum. The jig will attach to brackets, which will then attach to the existing external backpack fame.

The jig will also provide a point of attachment for the spring components as well as the damping system.

To design for a variable load, we will include a two-inch diameter piece of aluminum attached to the center of the load plate. This will allow us to attach standard Olympic size free weights. The plates will then be secured using standard two-inch plate clamps, common in any weight room. This option will allow for the load to be easily and quickly changed, along with making it standard for others who wish to recreate the pack.

Damping using Motor: To add damping to the system we are mounting a motor on the load plate and connecting it to the jig plate with a capstan system. As the motor spins it creates a voltage between two electrical terminals, as shown in equation (1) below where $\dot{x}$ is the vertical velocity of the load plate, K_e is a motor constant and r is the radius of the capstan. By connecting these two terminals with a resistor we can create a current flow through the terminals and motor. This current then creates a torque in the opposite direction of to the motors angular velocity and acts as a damper, as shown in equations (2) and (3) below where τ is torque, R is resistance, K_m is a motor constant, B is the damping coefficient, and m is mass.

$$V_{emf} = K_e \frac{\overset{\circ}{x}}{r} \quad (1)$$

$$\tau = K_m \frac{V_{emf}}{R} \quad (2)$$

$$F_{damping} = \frac{B}{m}\overset{\circ}{x} = \frac{\tau}{r} = \frac{K_m K_e}{Rr^2}\overset{\circ}{x} \quad (3)$$

DESIGN ANALYSIS

Engineering Design Parameter Analysis

***External Force Analysis in Locked Position*:** An external force analysis was preformed to approximate the maximum horizontal and vertical forces on the pack in the locked position. These forces were used to determine the vertical acceleration range we need to measure with the accelerometer. The horizontal force is used in a later analysis to determine the horizontal rail deflection during use.

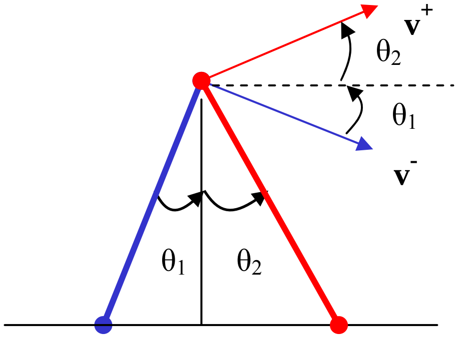


Figure 1: Resultant vectors modeled from the motion of walking

$$a = \frac{dv}{dt} \approx \frac{v^{-} - v^{+}}{t_{double-\sup port}} \qquad (4)$$

$$a_x \approx v_0 \frac{(\cos\theta_1 - \cos\theta_2)}{t_{double-\sup port}} \qquad (5)$$

$$a_y \approx v_0 \frac{(-\sin\theta_1 - \sin\theta_2)}{t_{double-\sup port}} + 9.81 \qquad (6)$$

From these equations, where v^+ and v_- are the resultant velocity vectors, θ_1 and θ_2 are their corresponding angles, we were able to determine that a maximum 1.72 g's and 0.21 g's would occur in the horizontal and vertical directions, respectively. We also found that a maximum force of 31.47 N would be felt in the horizontal direction. These findings have allowed us to select an accelerometer and perform the rail deflection analysis which is explained later.

***Pack Dynamics Analysis in Unlocked Position*:** We analyzed the dynamics of our pack in the unlocked position to determine the response the load would have to an input at walking frequency.

$$m\ddot{x}_2 = -(k_1 + k_2)(x_2 - x_1) - T \qquad (7)$$

$$m\ddot{x}_2 = -(k_1 + k_2)(x_2 + x_1) - \frac{J(\ddot{x}_2 - \ddot{x}_1)}{r^2} + \frac{K_e Kt(\dot{x}_2 - \dot{x}_1)}{Rr^2} \qquad (8)$$

From this analysis we were able to produce the transfer function seen in Equation (9) where K_e and K_t are motor constants, R is the resistance, r is the capstan radius, m is mass, J is the rotational inertia, k_1 and k_2 are the spring constants above and below the load plate, and x_1 and x_2 are the positions of the frame and load plate, respectively, relative to ground.

$$H(s) = \frac{x_2}{x_1} = \frac{\frac{J}{r^2}s^2 + \frac{KeKt}{Rr^2}s + (k_1 + k_2)}{\left(\frac{J}{r^2} + m\right)s^2 + \frac{KeKt}{Rr^2}s + (k_1 + k_2)} \qquad (9)$$

A bode plot of this transfer plot, Figure 2, shows we will be able to make the load oscillate out of phase with the walking frequency as well as control how far out of phase and its magnitude with damping.

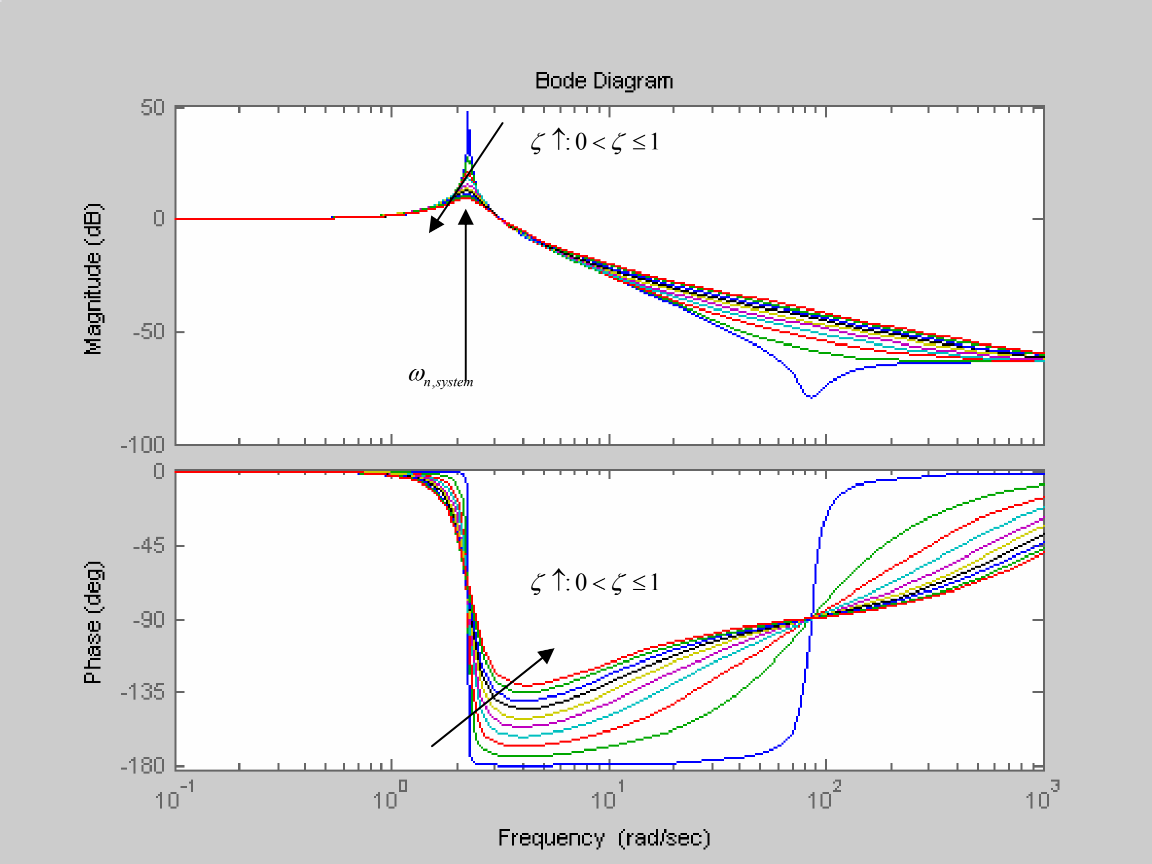


Figure 2: Bode plot showing the transfer function in Equation 9.

***Motor selection*:** We have been tasked to provide a zeta (damping) range between 0 and 1. To do this we needed to select a motor that would allow for damping would allow for that damping range. To accomplish this we first characterized the dynamics of a motor and then simplified the pack dynamics, so we were only analyzing motion between the jig plate and the load plate. This allowed us to determine the equations for the effective inertial mass, *M*, the damping coefficient, *B*, and the damping ratio, ζ, as seen below in relation to motor characteristics.

$$M\ddot{x} + B\dot{x} + Kx = 0 \qquad (10)$$

$$B = \frac{K_e K_f}{R r^2} \qquad (11)$$

$$M = \frac{J}{r^2} + m \qquad (12)$$

$$\xi = \frac{B}{2\sqrt{KM}} \qquad (13)$$

From these equations, we were then able to take a 'guess and check' approach to selecting a motor. We used values from the specification sheets of different motors to determine if they would give us the proper damping range.

Through this analysis, we have determined that we could use a Maxon Motor RE-25-055-38EBA2-011 with a planetary gear head GP32C with a gear ratio 14:1. This combination will give us the correct zeta range.

Internal Force Analysis: Internal force analysis was used to determine the spring force, damping force, and max velocity on the load plate.

$$F_{spring} = K(h + \frac{A}{2}) \qquad (14)$$

$$F_{damping} = B\dot{x}_{\max} \qquad (15)$$

Here, h is the hang height and A is the amplitude of the load plate oscillation. With this analysis, we were able to approximate the maximum forces applied to the Jig plate from the springs and our damping system. These values are used in further structural analysis of the pack, explained later.

Bending and Buckling Analysis: We performed bending and buckling analysis to ensure that a jig frame width of 1.5 inches would not deflect beyond 1.58 mm. We used the Secant Theorem for Column Deflection with Eccentric Loading to calculate the deflection of the jig plate along the length in the z direction as seen in Figure 3.

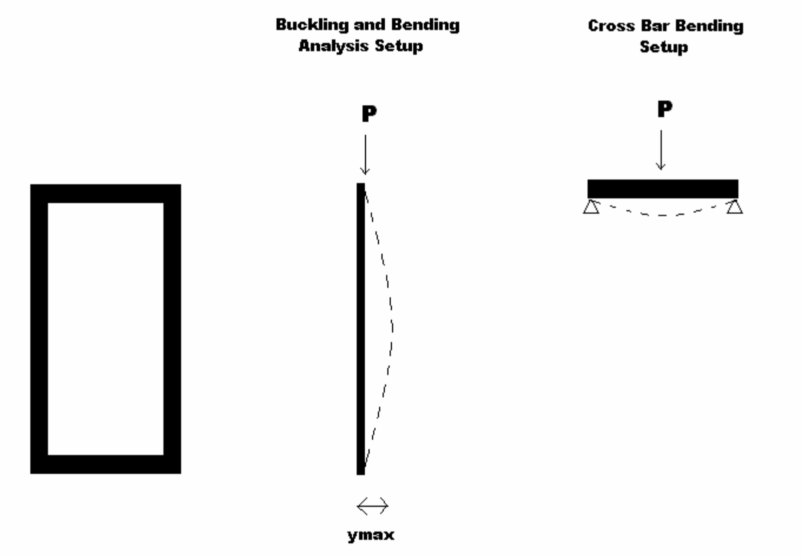


Figure 3: Force Analysis Setup

To calculate this we used Equation (16), where P is the load in Newtons, L is length in meters, E is the elastic modulus in Pascals, I is the moment of inertia in m^4, and e is the eccentricity of the load in meters. Using the values for 6061 Aluminum and the loads that we expect to see, we found that the deflection, y, would equal less than 1 mm.

$$y_{\max} = e * \left[\sec\left(\sqrt{\frac{P}{EI}} \frac{L}{2} \right) - 1 \right] \qquad (16)$$

We also used Equation (17) to calculate what size force would be needed to buckle the structure. We found it to be approximately 1.5 kN. This is about 5 times larger than the maximum force we expect to see.

$$P_{cr} = \frac{EI\pi^2}{L^2} \qquad (17)$$

We also calculated the maximum deflection of the cross bar. Using simple beam bending analysis, Equation (18), we found that the bar would deflect less than 0.1 mm.

$$y_{\max} = \frac{PL^3}{48EI} \qquad (18)$$

This is a worst case calculation, where only the two ends are secured. We will likely see far less deflection because our design includes for points of attachment spread over the length of the bar.

We also performed a bending analysis on the rails to be sure that they would not deform under a max load of 25 kg. Using the above equation as well, we found that they would deflect less than 0.3 mm.

These calculations validate our frame and rod material selection as well as the proposed dimensions.

Failure Analysis

To assess the safety of the suspended-load backpack, we made use of DesignSafe 3.0 software. Though our pack is intended for research personnel who have a great deal of experience in performing the calculations necessary to assure safe operation of our prototype, there is room for human error. DesignSafe suggested our greatest risks were ‘crushing’, ‘cutting/severing’, and ‘pinch points’; all with a risk level of ‘moderate’. These risks all come from the moving load plate, which could be loaded with up to 25 kg. In order for any of these hazards to occur, the user would have to be using the backpack improperly with a significant amount of weight on the load plate. If this were to happen, an appendage of the user could be caught between the jig and the load plate.

There were several other hazards that were assessed using DesignSafe, but there were all categorized with a risk level of ‘low’. The other hazards included ergonomic considerations, loss of balance, and electrical considerations. The ergonomic and loss of balance hazards were at worst only slightly more dangerous than those of a normal backpack. The electrical hazards were minimal due to the low amount of power being used by the pack.

The structure of the pack is designed with a large factor of safety (on the order of 10) and under normal use would have a negligible chance of failure. The potential hazard arises in the user specified spring constant. If the constant is too low, the springs may not be able to support the weight of the load plate and could break, causing the plate to slam into the jig. The safety factor for the spring portion of the pack must be specified by the user to allow for the pack to be versatile enough for research use.

Based on the requirements of our design and its intended users, we believe our design is extremely safe and would not be capable of causing lasting injuries under normal use. The structure itself is very strong and the only danger comes from user input into the system. These hazards cannot be limited without limiting the usefulness of the pack in its intended research environment.

FINAL DESIGN

Backpack frame: The backpack frame that will be directly worn by our user is an existing external frame. The frame is 24.5 inches in height and 12 inches in width.

Attachment brackets: There will be two brackets used to secure the jig plate to the external backpack frame. These brackets will be made from aluminum strips with dimensions 1.5 inches in height, 22.5 inches in width, and 1/16 inches in thickness. Both strips will be bent at 90° in two places, producing a long 'C' shape. Each bend will be 6 inches from either end of the strip. These brackets will keep the jig frame 3 inches from the external frame. 4 holes will be put in each strip, 2 located in 0.5 inches from either of the 90° bends. The other two holes will be located in 3.25 inches from the bend.

Jig Frame: The jig frame will be used to ensure tolerances are kept for vertical motion. A 6061 aluminum alloy plate with dimensions 24 inches in height, 12 inches in width, and 0.25 inches in width will be milled to produce the jig frame. Milling will remove a rectangle 9 inches in width, 21 inches in height, and 0.25 inches in thickness from the center of the aluminum plate.

There will be 8 holes, 0.25 inches in diameter, in the jig frame. 4 holes will be in the top section of the frame, 2 located 1.25 inches towards the center from either right or left outside edge and be centered between the top outside and inside edge of the frame (down 0.75 inches from top). Two more holes will be drilled 4 inches in from both the right and left outside edges of the jig frame also located 0.75 inches down from the top edge. The bottom section of the frame will be a mirror image of this layout.

Four grooves will be milled into the jig frame to lay our rods into. Two grooves will be in the top section of the frame, located 2.5 inches towards the center from either right or left outside edge of the frame. These grooves will be 1 inch long, beginning at the inside top edge of the frame, and will be 3/32 inches deep. The bottom section of the frame will be a mirror image of this layout.

2 Attachment (sandwich) plates: Two plates will be attached to the top and bottom section of the jig frame. These plates and the jig frame will act as the bread of a sandwich, clamping two steel rods between them. Each attachment plate will be aluminum with dimensions 2.5 inches in height, 12 inches in width, and 0.25 inches in width.

The top attachment plate will have 4 holes for connecting to the top of jig frame. These holes will be 1/4 inch in diameter, 2 located 1.25 inches towards the center from either outside edge and 2 located 4 inches from the outer edges. All 4 will be located 0.75 inches from the top of the plate. The attachment plate for the bottom of the frame will be a mirror image of the top attachment plate.

Both attachment plates will have five holes for connecting springs and the capstan tension screw. These holes will be 0.25 inches in diameter. For the top attachment plate, the center spring hole will be located 6 inches from either right or left outside edge of the plate and 0.5 inches from the bottom edge. Two holes will be on either side of the center hole, with a spacing of 1 inch between the centers of each hole. The bottom attachment plate will be a mirror image of this layout. The central hole will be used for the capstan tension screw while the other four can be used for spring attachment.

Meat of the sandwich (parts for the jig): The jig will provide a toleranced attachment for our steel rods and springs. Two steel rods will be placed into the machined grooves, between the two pieces of aluminum. The rods will be 23 inches in length and 3/32 inches in diameter. Four springs will be attached to the top and bottom of the attachment plate.

Load Plate: The load plate will provide an attachment place for the variable weight, the motor used for damping, and the springs. This plate will be 6061 aluminum alloy with dimensions 9 inches in height, 9 inches in width, and 0.25 inches in thickness.

The top and bottom ¾ of an inch will be milled down by 1/8 inch. In the region at the top and bottom of the plate there will be 4 holes, each with diameters of 0.25 inches. The center hole at the top of the plate will be 4.5 inches from either right or left outside edge and 3/8 inches from the top edge. Two holes will be on either side of the center hole, with a spacing of 1 inch between the center of each hole. The bottom region will be a mirror image of this layout. This will allow for spring attachment without interfering with the weights that will be added.

At the center of the load plate, 4.5 inches from the top and 4.5 inches from either side, there will be a hole with a 2-inch diameter. Through the backside of the hole, a 2-inch diameter, aluminum tube with an inner diameter of 1.5 inches will be inserted. This tube will have a collar with a 4-inch outer diameter and thickness of 0.25 inches. This collar will have six 0.25 inch holes to be used to screw the attachment to the backside of the load plate. The load plate itself will have 6 corresponding holes. The metal pipe will protrude out 4.75 inches from the load plate. This will provide an attachment for free weights with a 2-inch diameter, which allows for varying loads to be placed on the system. The inside of the 2-inch metal pipe will house our motor.

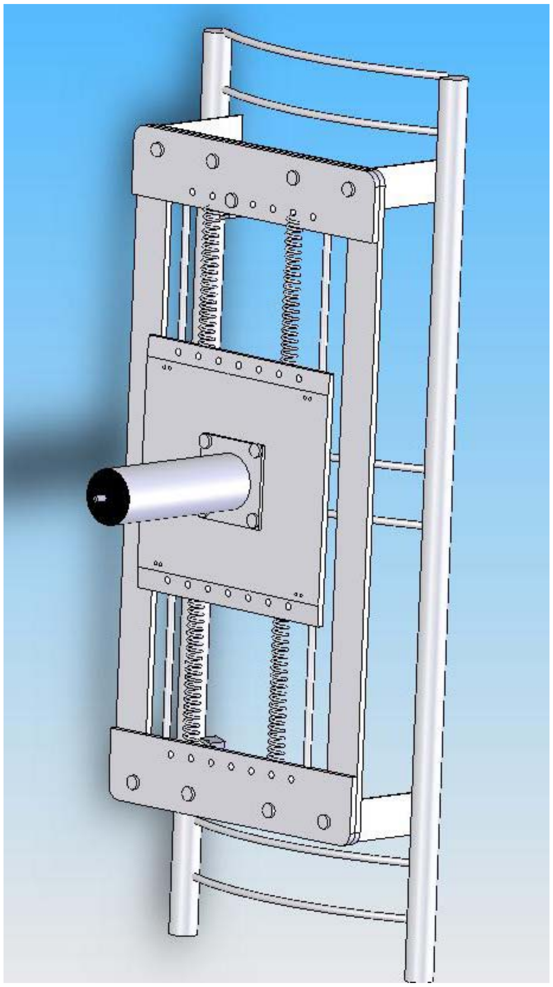


Figure 4: This SolidWorks model shows our final pack design as described above. More design models can be seen in Appendix C.

MANUFACTURING PLAN

Jig Frame: The jig of the backpack was manufactured on a mill. The mill used has a digital coordinate readout which is accurate to five-ten-thousandths of an inch. The central rectangular hole was cut out using a ¼" end mill bit. We chose this size bit because it is strong enough to cut through the material while still removing as little material as possible. The holes for spring attachment were drilled at the specified locations using a ¼" drill bit on the mill machine. The grooves for the rods were milled out using a ¼" ball mill and cutting 1/8" into the material. To ensure accuracy, once the aluminum plate was placed and clamped to the mill table, it was not moved until all cuts were made. This helped keep the grooves parallel which in the end dictates how parallel the rods are.

Top Slice: These two pieces were cut from the extra material extracted from the center of the jig plate. They will be cut to size on the same mill, once again using a ¼" end mill bit for the edges and a ¼" drill bit for the spring and connection holes.

Rods: The rods were bought 36 inches in length. Thus, they simply need to be cut down to 23 inches. This is most easily done using a bandsaw because this is a quick, and although not quite as accurate, simple process. The accuracy of the rod length is not essential to the function of the design as long as they are within 1/32 of an inch. This was able to be obtained from the bandsaw.

Load Plate: Once again, the largest contributor to the manufacturing of the load plate was the mill. After locating the center of the plate, a 2"core bit was used to cut the hole for the weight attachment piece. A ¾" end mill was used to cut half way through the material on the top and bottom edges. This creates the lip where the spring holes (using ¼" drill bit) are located. Four ¼" holes equally spaced around the central hole were drilled using the mill so that the weight attachment could be bolted to the load plate.

Weight Attachment: The weight attachment required the use of welding. After the central 2" hole and four ¼" corner holes were cut into the connection plate, the 2" metal tube was welded to the connection plate ½" up the tube. The ½" dimension was chosen in order to more easily weld the pieces together. After welding, the lathe was used to cut the tube down so only ¼" of the tube remained on one side of the connection plate while 4.5" remained on the other. .

Tensioning Pieces: The tensioning pieces were manufactured purely on the mill using a ¼" end mill bit. Using the digital readout of the machine, the accurate dimensions were able to be obtained. Number 42 drill bits were used for the small screw holes. They were then threaded using a 6-32 tap. A #39 drill bit was used for the cable holes while a ¼" drill bit was used for the connection hole.

Capstan & Bracket: The capstan was manufactured using both the lathe and the mill. Because of the length of the capstan, we felt it was necessary to include a bracket for the far end of the capstan where the far end would be inserted in a bearing which would allow it to rotate freely. Thus, one end of the capstan was lathed down to 3 mm diameter. The capstan was then turn on end and a small groove was milled out of the end using a 1/8" end mill bit. A small bar was then milled to size to fit in the capstan end to reduce any slipping. In order to do this, the band saw was used to make a small slit. Two holes were drilled using a #39 drill bit in adjacent sides; one located in the center and the other on the end. The bracket for the capstan was machined on a mill using a ¼" end mill bit. The hole for the capstan bearing was drilled using a 7mm drill bit also on the mill. The bearing was then press fit into place.

Load Plate to Rod Brackets: The brackets were machined using the bandsaw and the mill. They were cut to 2" lengths using the bandsaw and then 3/8" holes were drilled using the mill to ensure the accuracy of the hole location. The bushings were then press fit into the bracket holes. The Smaller holes, using a #42 drill bit, were drilled in the adjacent side and tapped.

Jig to Frame Brackets: The large brackets were made from 1.5"x 1/8" x 18". The ¼" holes for the frame attachment and jig attachment were drilled using the mill. The metal was then bent to shape using a 90 degree angle bender.

After applying these machining processes, the final product was produced. Photographs as well as the bill of materials for the final prototype can be seen in Appendix D.

DESIGN VALIDATION

To validate our final design, we first checked that all of the engineering specifications had been met. Based on our final design we were able to vary the amount of damping by varying the resistance of the motor. The stiffness could be changed by varying the number of springs attached from the load plate to the pack frame or by using springs with a different spring stiffness. By incorporating the 'Standard Barbell Attachment' to our load plate we were able to meet the engineering specification indicating the need for variable weight. This feature also allows the user to change weights quickly and easily. To secure the load plate into a locked position we used simple locking straps found that are easily attachable to the load plate and frame and then tightened. We used low friction steel-backed PTFE coated bronze plane bearings to ensure the pack was as frictionless as possible. As requested, the final prototype frame weighed only 3.26 kg, less than 20% of the max load (25 kg). By using two hip straps in our final design we were able to minimize the backpack frame to body motion along with making the pack very comfortable to wear. Through the use of LabView, a rotary encoder, and an accelerometer, we were able collect real-time position and acceleration data, meeting one of the most engineering specifications. The proper setup and the LabView output can be seen in Appendix E.

The true validation for many of our engineering specifications was accomplished during hands on 'testing' of our pack. This included simply wearing the pack and walking. From these initial experiments we found that there was very little motion between the backpack frame and the body. Everyone within our design team found the pack comfortable to wear and there was no interference with the normal walking motion. This was further tested at the Design Expo. During the Expo a variety of people wore the pack, from large men to children. We encountered no problems with the fit of the pack, and many people even commented on the comfort of the straps.

DISCUSSION

Overall our design has performed very well. The weakness, however, is with the damping system. The motor we are currently using is not strong enough to provide the full range of damping we wanted to achieve. This is not to big of a problem though because we designed the pack so that it would be possible to switch motors. During the manufacturing stage of our project Professor Gillespie mentioned a new method of increasing the damping from a motor using what is called negative resistance. He never got into the details of how the system worked but mentioned it was a simple circuit involving op amps and could produce large damping out of small motors. Further investigation into negative resistance would definitely be beneficial to this project.

Another method for increasing the damping of the motor is to use a gearbox. Ideally, we would have looked into this earlier in the design process. While specking out parts for our final design we realized that we could not find a motor with the we needed and that we would have to attach a gear box to get the full damping range out of one motor. Upon diving into the equations and then trying to spec out a gearbox we decided that we did not have enough time to find an appropriate gearbox within a reasonable price range for our application.

There are gearboxes designed to fit on the size of the motor we are currently using in the prototype and the motor can be sent in to get fit with one. If it is determined that another motor should be used, and it does not fit in the current configuration a new capstan could be made and the new motor could mount to the back of the faceplate with a pulley attaching it's output shaft to a pulley on the capstan. The rest of the assembly could then remain the same. Using different pulleys of different radii would also serve as a gearbox.

Looking back at the entire project we could have done less analysis and spent less design time on the structure of Jig Plate and rails, built the pack assembly earlier and spent more prototyping different ideas for getting the damping we wanted out of one motor. When planning out the project we did not know enough about available motors to realize we could not get our full range of damping with our plan and so didn't set aside enough time to design around that.

RECOMMENDATIONS

We think it will be most useful to buy a set of springs that do not plastically deform over time. The springs that we purchased and have been using slowly deform and will lead errors when they stretch to their pre-loaded length.

We also recommend the lab purchase a data acquisition system that can measure both digital and analog signals real time. The LabView software an National Instruments Equipment we used for this project was great to work with but any real time digital and analog DAQ would work fine.

To get a larger damping range we recommend some research first into the negative resistance method. It seems like a quick solution and will allow for testing of the metabolic theory while more research can be done other methods. The use of gearboxes is a good option, and was used by Professor Rome, but it will likely limit the lower range of damping attainable with the motor as gears will amplify the affect of motor friction and reduce efficiency of power conversion between electrical and mechanical power. Another option is using multiple motors in parallel. This would require a redesign of the load plate but might have better efficiency than a gearbox.

Further, for motor selection we recommend setting aside a large amount of time for testing design ideas to see how analysis compares to actual performance.

CONCLUSION

We were given the task of creating a versatile suspended-load backpack for use in a research environment. The pack had to be capable of measuring system dynamics to study the possible energy-saving effects of a suspended-load system. The system parameters (spring constant, damping constant, and mass) had to be as variable as possible while keeping tolerances for non-vertical and pack-to-body movement.

Using PTFE coated plane bearings on hardened steels rods, we were able to create a very low friction path for the load plate to obtain maximal damping ranges. Variable spring constants were made possible through the simple parallel spring attachment method. Variable damping was achieved through a motor and capstan system in conjunction with a potentiometer. The mass of the system is easily varied using standard 'Olympic-sized' weights and weight clips.

Many alternatives to our final design were considered and rejected. Our design meets or exceeds the final requirements of the customer. The parts are easily obtainable, allowing for reproducibility and repair. The self-contained pack can be easily wired to LabView hardware for measurement of the system dynamics. This design allows for simple and quick experiment setup able to yield accurate and conclusive results. Given its simplicity, it is capable of quickly proving or disproving theories regarding suspended-load walking.

ACKNOWLEDGEMENTS

We would like to thank our sponsor Professor Arthur D. Kuo of the University of Michigan for the great design problem, funding and all his advice and guidance, our design lab instructor Professor R. Brent Gillespie for his advice and guidance, and Robert Coury and Marvin Cressey for their help and advice manufacturing our prototype.

We would also like to thank and acknowledge the help given by:
Felix Huang
Kevin King
The Kuo Biomechanics Lab Group

REFERENCES

Science Journal:
Harvesting Energy by Improving the Economy of Human Walking
Arthur D. Kuo
Science 9 September 2005:
Vol. 309. no. 5741, pp. 1686 – 1687
http://www.sciencemag.org/cgi/content/full/309/5741/1686

__Generating Electricity While Walking with Loads__
Lawrence C. Rome, Louis Flynn, Evan M. Goldman, Taeseung D. Yoo
Science 9 September 2005:
Vol. 309. no. 5741, pp. 1725 – 1728
http://www.sciencemag.org/cgi/content/full/309/5741/1725?ijkey=Vm99YWJsA0hlI&keytype=ref&siteid=sci

Patents:

Backpack for harvesting electrical energy during walking and for minimizing shoulder strain
Rome, US Patent # 6,982,497
January 3, 2006
http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=/netahtml/srchnum.htm&r=1&f=G&l=50&s1=6,982,497.WKU.&OS=PN/6,982,497&RS=PN/6,982,497

Backpack and load conveyance apparatus
Cordova, US Pat # 5,769,431
June 23, 1998

See other patents and references in Rome patent # 6,982,497

Other:

To original online articles:

Backpack generates its own electricity
New design may offer way for relief workers to power crucial equipment
By Daniel B. Kane
Science
Updated: 4:23 p.m. ET Sept. 8, 2005
http://msnbc.msn.com/id/9245155/

__Backpack generates a powerful punch__
19:00 08 September 2005
NewScientist.com news service
Paul Marks
http://www.newscientist.com/article.ns?id=dn7970

New Backpack Generates Its Own Electricity
John Roach
for National Geographic News
September 8, 2005
http://news.nationalgeographic.com/news/2005/09/0908_050908_backpack.html

Shoe Leather as a Renewable Resource: Penn Biologists Invent Power-Generating Backpack

Greg Lester
University of Pennsylvania News Release
September 08, 2005
http://www.upenn.edu/pennnews/article.php?id=841

The Suspended-load Backpack
By Heather Handley Goldstone
Broadcast September 13, 2005
(Heather Handley Goldstone reports on science and technology for the Cape and Islands NPR Stations.)
http://www.wgbh.org/cainan/article?item_id=2443039

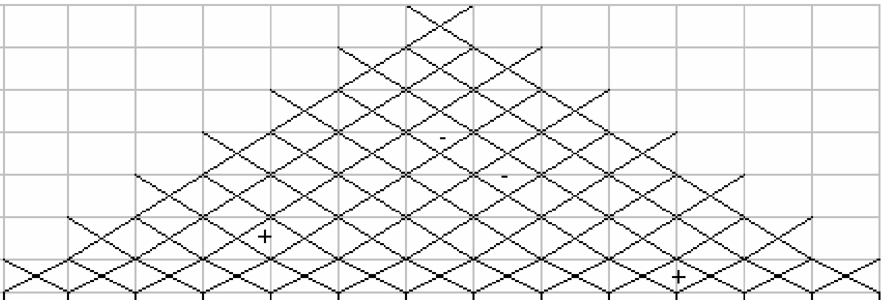
A New Twist on Muscle Power
MBL Scientist Invents Backpack that Empowers Wearers to Generate Electricity
LabNotes, Fall 2005
Volume 15, Number 2
http://www.mbl.edu/inside/what/news/publications/labnotes/05_fall04.html

Videos:
Lightningpacks.com
http://www.lightningpacks.com/media/15MBLoResClip.mpg

APPENDIX A: *Quality Function Deployment (QFD)*

+ Positively Related

- Negatively Related



	Weight	Range of Controlled System Damping	Range of Controlled System Stiffness	Frame Weight	Motion btw load and frame when locked	Movement btw Frame and Body	Force the frame is able to withstand	Time to Change System Dynamics	Trials before replacing parts	Ease to find and replace parts	Range Waist Adjusts To	Duration of Comfortable Wear	Ease to Measure Motion btw Load and Frame	Ease to Measure Motion btw Frame and Ground
Goal: + Max - Min 0 Target		+	+	-	-	-	+	-	+	+	+	+	+	+
Variable Damping	9	9												
Variable Spring Stiffness	9		9											
Low Friction	3	3												
Light Weight	1			9			1							
Ability to Lock Movement	9				9	3								
Fits Multiple Sized People	3			1							9	3		
Min. Frame to Body Motion	9				9								1	
Comfortable	1			3		3					3	9		
Durable	1						9		9					
Non-invasive	3											1		
Variable Loads	9			1			9							
Easy to use	9							9	9	9			9	9
Able to Collect Data	9												9	9
Measurement Unit		N-s/m	N/m	kg	cm	cm	N	s	trials	1-5	in	hrs	1-5	1-5
Importance Rating		**9**	**9**	**3**	**9**	**9**	**3**	**1**	**3**	**1**	**3**	**3**	**9**	9
Total		**90**	**81**	**24**	**162**	**30**	**91**	**81**	**90**	**91**	**30**	**21**	**171**	**162**
Normalized		0.08	0.07	0.02	0.14	0.03	0.08	0.07	0.08	0.08	0.03	0.02	0.15	0.14

APPENDIX B: *Concept Generation Figures 1-9*

These figures are referenced throughout the text and have been provided here for clearity.

Figure 1: This first idea for damping.

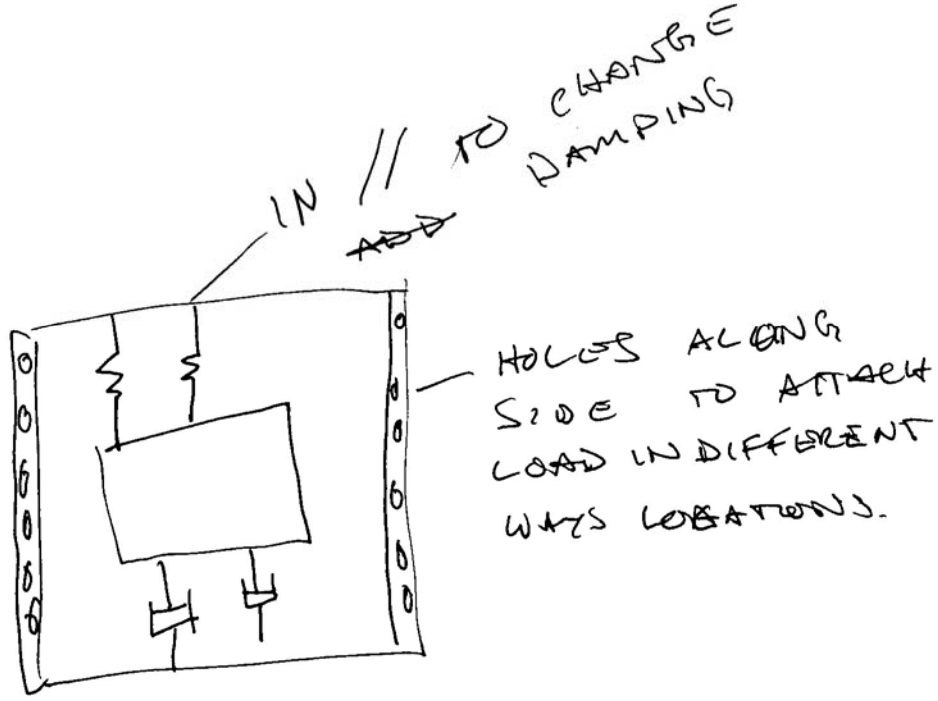


Figure 2: Concepts for varying spring stiffness.

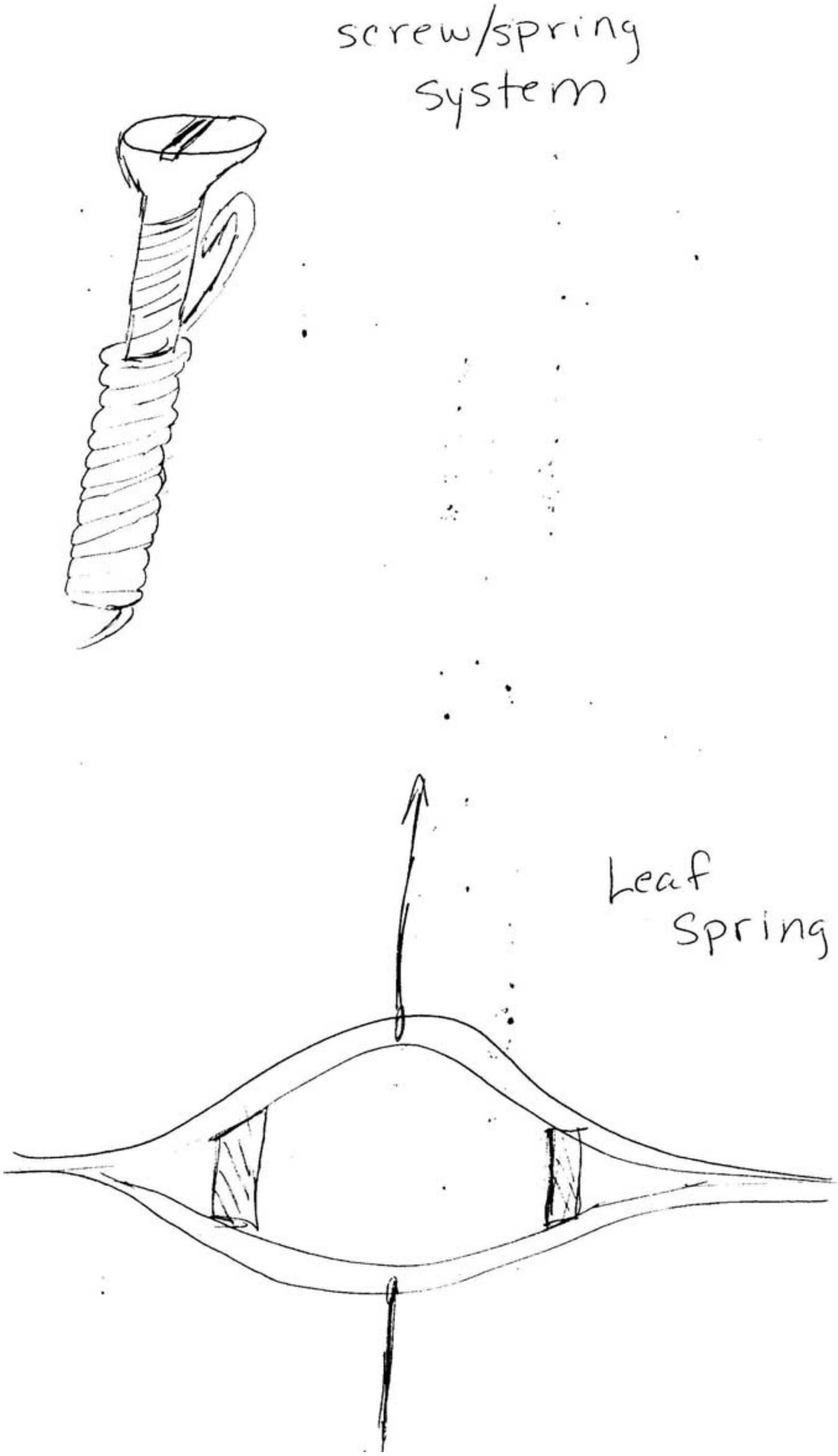


Figure 3: Concept for varying spring stiffness.

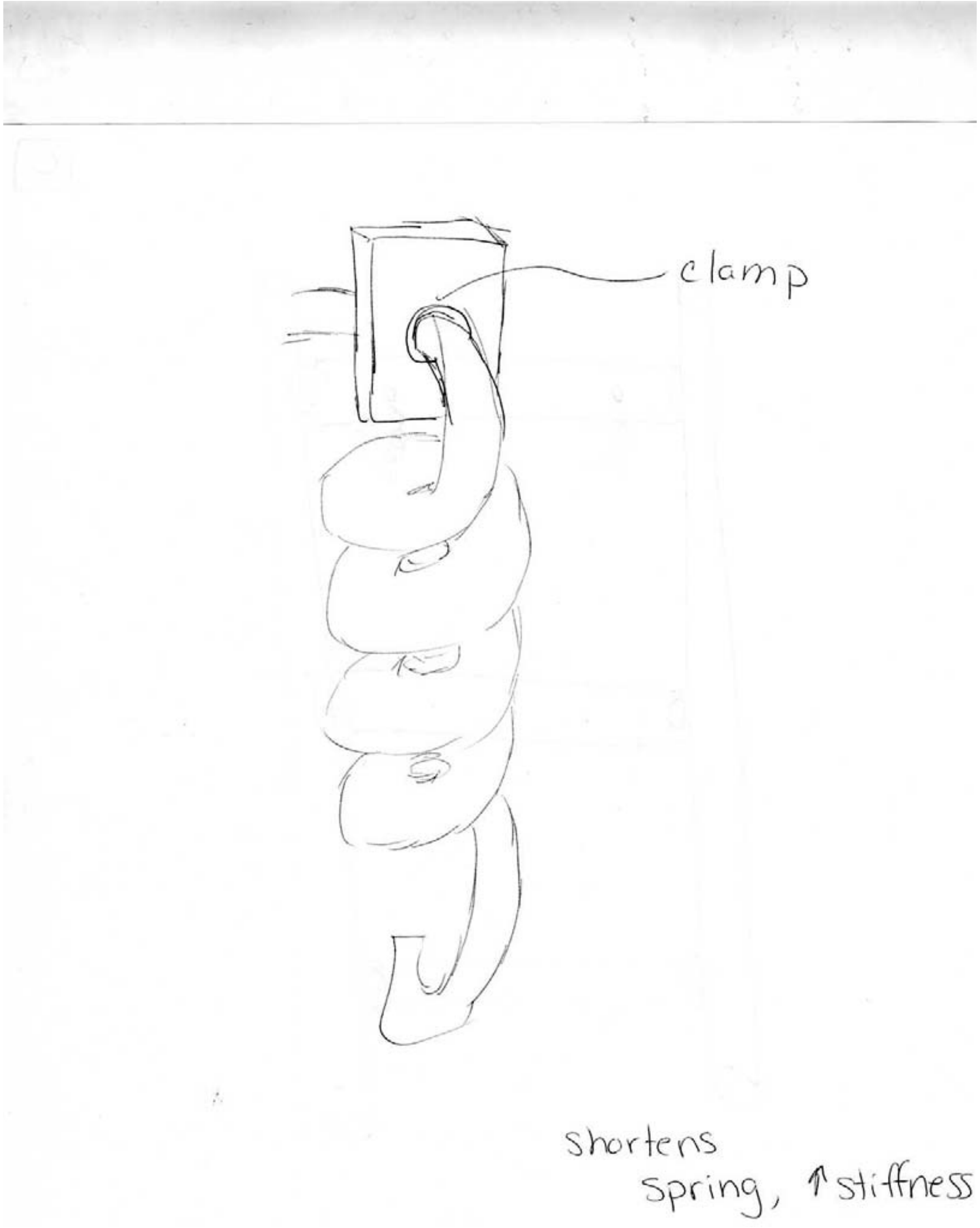


Figure 4: Concept for vertical motion path using heavy duty wire.

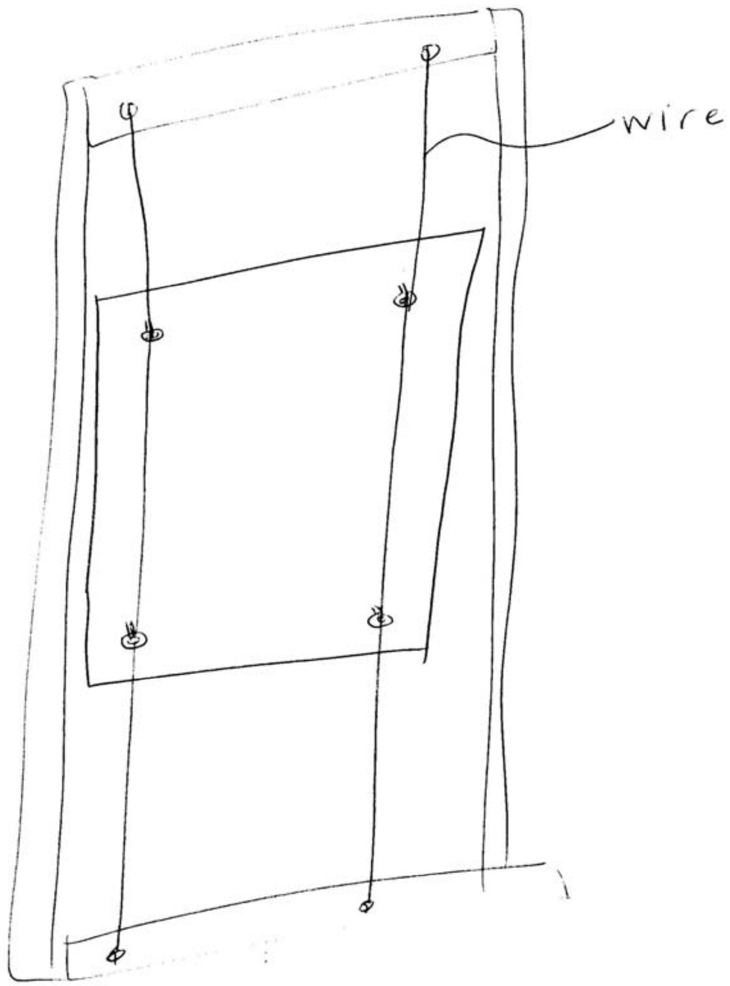


Figure 5: Concept for attaching components to the frame and possibly to the existing back pack using Velcro.

Figure 6: Concept for the locked position.

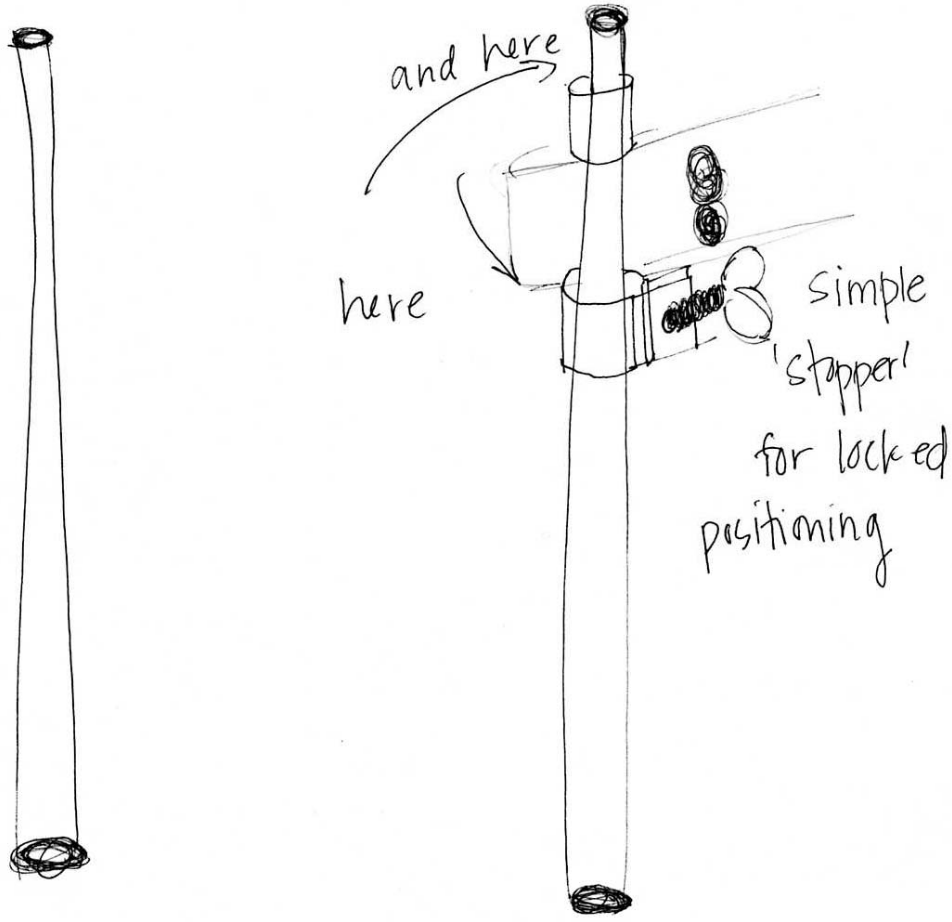


Figure 7: Concept for attaching varying weights to the pack using the idea of free weight attachment.

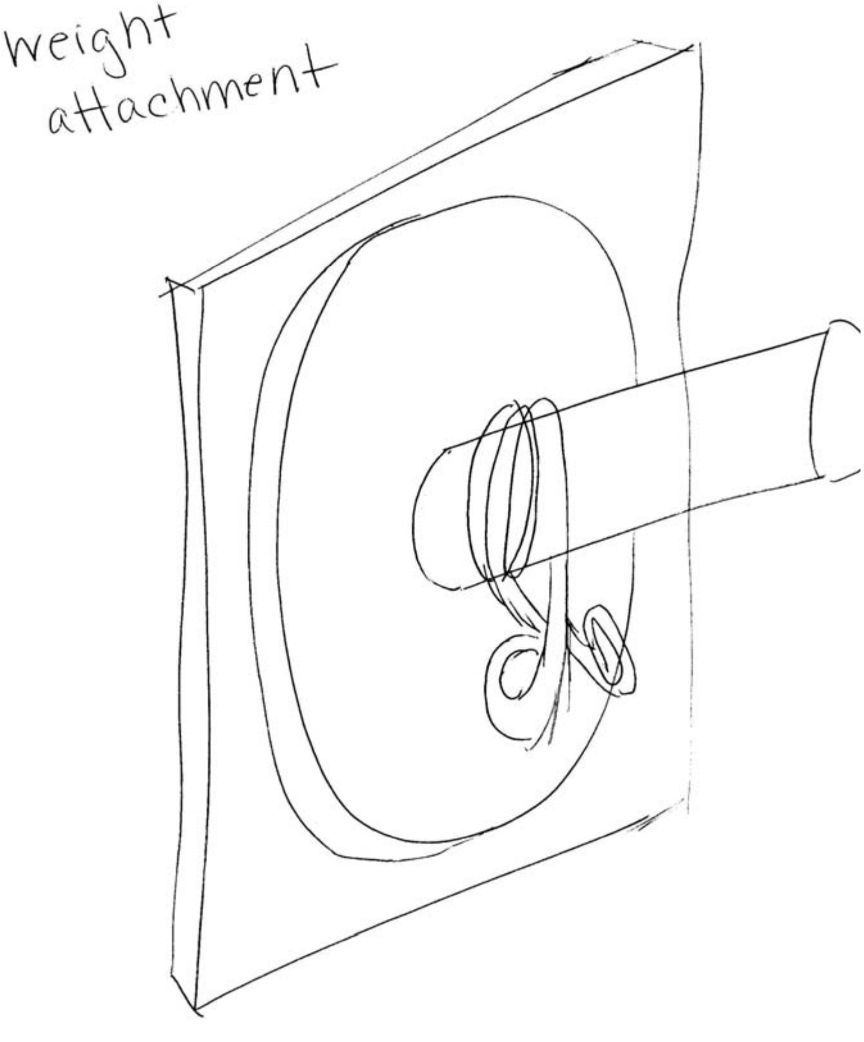


Figure 8: Solid works models for our Beta prototype Capstan motor.

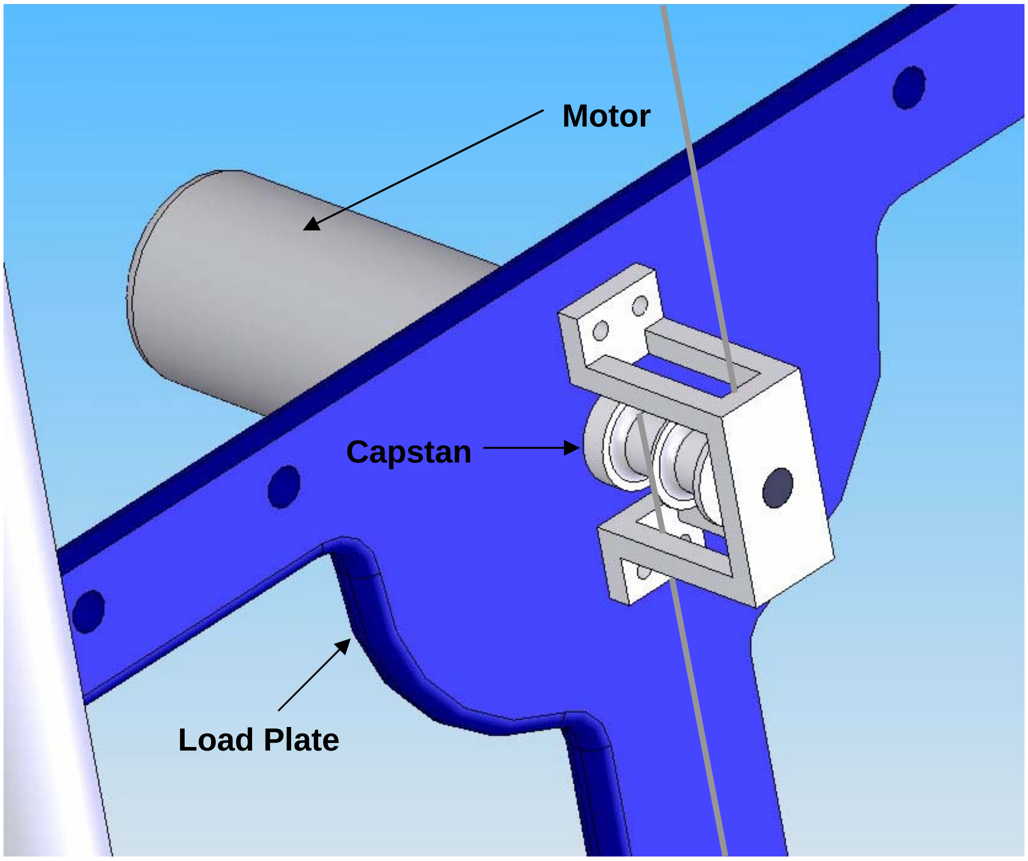
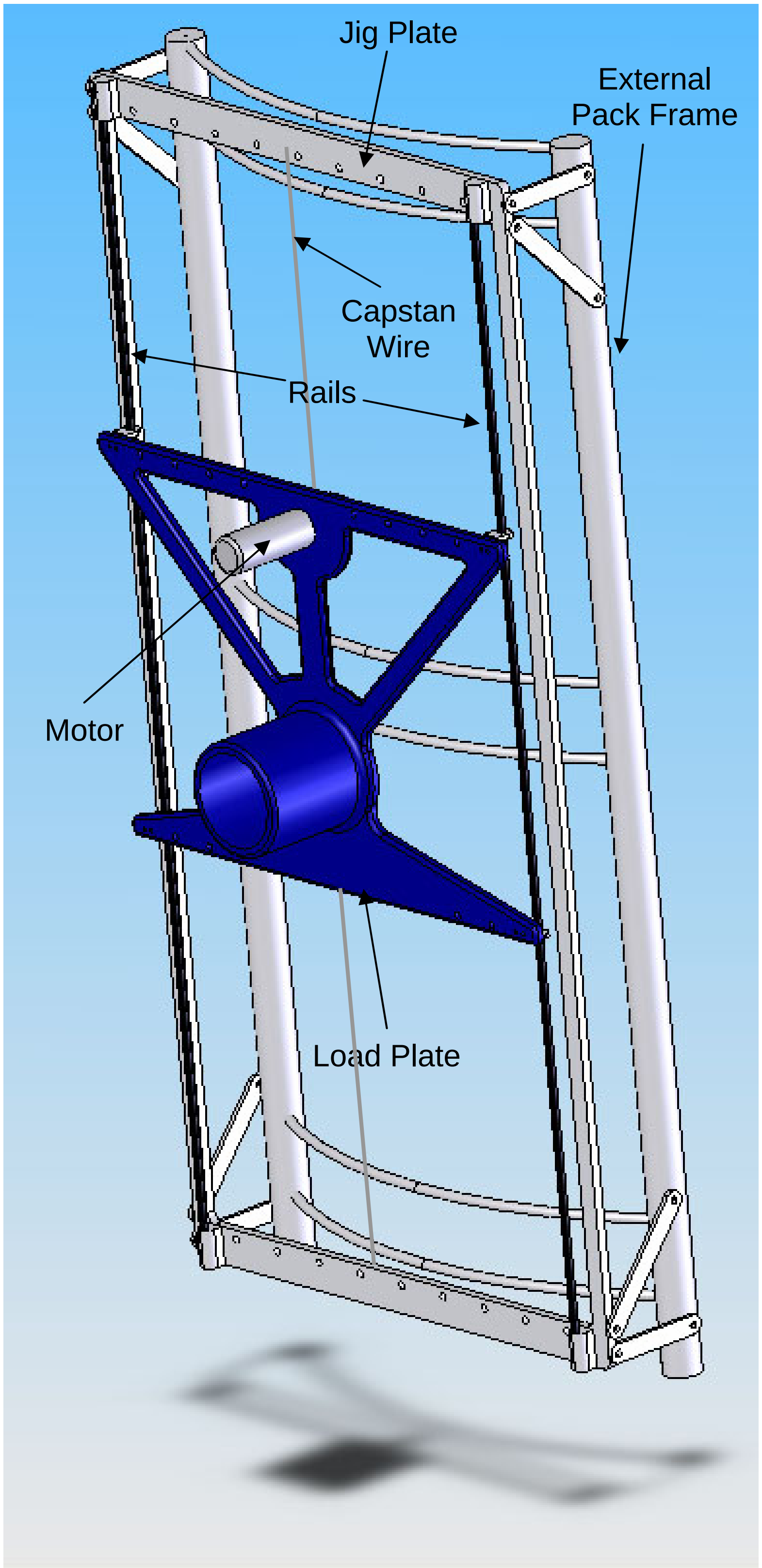


Figure 9: Solid works drawings for our Beta prototype.



APPENDIX C: *Final Design Drawings*

Figure 1: SolidWorks Final Design Model – Front Isometric View

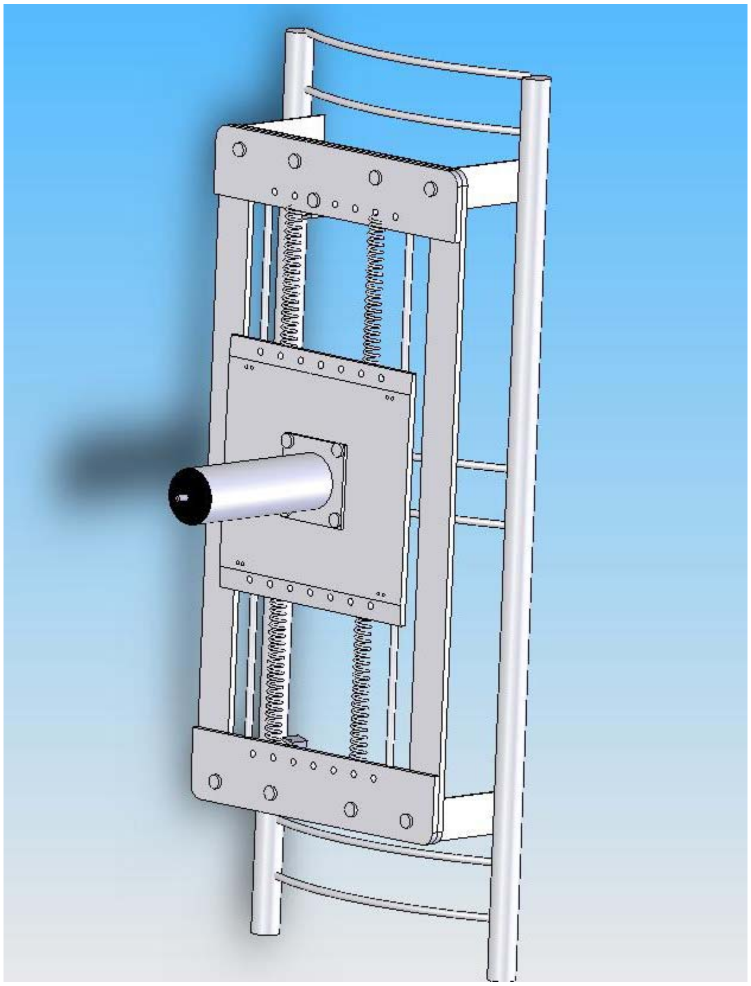


Figure 2: SolidWorks Final Design Model – Side Isometric View

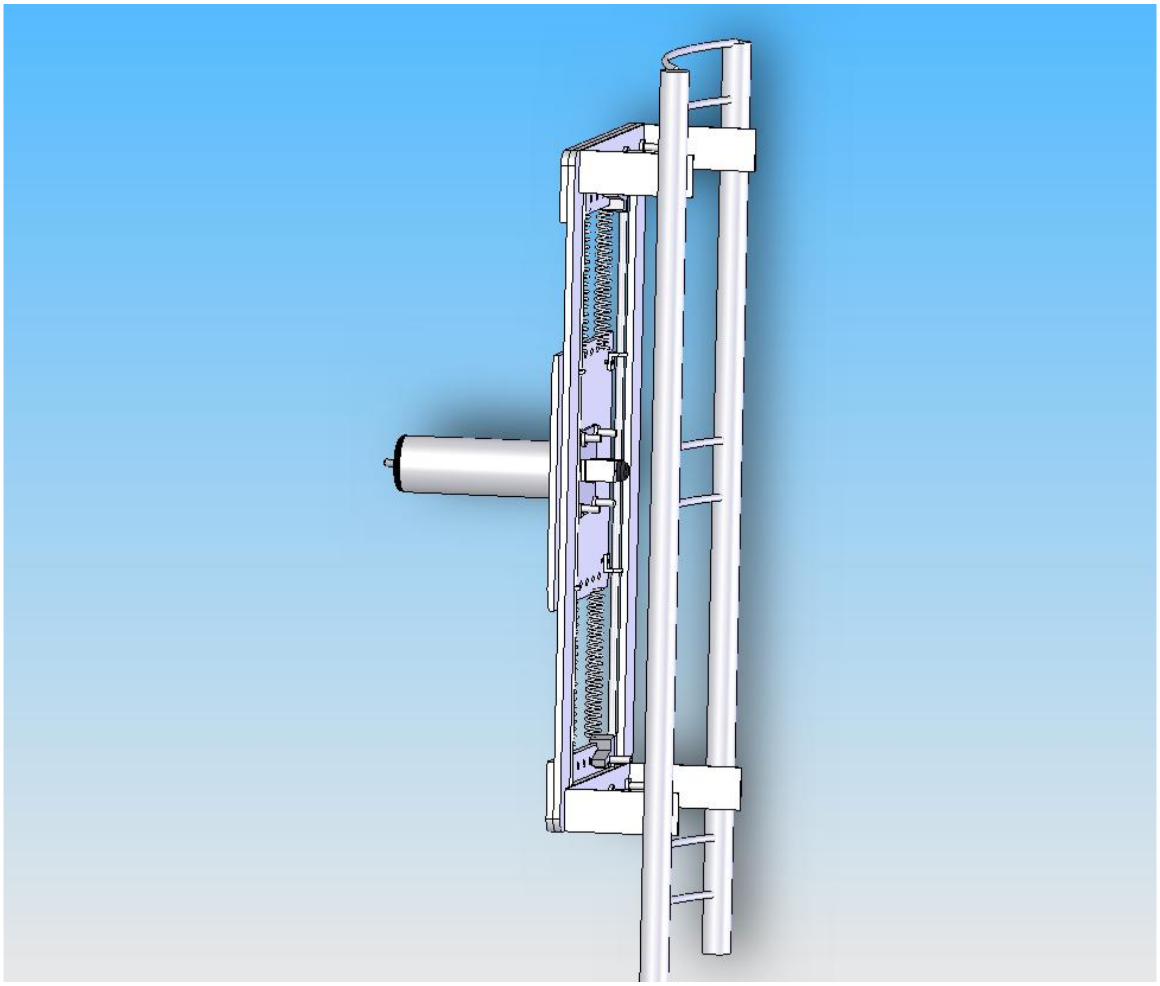


Figure 3: SolidWorks Final Design Model – Back View

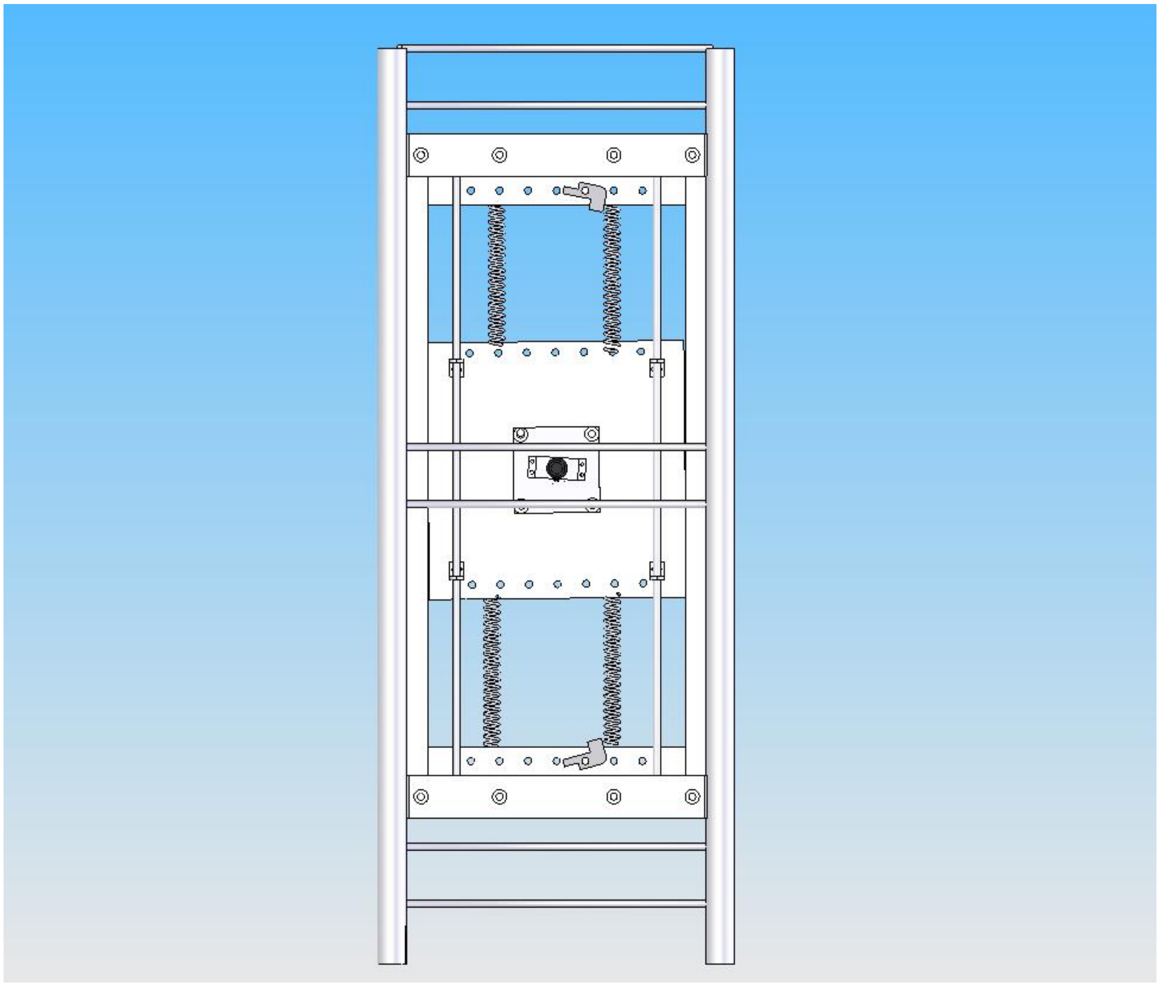


Figure 4: SolidWorks Final Design Model – Top View

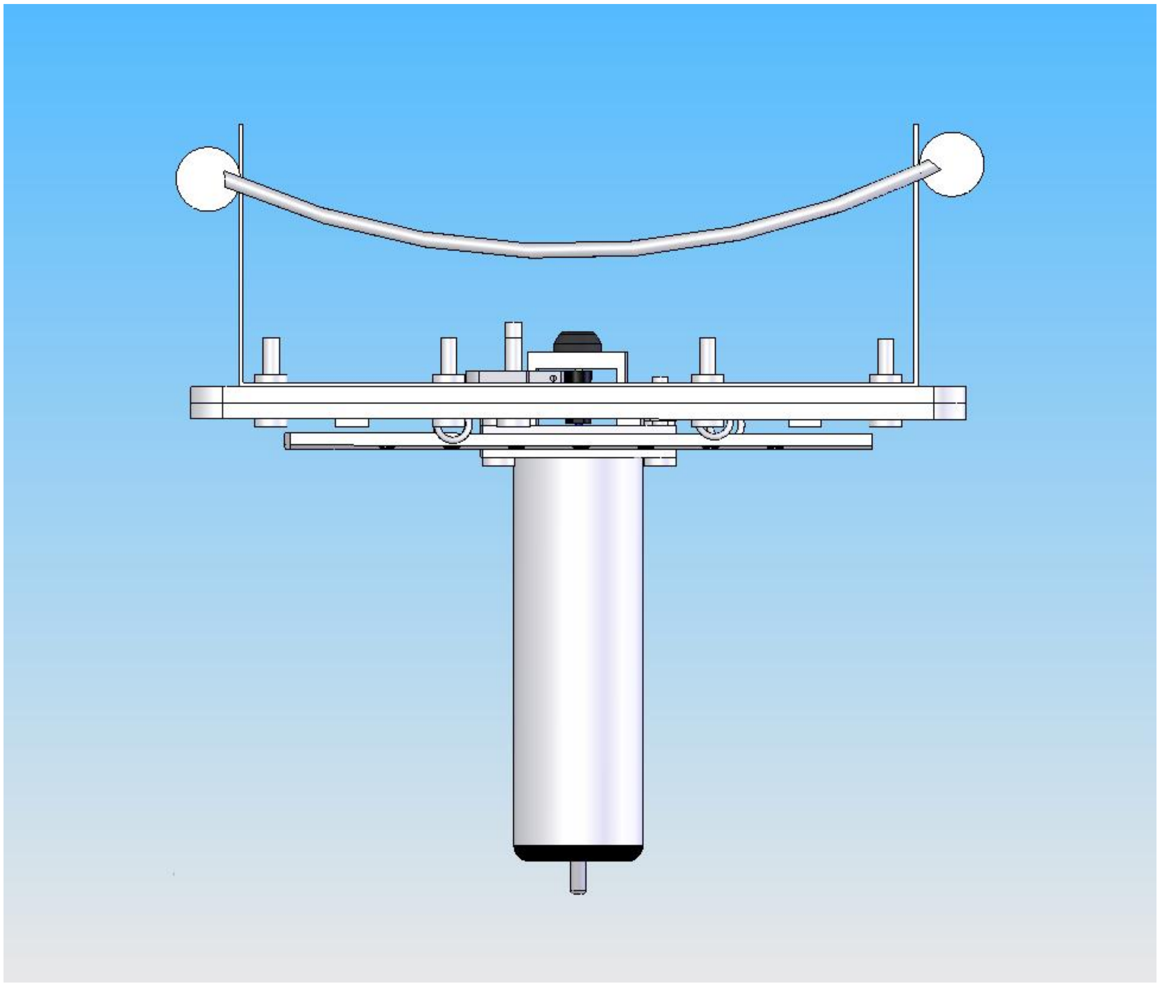
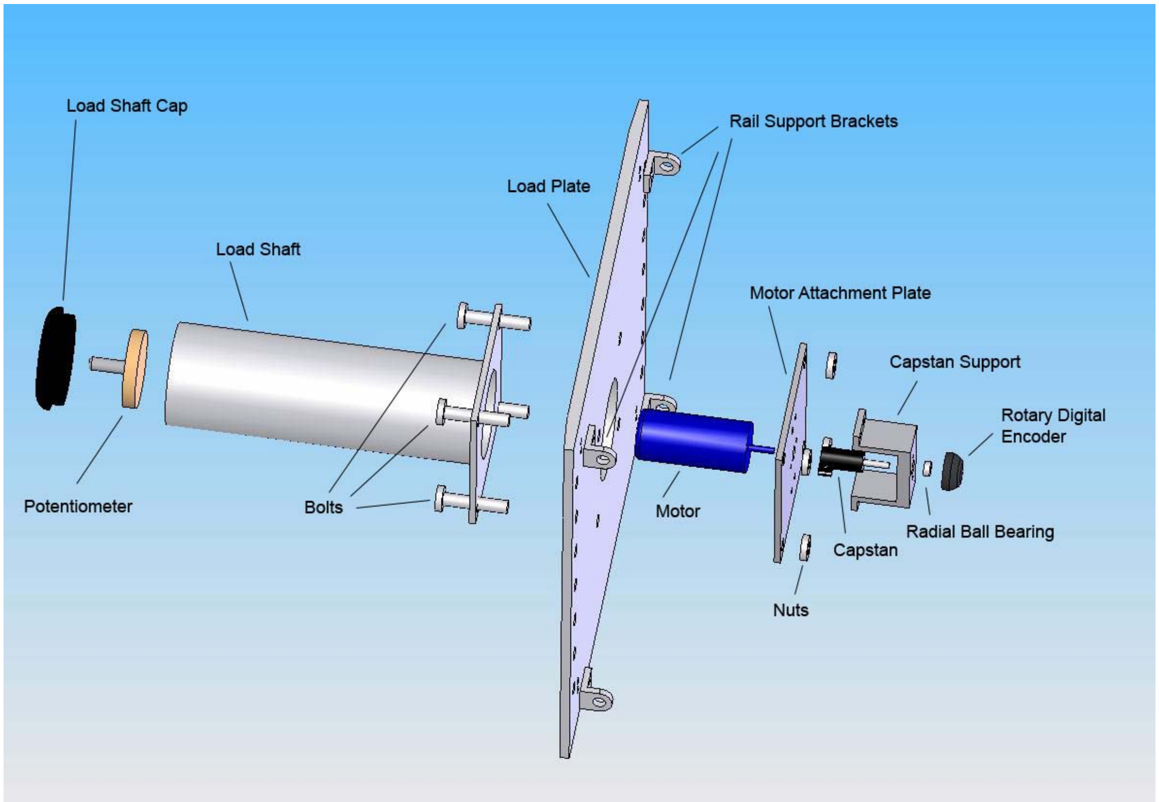


Figure 5: Exploded SolidWorks Model of Load Plate, Weight Attachment, Motor, and Capstan



APPENDIX D: *Final Prototype*

Figure 1: Complete Prototype

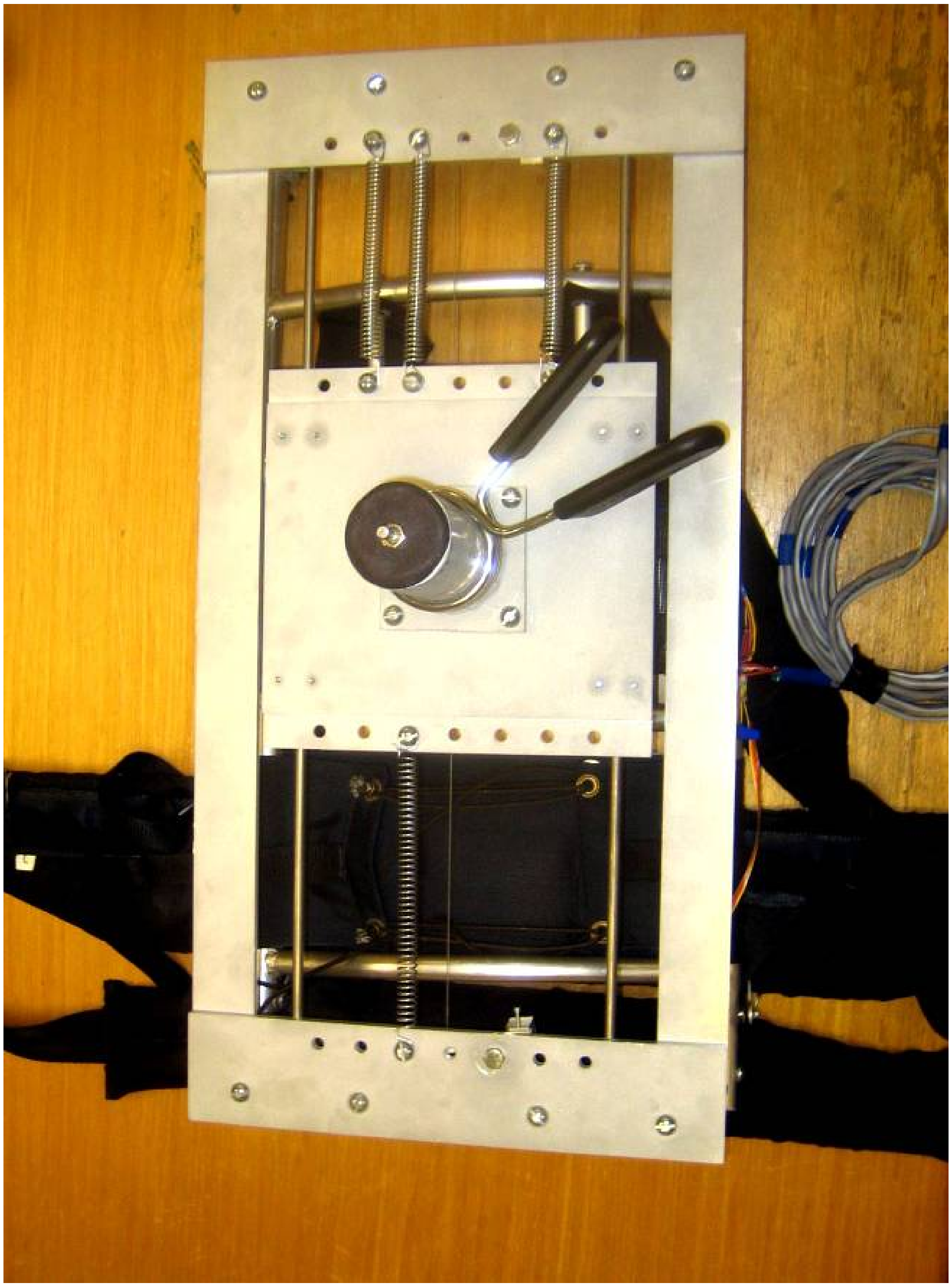


Figure 2: Accelerometer

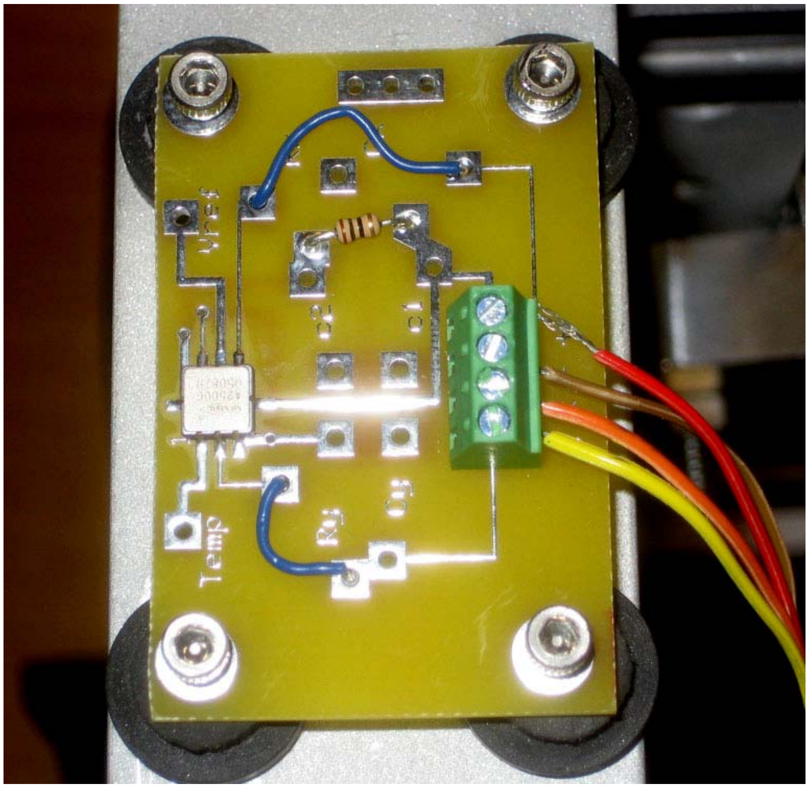


Figure 3: Capstan Setup

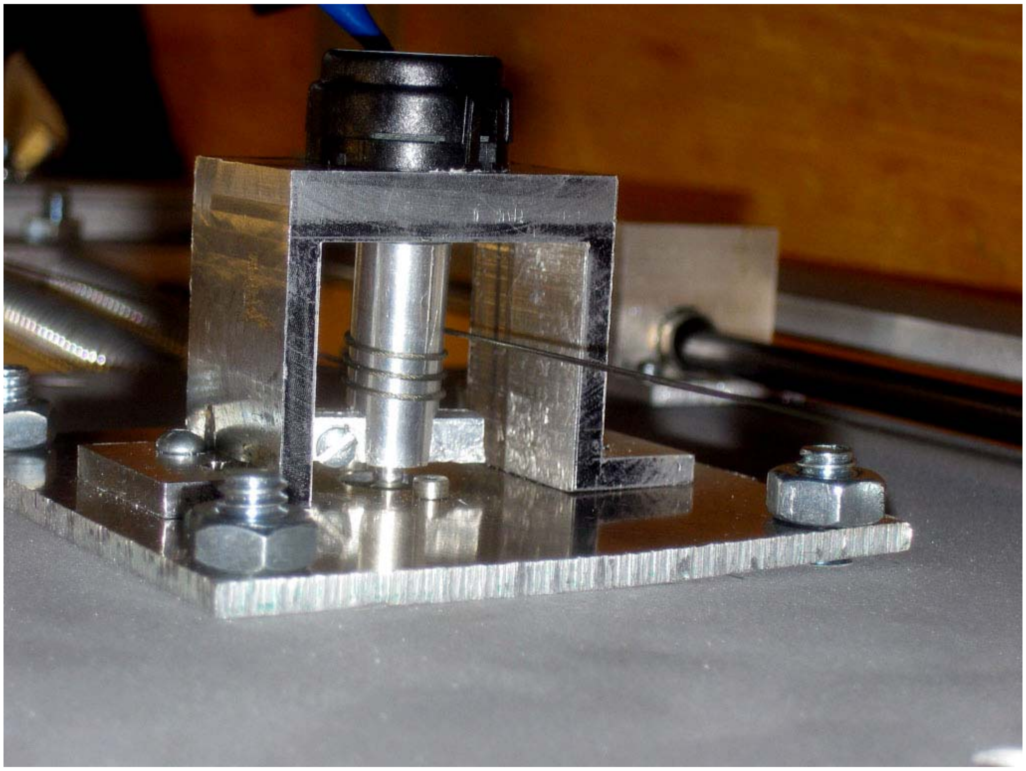


Figure 4: Cable Tensioner

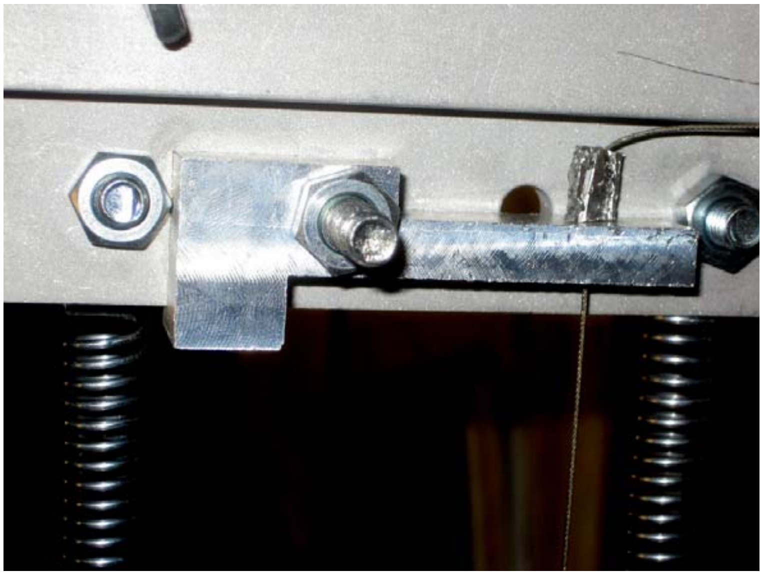


Figure 5: Prototype Modeled by Matthew Vanderpool

Figure 6: Bill of Materials

Raw Materials						
Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
12 x 24" Aluminum Plate	*1*	*ASAP*		*$67.00*		
1/4" Steel Rod	*2*	*ASAP*		*$9.00*		
3/4 x 3"x2.5" Aluminum Block	*3*	*Machine Shop*		*$0.00*	*Bob Coury*	*Scrap in Machine Shop*
1/2" x 3" Aluminum Rod	*1*	*Machine Shop*		*$0.00*	*Bob Coury*	*Scrap in Machine Shop*
1/16 x 2" x 36"	*1*	*Stadium Hardware*		*$5.00*		
Fasteners						
Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
1/4-20 x 1"	*12*	*Machine Shop*		*$0.00*	*Bob Coury*	*Supplied in Machine Shop*
1/4-20 x 1/2"	*2*	*Machine Shop*		*$0.00*	*Bob Coury*	*Supplied in Machine Shop*
Mechanical Components						
Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
5/16" Steel Backed, Bronze, PTFE Coated Sleeve Bearings	*4*	*McMaster Carr*	60695K62	*$1.59*	www.mcmaster.com	
Cable		*Sava Cable*		*$0.00*		*Free Sample*
Various Sized Springs	*8*	*Stadium Hardware*		*$1-5*		
Electronics						
Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
2 Axis ± 2g Accelerometer	*2*	*Memsic*	*MXR2312G/M*	*$0.00*	www.memsic.com	*Free Sample*
Rotary Encoder	*1*	*US Digital*	*E4P-108-118*	*$19.00*	www.usdigital.com	
Encoder Cable	*1*	*US Digital*	*CA-3285-1FT*	*$5.25*	www.usdigital.com	
Motor	*1*	*Maxon Motor USA*	*RE 25*	*??*	www.maxonmotorusa.com	*We were given the motor By Professor Brent Gillespie (brentg@umich.edu)*
Circuit Boards	*1*	*Express PCB*	*Custom*	*4.916667*	www.expresspcb.com	*Must order 12 boards for at total of $59*

APPENDIX E: Validation Setup

Figure 1: Wiring Connections

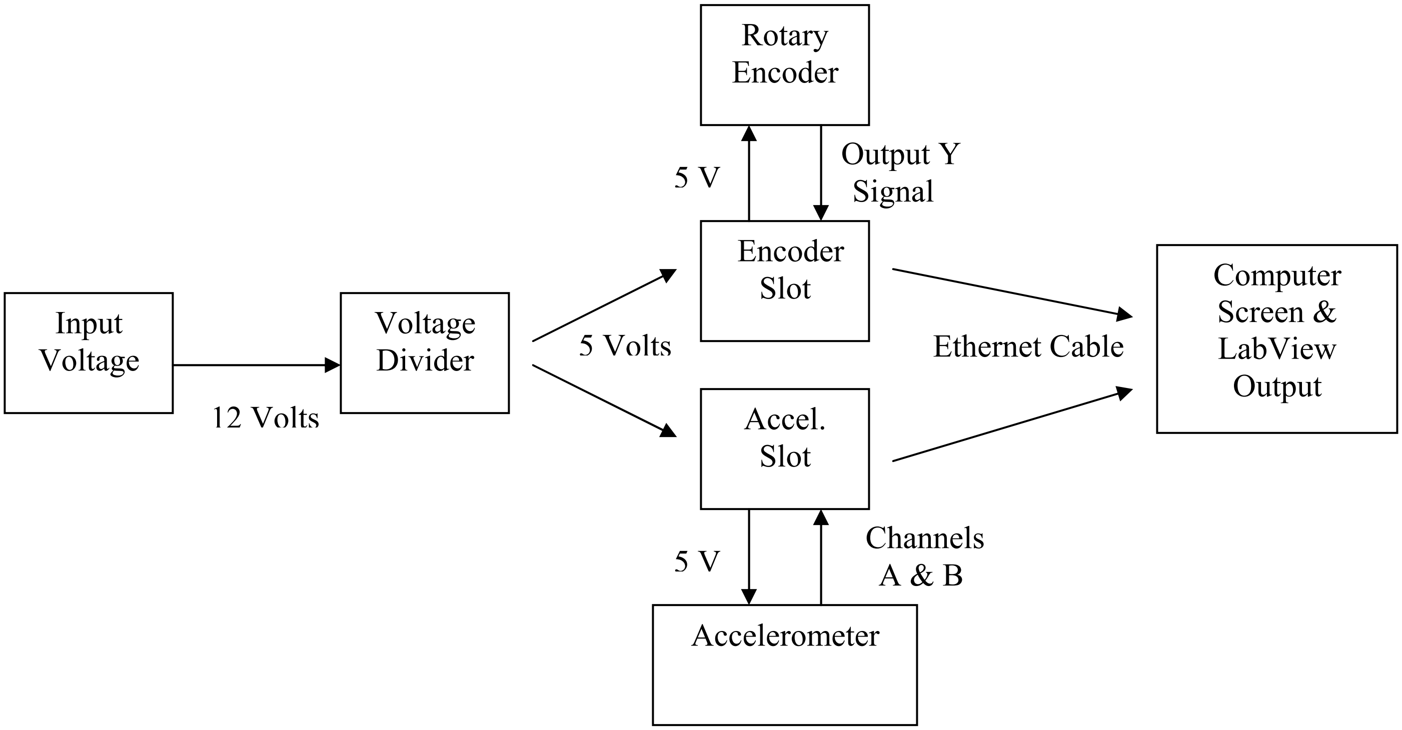
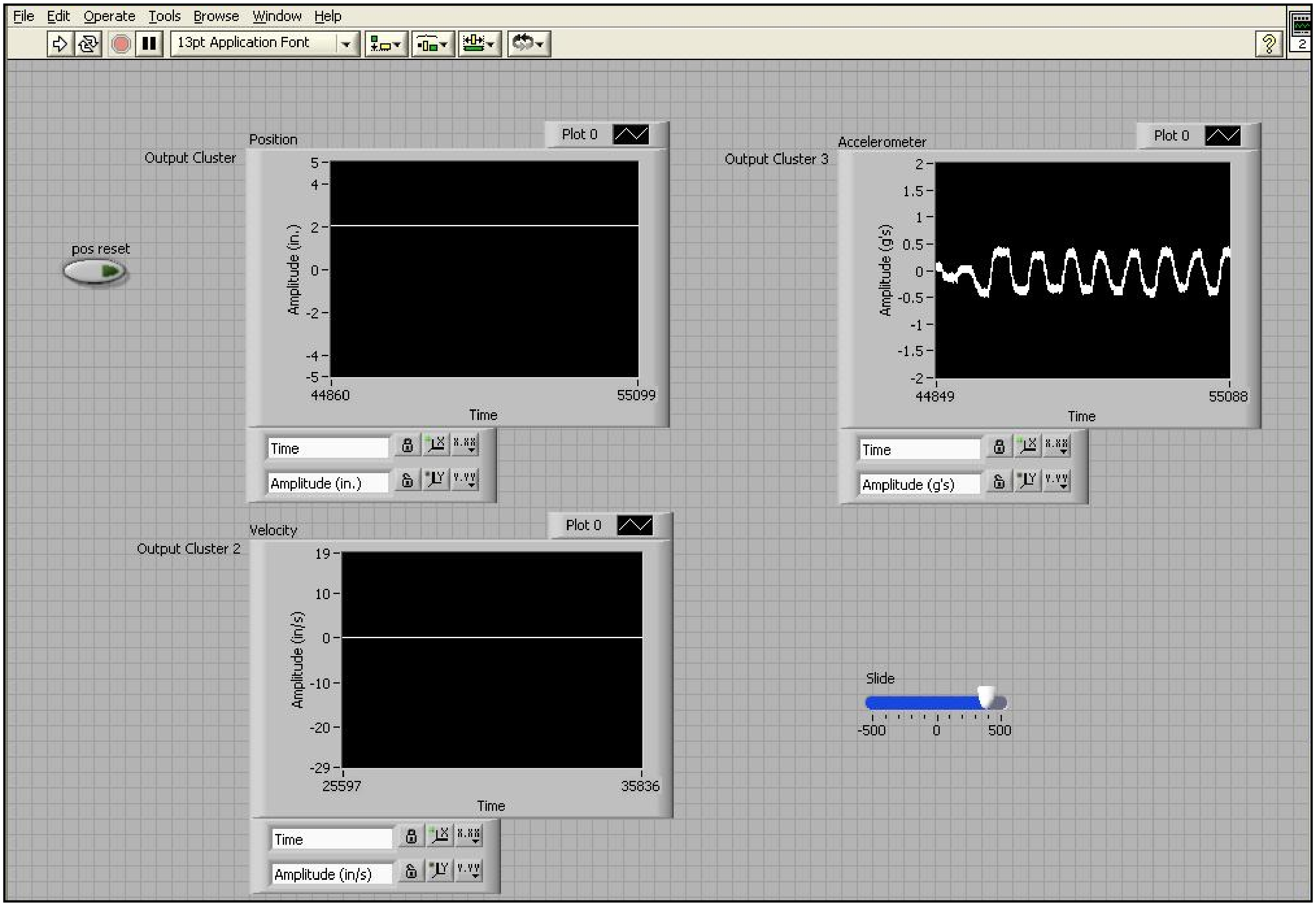
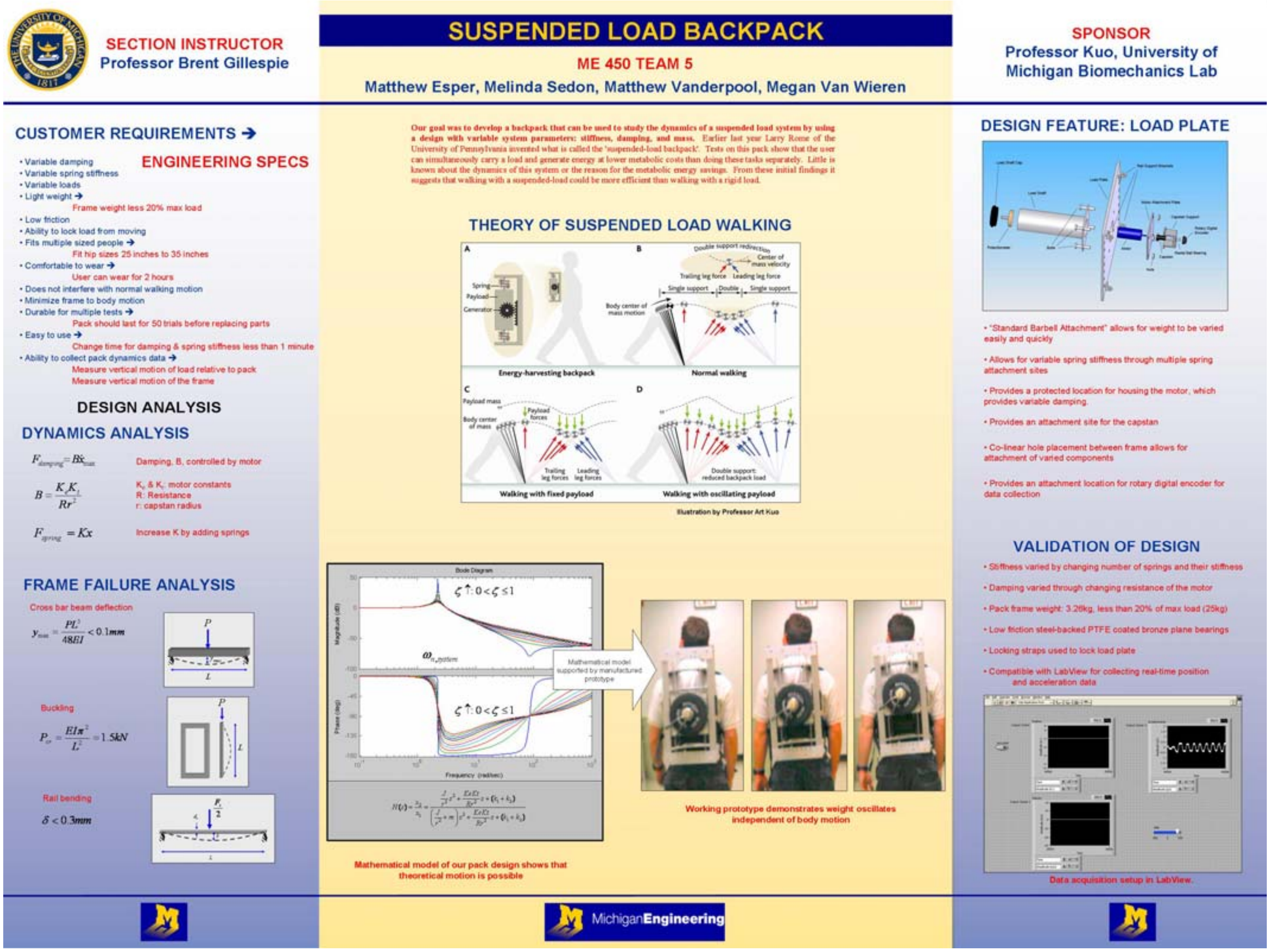


Figure 2: LabView Output Screen



APPENDIX F: Poster Presentation



SECTION INSTRUCTOR
Professor Brent Gillespie

SUSPENDED LOAD BACKPACK

ME 450 TEAM 5

Matthew Esper, Melinda Sedon, Matthew Vanderpool, Megan Van Wieren

SPONSOR
Professor Kuo, University of Michigan Biomechanics Lab

CUSTOMER REQUIREMENTS ➔

ENGINEERING SPECS

- Variable damping
- Variable spring stiffness
- Variable loads
- Light weight ➔
  - Frame weight less 20% max load
- Low friction
- Ability to lock load from moving
- Fits multiple sized people ➔
  - Fit hip sizes 25 inches to 35 inches
- Comfortable to wear ➔
  - User can wear for 2 hours
- Does not interfere with normal walking motion
- Minimize frame to body motion
- Durable for multiple tests ➔
  - Pack should last for 50 trials before replacing parts
- Easy to use ➔
  - Change time for damping & spring stiffness less than 1 minute
- Ability to collect pack dynamics data ➔
  - Measure vertical motion of load relative to pack
  - Measure vertical motion of the frame

DESIGN ANALYSIS

DYNAMICS ANALYSIS

$F_{damping}=B\dot{x}_{max}$ Damping, B, controlled by motor

$B=\frac{K_eK_t}{Rr^2}$ K_e & K_t: motor constants
R: Resistance
r: capstan radius

$F_{spring}=Kx$ Increase K by adding springs

FRAME FAILURE ANALYSIS

Cross bar beam deflection

$y_{max}=\frac{PL^3}{48EI}<0.1mm$

Buckling

$P_{cr}=\frac{EI\pi^2}{L^2}=1.5kN$

Rail bending

$\delta<0.3mm$

Our goal was to develop a backpack that can be used to study the dynamics of a suspended load system by using a design with variable system parameters: stiffness, damping, and mass. Earlier last year Larry Rome of the University of Pennsylvania invented what is called the 'suspended-load backpack'. Tests on this pack show that the user can simultaneously carry a load and generate energy at lower metabolic costs than doing these tasks separately. Little is known about the dynamics of this system or the reason for the metabolic energy savings. From these initial findings it suggests that walking with a suspended-load could be more efficient than walking with a rigid load.

THEORY OF SUSPENDED LOAD WALKING

Illustration by Professor Art Kuo

$$H(s)=\frac{x_2}{x_1}=\frac{\frac{J}{r^2}s^2+\frac{KeKt}{Rr^2}s+(k_1+k_2)}{\left(\frac{J}{r^2}+m\right)s^2+\frac{KeKt}{Rr^2}s+(k_1+k_2)}$$

Mathematical model supported by manufactured prototype

Mathematical model of our pack design shows that theoretical motion is possible

Working prototype demonstrates weight oscillates independent of body motion

DESIGN FEATURE: LOAD PLATE

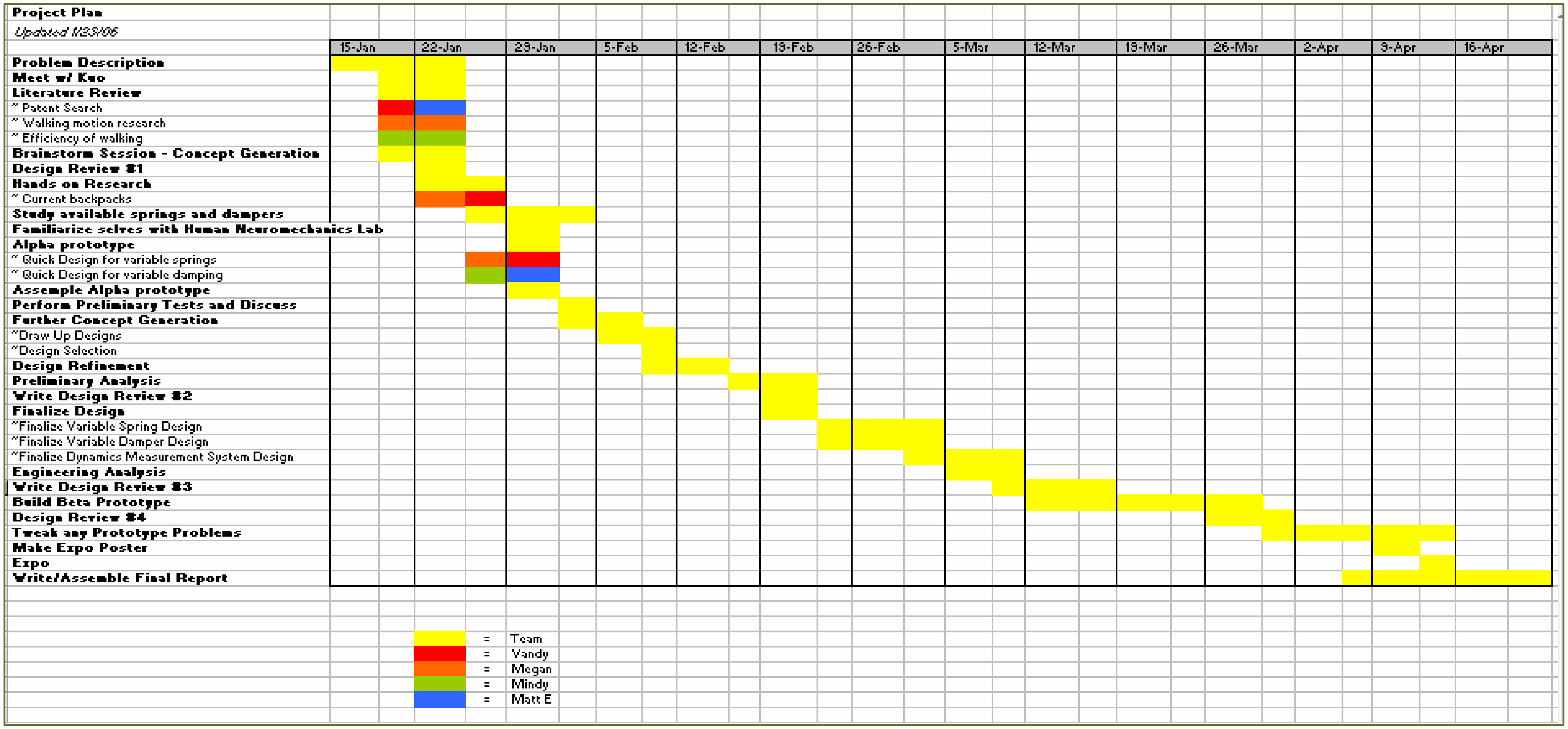
- "Standard Barbell Attachment" allows for weight to be varied easily and quickly
- Allows for variable spring stiffness through multiple spring attachment sites
- Provides a protected location for housing the motor, which provides variable damping.
- Provides an attachment site for the capstan
- Co-linear hole placement between frame allows for attachment of varied components
- Provides an attachment location for rotary digital encoder for data collection

VALIDATION OF DESIGN

- Stiffness varied by changing number of springs and their stiffness
- Damping varied through changing resistance of the motor
- Pack frame weight: 3.26kg, less than 20% of max load (25kg)
- Low friction steel-backed PTFE coated bronze plane bearings
- Locking straps used to lock load plate
- Compatible with LabView for collecting real-time position and acceleration data

Data acquisition setup in LabView.

APPENDIX G: *Gantt Chart*



Project Plan

Updated 1/23/06

	15-Jan		22-Jan		29-Jan		5-Feb		12-Feb		19-Feb		26-Feb		5-Mar		12-Mar		19-Mar		26-Mar		2-Apr		9-Apr		16-Apr	
Problem Description	🟨	🟨	🟨																									
Meet w/ Kuo		🟨	🟨																									
Literature Review		🟨	🟨																									
~ Patent Search		🟥	🟦																									
~ Walking motion research		🟧	🟧																									
~ Efficiency of walking		🟩	🟩																									
Brainstorm Session - Concept Generation		🟨	🟨																									
Design Review #1			🟨																									
Hands on Research			🟨	🟨																								
~ Current backpacks			🟧	🟥																								
Study available springs and dampers				🟨	🟨	🟨																						
Familiarize selves with Human Neuromechanics Lab					🟨																							
Alpha prototype					🟨																							
~ Quick Design for variable springs				🟧	🟥																							
~ Quick Design for variable damping				🟩	🟦																							
Assemple Alpha prototype					🟨																							
Perform Preliminary Tests and Discuss						🟨																						
Further Concept Generation						🟨	🟨																					
~Draw Up Designs							🟨	🟨																				
~Design Selection								🟨																				
Design Refinement								🟨	🟨																			
Preliminary Analysis										🟨	🟨																	
Write Design Review #2											🟨																	
Finalize Design											🟨																	
~Finalize Variable Spring Design												🟨	🟨	🟨														
~Finalize Variable Damper Design												🟨	🟨	🟨														
~Finalize Dynamics Measurement System Design														🟨	🟨	🟨												
Engineering Analysis															🟨	🟨												
Write Design Review #3																🟨	🟨	🟨										
Build Beta Prototype																	🟨	🟨	🟨	🟨	🟨							
Design Review #4																					🟨	🟨						
Tweak any Prototype Problems																						🟨	🟨	🟨	🟨	🟨		
Make Expo Poster																									🟨			
Expo																										🟨		
Write/Assemble Final Report																								🟨	🟨	🟨	🟨	🟨

🟨 = Team
🟥 = Vandy
🟧 = Megan
🟩 = Mindy
🟦 = Matt E