Lower Extremity Strength Tester (LEST)

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Abstract

It is common for women to experience conditions related to pelvic instability during and after pregnancy. This can lead to pain and irritation during everyday activities that could last years. In addition, it can cause lower extremity weakness, thus leading to further damage to the muscles, bones, and organs. Dr. Bryan Heiderscheit and Dr. Rita Deering intend to determine if this condition can be assessed by measuring the maximum voluntary contraction (MVC) of the lower extremities of a postpartum female performing a straight leg raise. They will then compare it to the MVC produced by a nulligravida. The two have been able to confirm that there is a correlation between pelvic instability and pregnancy, but have not been able to quantify their findings. They need a device that can interface with the computers in their lab to accurately measure the MVC of a postpartum adult female performing the predescribed task. The LEST (Lower Extremity Strength Tester) is an apparatus developed last semester specifically for this task. It includes load cells fixed into upright supports of the frame that record the force of the subject's MVC. Additionally, numerous design changes have been implemented this semester to improve the overall effectiveness of the device based on testing of the initial prototype. With the LEST, Dr. Heiderscheit and Dr. Deering hope to quantitatively measure the effect of pregnancy on lower extremity strength in order to create a baseline for diagnosing pelvic instability in future clinical settings. This will allow for replacement of the current, subjective diagnosis methods and higher standards of care for women around the world after childbirth.

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I.Introduction

A. Motivation

Following childbirth, women experience a loss of muscle strength in the hip flexors (iliopsoas) and knee extensors (rectus femoris, quadriceps). This is due to the constant increased pressure on these muscles during pregnancy, which causes abnormal stretching. Additionally, there is hormonal influence over connective tissues that causes joint laxity [1], which is the looseness or instability of the joint [2]. As a result, some women lose passive lumbopelvic joint stabilization, and overcompensation by the abdominal muscles is needed to achieve muscular stabilization [1]. These changes can lead to pain and discomfort. According to H.S Robinson et al., 2010, 52% of pregnant participants experienced pelvic girdle pain. In the study by Albert et al., 2003, 8.5% of women were experiencing consistent pelvic girdle pain even 2 years postpartum. Women who experience pelvic pain during their first pregnancy are also likely to observe a recurrence and worsening of symptoms with subsequent pregnancies. Thus, research has been conducted in order to better understand the underlying causes of pelvic instability and pelvic pain. Previous research has shown that the force generated by the hip flexor muscles during the active straight leg raise correlates with pelvic instability. In one study, 21 nonpregnant women with peripartum pain in the pelvic girdle completed an active straight leg raise with and without a pelvic belt, which was used to compress the pelvic joints. The subjects rated their ability to perform the test using a subjective four-point scale, and it was found that use of the pelvic belt led to an increase in the ability of subjects to raise their leg during the test [3]. A similar test is performed by clinicians to diagnosis pelvic instability. In this test, a patient performs a straight leg raise and qualitatively rates the difficulty of doing so on a scale of 0-5, with 5 being the highest difficulty. If the patient does not give a rating of 0, the patient performs the leg raise again while the clinician compresses their hips. If this extra pressure makes the straight leg lift easier for the patient to perform, this is indicative of pelvic instability. The limitation of these research and diagnostic methods is that they do not provide objective data. More quantitative data is needed to develop robust criteria for diagnosis, which will increase the reliability of diagnosis and assessment outcomes.

To address this need, our client proposed that we design a device that can measure the MVC of the hip flexor (iliopsoas) and knee extensor (quadriceps, rectus femoris) muscles during a straight leg raise task. Our device, named the LEST (Lower Extremity Strength Tester), is designed to quantitatively measure the force applied by the anterior portion of the subject's ankle in the positive and negative z directions (parallel to the supports) as accurately as possible. The measured force is the maximum voluntary contraction of the subject's hip flexor muscles. One of the benefits of this device will be the ability to collect quantitative data that can be used to precisely monitor changes in strength over time and detect differences between subject groups. This information can be used to establish criteria for diagnosing pelvic instability and will be useful for investigating correlations between pain and hip flexor strength. Furthermore, the efficacy of various treatment and physical therapy options can be evaluated by collecting data using this device. Muscle strength can be assessed following other types of rehabilitation, such as ACL reconstruction, knee replacement, and hip and abdominal surgery. This is because the device can directly or indirectly measure muscle groups in each of these procedures. If subjects change their body position, the device can also measure strength of the hamstring, gluteus maximus, other hip flexors, rectus abdominis, obliquus externus, and rectus femoris [4].

B. Problem Statement

During and after pregnancy, it is common for women to experience a loss of strength in pelvic girdle muscles. This can cause serious pain and discomfort, and new methods are continually being researched to relieve women of this condition during and after their pregnancy. There is currently no existing device that can be used to objectively diagnose pelvic instability by assessing the MVC of the hip flexor and knee extensor muscles during a straight leg raise. Because of this, our team has created the LEST to quantify the MVC of the previously mentioned muscles. Our clients will then use the collected data to set a baseline for diagnosis of pelvic instability. Using the LEST, the subject will first perform a fatiguing task (a standard straight leg raise) with one leg in between the supports of the apparatus while the other leg rests on the push plate. Then, the push plate will be raised and the fatigued leg will perform a straight leg raise against its bottom face, thus measuring the MVC of the intended leg muscles. By initially performing a fatiguing task, the affected patient will most likely experience an increased rate of fatigability and greater hip flexor and knee extensor muscle weakness. By quantifying the force data generated from these fatigued muscles, our clients can proceed to make conclusions on how to assess this common problem.

II. Background

A. Team Research

Pregnancy and childbirth create physical stress in many areas of the body. As the fetus grows, the abdominal muscles separate in order to allow the womb to protrude, thus altering the weight distribution of the mother. The physiological changes of childbirth due to the stress of delivery contribute to weakened postpartum pelvic floor muscles. Pelvic floor muscles consist of multiple layers of musculature between the tailbone and sacroiliac joint. The purpose of the sacroiliac joint is to connect the spine to the pelvis [5]. These muscles contribute to sphincter closure and sexual function, as well as supporting the spine, bladder, and internal organs. As a result, weakened pelvic floor muscles are associated with higher chances of pelvic organ prolapse; an occurrence in which internal organs “fall” to a lower location in the abdomen due to lack of support [6].

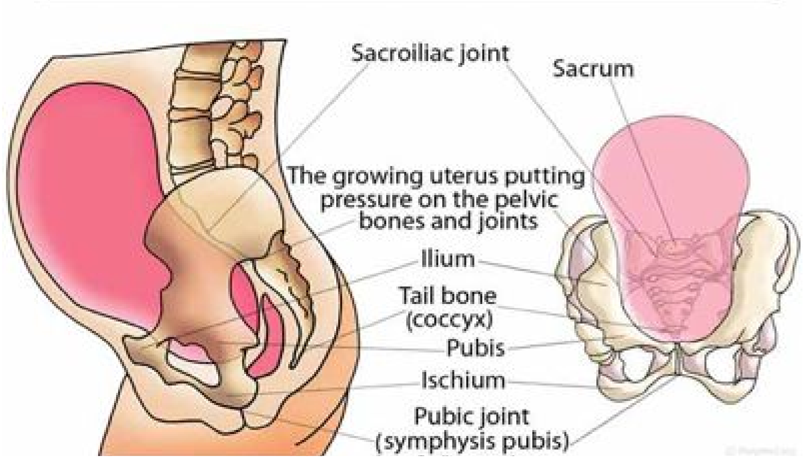


Image 1: Pressure is placed on the pelvic girdle during pregnancy due to the growing uterus [19].

Image 2 shows the left and right hip bones, coccyx, and sacrum bones that forms the pelvis. The ilium is the superior portion of the hip bone and it connected to the sacrum at the sacroiliac joint. The anterior portions of each hip bone are connected at the pubis symphysis. The iliac spine is located at the outer edge of the ilium. The anterior superior and anterior inferior iliac spines serve as attachment points for muscles of the thigh, while the posterior superior and posterior inferior iliac spines serve as attachment points for muscles and ligaments that support the sacroiliac joint. The ischial tuberosity serves as the attachment point for the posterior thigh muscles and carries the weight of the body while sitting [7].

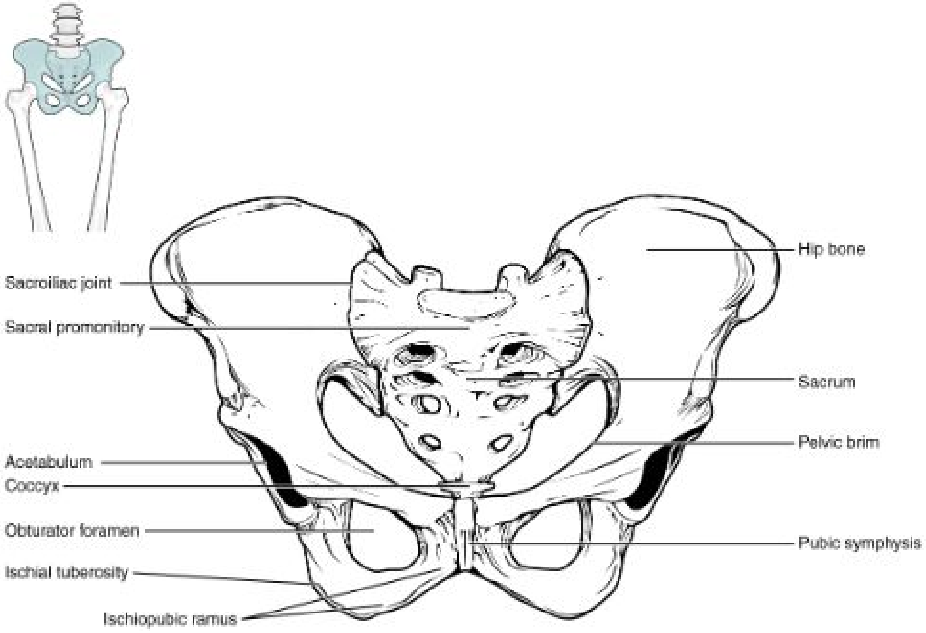


Image 2: The pelvis, consisting of the left and right hip bones, coccyx, and sacrum bones [7].

Pelvic bowl muscles (along with ligaments and other tissue) support the sacrum and ilium bones of the pelvis. When these muscles are weakened from childbirth, they distribute forces to unsuitable areas, thus increasing the chance of injury not only in the hip area, but also in the knees or ankles [5]. Evidence that pelvic muscles bear relevance to other parts of the body is clear through studies of the Active Straight Leg Raise test (ASLR) in which the test has been shown to transfer loads between the legs and lumbosacral spine [8]. The test is simply performed by raising one fully extended leg while in the supine position.

To obtain an optimal design for the client, the device had to be able to withstand the strength of an adult women applying an upward force against the push plate. This force is the MVC of the hip-flexors/knee-extensors. During the test, the patients will need to perform a fatiguing task, and soon after, their MVC will be measured. Thus, the device will need to be set in place within 60 seconds after the fatiguing task. Since the patients are applying the maximum force possible, it is necessary that the push plate (where the patient's ankle applies pressure) is soft enough to not cause them any pain. Any pain to the patient will cause skewed results due to a decrease desire to produce a maximum force. A complete list of product design specifications can be found in the Appendix, section 1- PDS.

Using this device, participants will be asked to lie on their backs and perform a straight leg raise while measuring their MVC. During this motion, the hip flexor, as well as the rectus femoris, sartorius, and tensor fasciae contribute to the motion of raising the leg. The knee extensor muscles (quadriceps and rectus femoris) contribute to stabilizing the leg [9]. For a detailed description of the testing process, see the testing procedure portion of the appendix (Section V, E).

Dr. Rita Deering has qualitatively researched the correlation between the Active Straight Leg Raise and pelvic instability. The LEST team has included this research and its findings here as they provide additional background information.

Dr. Deering, along with fellow researchers, used the Active Straight Leg Raise to assess the stability of the lumbopelvic muscles. Comparing the results of women up to twenty-six months postpartum with women who had never been pregnant allowed them to explore the effects of pregnancy on the lumbopelvic muscles. Postpartum women often experience pain in the lower back and pelvic girdle which could be a result of this loss of stability.

All of the women used in the study were free of other health problems that could have impacted the results of the test. Postpartum women completed their first test eight to ten weeks after delivery and their second test 24 to 26 weeks after delivery. Test subjects had to raise their leg 20 centimeters and hold for five seconds before lowering their leg. They then rated the difficulty of that task on a scale of zero to five with zero being not difficult at all and five being unable to lift their leg. Pressure was applied to the region if the score reported was higher than a zero. The straight leg raise is then repeated with the applied pressure and if the difficulty decreased, then lumbopelvic instability was reported. Then participants performed the active straight leg fatigue test in which their leg was raised to twenty centimeters and held. Failure occurred when an air bladder under their lower back changed pressure by twenty or more mmHg or their leg dropped below ten centimeters. Initially, 23% of the control and 37% of postpartum women tested positive for instability. Later tests reported 12.5% and 44% respectively. The fatiguing task showed a faster failure time for postpartum women than the control groups. No significant difference was found between the time to failure of those testing positive and those who tested negative for the active straight leg initial test[1].

B. Anthropometric Calculations

There are several important dimensions that were taken into consideration for the dimensions of the LEST design. The dimension of utmost importance was the height of the push plate. The average ankle circumference of an adult female is 20.14 cm [10] and the average width is 4.7 cm [11]. Using this information, the equation for the perimeter of an ellipse was used to determine the diameter of the ellipse (distance from the front to the back of the ankle, above the foot). The calculations for this value are as follows:

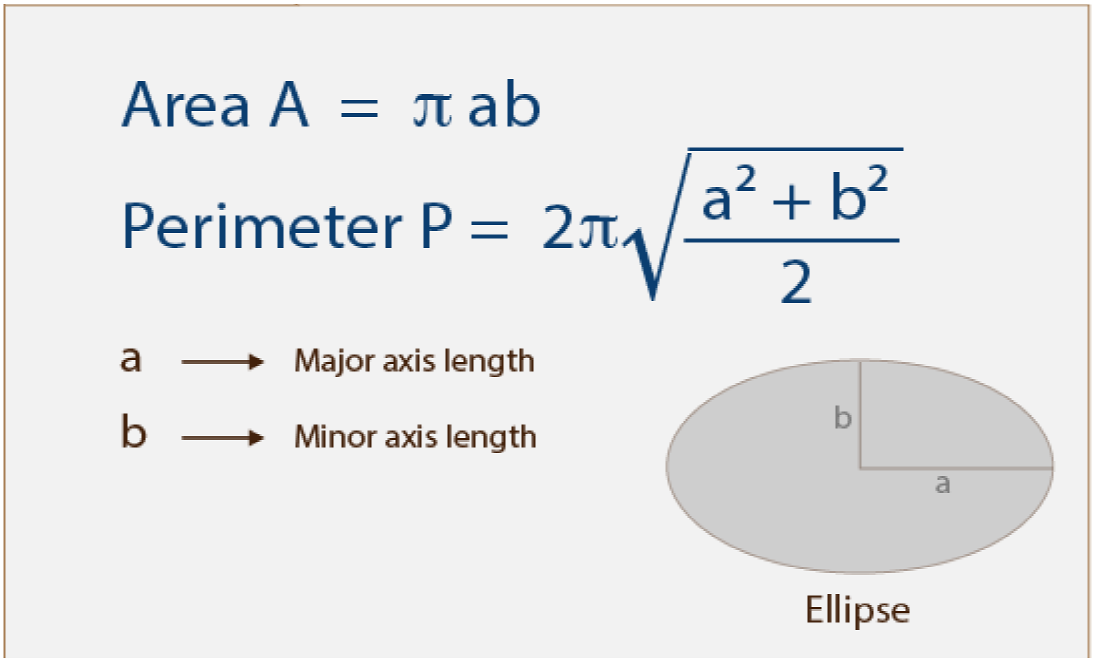


Image 2: *Equations for the perimeter of an ellipse.*

Known : P = 20.14 cm
b = 4.7 cm / 2 = 2.35 cm

a = sqrt(2*(P/2pi)^2 - b^2)
= sqrt(2*(20.14/2pi)^2 - 2.35^2)
= 3.88 cm
Therefore, the distance from back to front of ankle = 2*a = 7.768 cm

This dimension is important because the push plate will need to be at least this far from the base plate to allow the ankle to fit in between the two. However, this distance should not be much greater than the value of the average ankle height, as the forces produced by the lower extremity MVC should be as vertical as possible to ensure an accurate recording. Based on the previous math, the push plate needs to be at least 7.768 cm above the ground. Additionally, a few centimeters need to be added so the subject can easily move their foot and ankle underneath the push plate. To account for different ankle sizes, the push plate needs to be adjustable so the desired height can be obtained.

Three additional anthropometric values also needed to be considered. First among them is the average distance from the ground to the hip of the adult female. This distance is important because the base plate will have a hinge relatively in the center of it, but the exact location needs to be modified so that the subject's gluteus maximus will be exerting a downward pressure on the same piece of the base that the push plate assembly is fixed. This uses the weight of the subject as a downward force to hold the entire assembly against the ground while they push upwards against the push plate. Next, the distance from the base of the foot to the ankle of the subject has to be considered so that the push plate assembly can be fixed a proper distance from the end of the base plate, ensuring that the top of the subject's ankle comes into contact with the push plate and maximum comfort is achieved. Finally, the average hip width of adult females needs to be considered in order to make the width of the base plate and the distance between the vertical supports of the push plate assembly a proper distance apart in order for the subject to comfortably situate themselves within the design.

The calculations for the three previously described measurements utilized the average height of the adult American female listed in the CDC's Anthropometric Reference Data [12] of 161.8 cm and a figure of average body segments lengths based on height fraction [13], shown below:

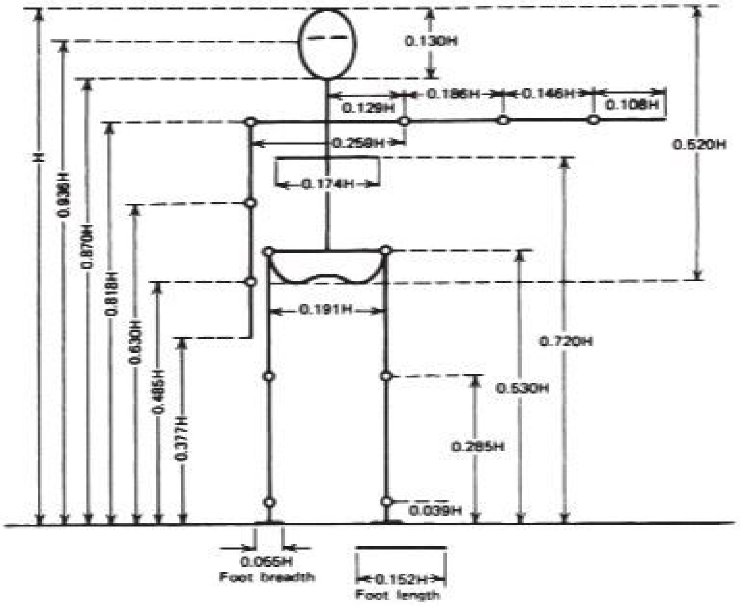


Image 3: *Average body segment length based on individual subject height.*

Using the values seen in this figure and the average adult American female height of 161.8 cm, the values can be calculated as follows:

Hip Height:

161.8 cm * .53 = 85.75 cm

Hip Width:

161.8 cm * .191 = 30.90 cm

Ankle Height:

161.8 cm * .039 = 6.31 cm

Knowing the values of these measurements, the apparatus can be appropriately sized in order to accommodate the average adult American female +20% to allow for variance in body size. Therefore, the length of the base plate that the subject will have their lower body on should be at least 101.6 cm, the width of the base plate should be at least 40.64 cm, and the distance from the end of the base plate to the center of the push plate apparatus should be at least 7.62 cm. These anthropometric calculations do not account for body composition which is difficult to calculate quantitatively.

C. Design Specifications

Although the data previously used to determine pelvic instability was purely qualitative, the findings of the researchers at Marquette University indicated that postpartum women often test positive for pelvic instability. An issue with this data is that the results vary. One way to develop more accurate and consistent results would be to produce quantitative data. This type of data would help clients determine ranges of maximum voluntary contractions in the hip flexor that is indicative of pelvic instability.

Our clients had certain design specifications for our project in order to fit their research standards. The device must be able to function in multiple settings as the testing locations will vary with their research. In order to be easily transported between testing locations, the device should not weight over 40 lbs. The device must also be able to support a maximum effort from an adult female, estimated to be 264.8 N for a 30-year old female [14]. The device must accurately obtain the appropriate force data (within 5% of actual force), as well as provide substantial room for the fatiguing task prior to maximum voluntary contraction. Based on the average hip width of the adult American female, the minimum width of the device should be 30.89 cm [12],[13]. All design specifications are further explained in the Appendix (PDS section I).

The Lower Extremity Strength Testing device generates numerical results that can be used to determine instability. The LEST allows women to press upward (from 7-12 cm off the ground) into a push plate that measures their force. This force can be analyzed to determine the maximum voluntary contraction (MVC) of the hip flexor muscles. The width of the device is 39.69 cm, well over the minimum width required.

For the device, there are sources of error that will need to be taken into consideration. One important factor is recovery time. It was required that the patient be able to quickly position themselves in the device (within 60 seconds post-fatiguing test) and perform the task as quickly as possible. The longer it takes for the subject to position themselves, the more time the muscles have to recover before the MVC. Additionally, since the device is secured to a somewhat flexible HDPE sheet, if enough force is applied, the sheet has the capability to bend. There are simple procedural measures that can be taken to mitigate this effect. Either the heel of the straightened, non-tested leg must be in contact and pressing down into the HDPE sheet or the non-tested leg can be bent. Both of these methods provide enough downward force to counteract the upward force of the straight leg raise and prevent significant bending of the HDPE sheet. Additionally, the test administrator could stand on the back of the design, preventing it from flexing upwards. Negligible amount of bending may still occur, however this is not a concern because it should not affect accuracy of measurement and a small amount of flexion will still provide enough resistance so that patients can exert their MVC.

D. Initial Prototype

The final design that was physically produced as a prototype can be seen below. The design consists of a metal structure attached to a piece of HDPE,which has a yoga mat on top for comfort. The base is cut and joined by hinges to allow for folding of the device. This allows for increased portability and easier storage. Several dado cuts on the bottom of the HDPE sheet run parallel to the longer edge in order to reduce the total weight. Two corner support towers have through holes for the aluminum tubing that attach to the push plate. These holes were reamed to be slightly above the diameter of the aluminum vertical supports to allow for them to move up and down within the corner towers. A relief cut is made on either side of the through hole, and there are two threaded holes on the side face of the tower. By tightening handles of an appropriate thread size and length, the two halves of material on each side of the relief cut can be “clamped” together, holding the vertical supports in place. In this way, tightening and loosening the handles allows for the height of the vertical supports (and more importantly the push plate) to be easily adjusted. Load cells are also incorporated into the upright supports. Essentially, each full vertical support was cut in two pieces and one end of each piece had its diameter turned down and was threaded. In this way, each part of the vertical support could thread directly into the threaded holes on each face of the load cell. Because the vertical supports are rigidly attached to the push plate, any force exerted upon the push plate will be equivalently recognized by the load cells in the vertical supports. When the non-fatigued foot is resting on the push plate, its force will be recognized in compression. When the fatigued leg is pushing up against the bottom of the push plate with its MVC, the force in the apparatus will be recognized by the load cells in tension. A 3D model of the design and several images of the completed prototype can be seen below:

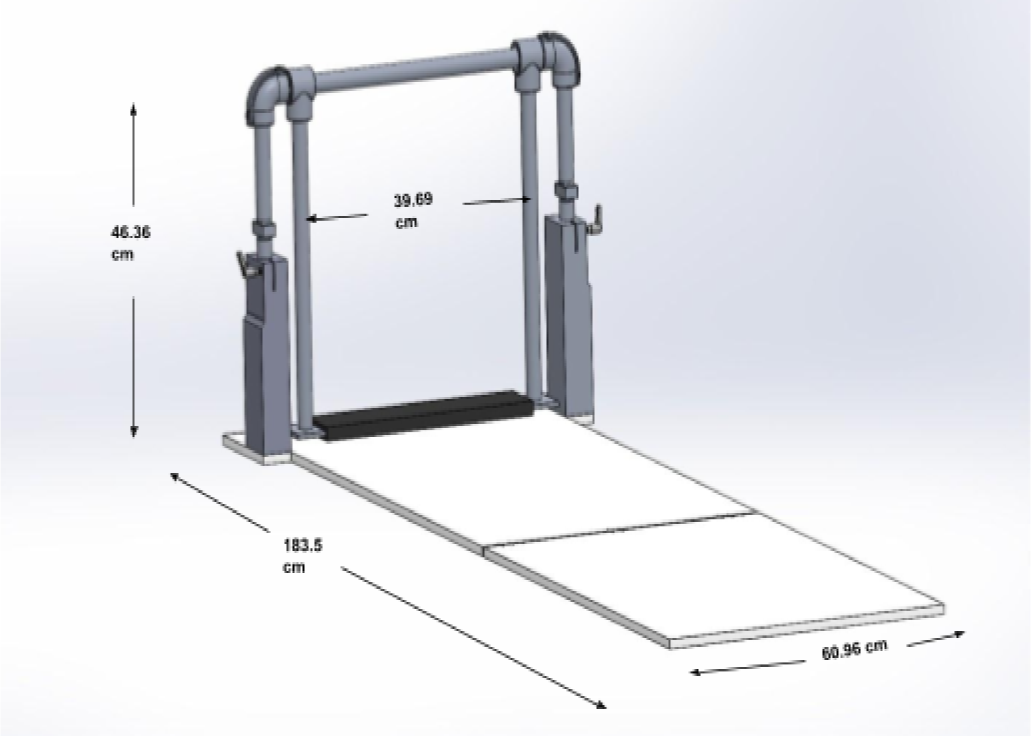


Image 4: *Solidworks rendering of final prototype.*

Image 5: *An isometric view of the completed prototype.*

Image 6: *A top view of the completed prototype.*

Image 7: *A closeup isometric view of the completed prototype, featuring the push plate apparatus.*

Image 8: *A closeup isometric view of the completed prototype, featuring the SST setup on the right side.*

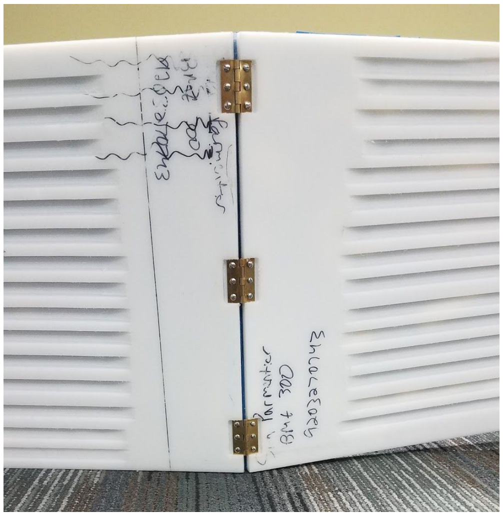


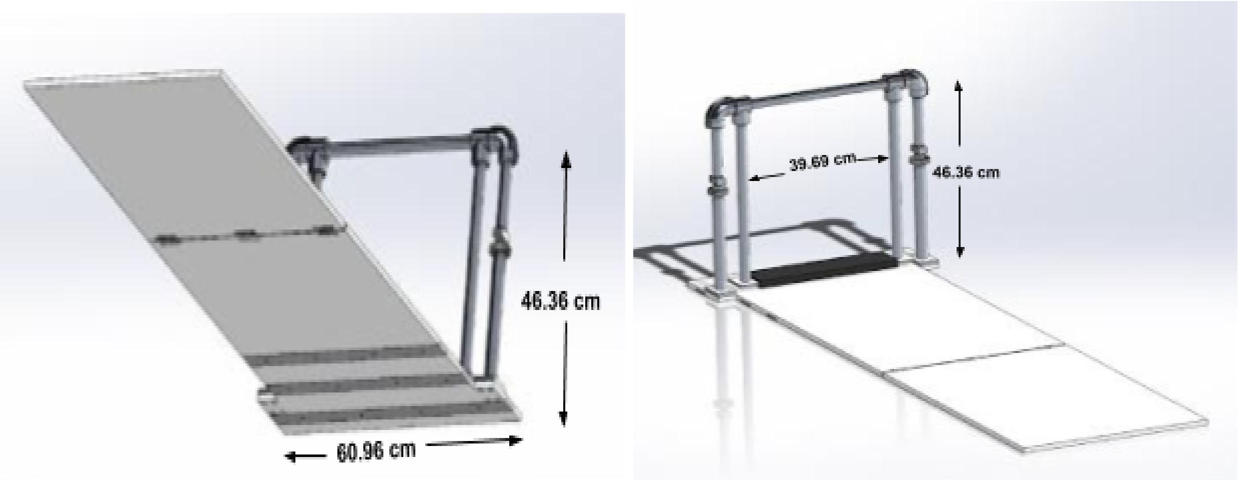
Image 9: *A bottom view of the completed prototype, featuring the base plates and the dado cuts that were made into them to reduce their overall weight. Also shown are the affixed hinges and the milled pockets.*

There are numerous flaws in our existing prototypes. These flaws include the excessive weight of the device, the flexibility of the HDPE base plate, faulty electronics, and unaesthetic push plate and base plate coverings. The weight of the corner towers and aluminum tubing contributed to a large percentage of the overall weight. In order to decrease this aspect, hollow aluminum tubing will replace the solid aluminum tubing in the push plate supports. The corner towers will also be replaced by hollow aluminum tubing in order to further decrease the weight as well as improve on adjustability. In order to decrease the flexibility of the HDPE base plate, metal sheets will be installed underneath the device to provide a more rigid support. Vacuum cups will also be added to ensure that the HDPE does not flex or move throughout the testing procedure. The faulty electronics will be replaced by the manufacturer and will enable the device to be tested. In addition, the push plate and base plate coverings will be replaced with a more aesthetically pleasing material that will provide a clean and professional overall look to the device.

III. Preliminary Design Modifications -

After collaboration with Dr. Deering on the existing prototype and what improvements she would like made to it, the LEST team developed three feasible design modifications:

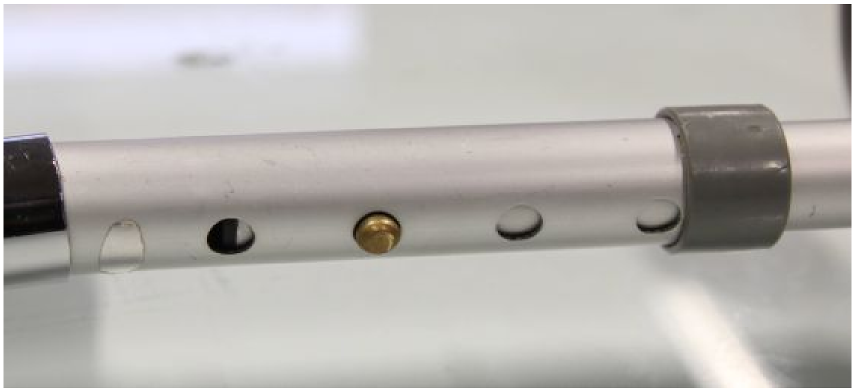
A. The Bike Mod

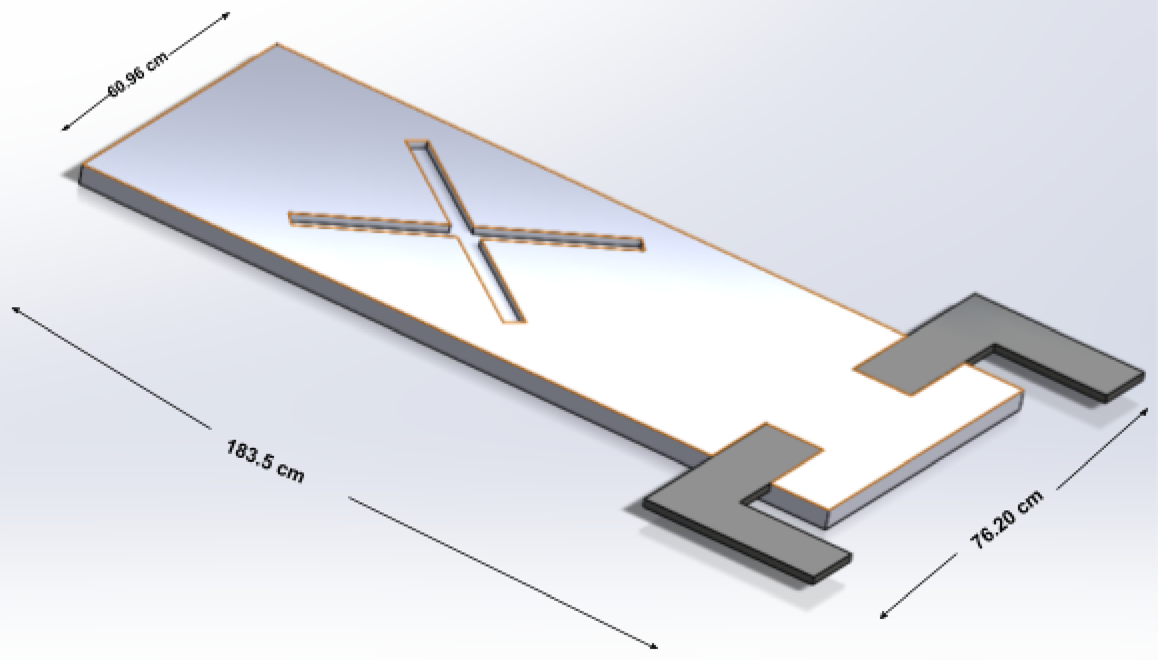


Images 10&11- *Images depicting the bottom view (left) and the isometric view (right) of the Bike Mod.*

The Bike Mod idea features two main design changes: replacement of the bulky corner towers with hollow tubes and base plate reinforcement. The bulky corner towers were the biggest area to reduce the overall weight of the design, so the Bike Mod features hollow aluminum tubes with an inside diameter slightly greater than the outside diameter of the vertical supports fixed to the load cells. Welded to the top of these hollow tubes is a quick-release clamping shaft collar, much like that used to adjust the height of a bike seat and hold it in place. Additionally, flat metal bars were added to the base of the design in order to reduce the overall flexion that was seen during testing last semester. Overall, the weight of the design was reduced by seven pounds with these design modifications. All dimensions for this modification remain the same as last semester’s design.

B. The Crutch





Images 12&13: *The top image shows a new corner tower design, while the bottom image shows a view of the base plate from the bottom.*

In the Crutch Design the corner towers would be replaced by a partially hollow metal rod that is concentric with the existing metal rod that rests in the corner towers. A spring-loaded metal cylinder would also be added to the existing metal rod and would be flush with the rod when fully pushed in. The height of the metal frame could be adjusted at specified intervals as shown in Image 4. The base plate would also be modified so that the metal frame could be detachable from the base plate; this would make the device easier to transport. For this design modification, rectangular slots would be cut in the base plate near the end with the metal frame. L-shaped HDPE pieces would be attached to the corner towers and these pieces would fit into the slots on the base plate, so that the base plate rests over these L-shaped pieces when the device is fully set up. Additionally, an X-shaped metal piece would be added within a slot on the bottom of the base plate to reduce flexion of the plate.

C. The Cufflink

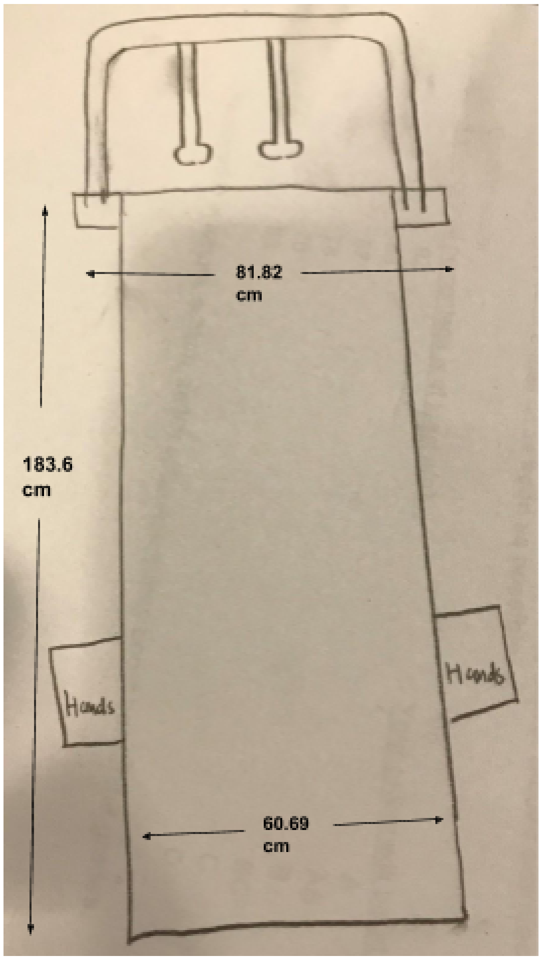


Image 14: *This image shows the push plate replaced with cuffs and the addition of a heart rate monitor.*

The cufflink design is quite similar to the current design, with two exceptions. Instead of the force plate, the client's legs would be attached to cuffs. This may allow for a more accurate reading and would be lighter weight. The other addition is a heart rate monitor where the user would rest their hands. A heart rate monitor would help analyze the user's fatigue even more accurately and provide an additional measurement.

IV. Preliminary Design Evaluation

A. Design Matrix

Design Criteria	Modification One - The Bike Mod	Modification Two - The Crutch Design	Modification 3 - The Cufflink Design
Weight Reduction (25)	5/5 25	5/5 25	3/5 15
Quickness of data collection after fatiguing task (25)	5/5 25	4/5 20	3/5 15
Reducing Base Plate Flexion (10)	5/5 10	4/5 8	1/5 2
User Comfort (10)	4/5 8	4/5 8	3/5 6
Ease of Fabrication/Assembly (10)	3/5 6	2/5 4	5/5 10
Cost (10)	3/5 6	4/5 8	4/5 8
Aesthetics (5)	4/5 4	4/5 4	5/5 5
Safety (5)	5/5 4	4/5 4	3/5 3

Table 1: *The LEST design matrix, showing overall scores for the three new proposed designs.*

B. Justification of Criteria and Weight

Weight Reduction-

This category was added to the matrix as it is the greatest focus for this semester. Because the device will be transported between clinics by one person, it is important for the weight to be minimized. Ideally, the maximum weight of the device should be 40 lbs. Because the weight of the existing device is 47.4 lbs, the modified design needs to address significant weight reduction. The Bike Mod and Crutch modifications both scored well in this category because they replaced the bulky corner towers with hollow aluminum tubing, thus greatly reducing the overall weight of the design. In contrast, the Cufflink modification did not modify the corner towers in any way and merely replaced the push plate with an equally weighted component.

Quickness of Data Collection After Fatiguing Task-

It is imperative that the MVC of the subject is able to be recorded quickly after completing the fatiguing task to prevent their muscles from recovering and skewing the data. Additionally, the patient should easily be able to place their legs between the aluminum supports without difficulty. The Bike Mod scored the highest in this category because of the easy adjustment with the quick clamp collars. The Crutch modification would be cumbersome to adjust due to the interval height adjustments as opposed to free range adjustment. The Cufflink modification would use the existing, mediocre height adjustment mechanism in the corner towers.

Reducing Base Plate Flexion-

The accuracy of MVC force measurement by the load cells relies on the base plate remaining relatively static; therefore, flexion of the base plate should be limited when force is applied to the bottom of the push plate. This category was added to the matrix this semester as this was a noticeable problem with the design in the previous semester. The extra metal base plates added into the Bike Mod and the Crutch modifications caused them to score the highest in the category, while the Cufflink design did not address this issue.

User Comfort-

As a patient's MVC is being measured, they should not endure any pain that could affect their results. This would likely be encountered between the surface that comes into contact with the ankles, where the MVC is exerted. Also, this surface should not be so hard that it causes discomfort, but should also not be so soft that it absorbs the force of the MVC. The Bike Mod and Crutch modifications scored highest in this category because they incorporate the already comfortable design. The Cufflink modification scored lower due to pinching concerns with the cuffs themselves.

Ease of Fabrication/Assembly-

Fabrication of the design should be completely within our ability. The device should not come in too many separate pieces as this would cause problems for the administrators performing the experiments during the assembly process. The Cufflink modification scored the highest in this category, as the only modification needed would be to replace the push plate with cuffs. Timely replacement of the corner towers is necessary in the other two modifications.

Cost-

The client offered a budget of 1000$ the previous semester. $488.16 is remaining in the budget for this semester. Because of less money remaining, the cost category received a higher portion of the overall matrix score compared to last semester. Because of the few changes involved in the Cufflink modification, it scored highest in this category.

Aesthetics-

Aesthetics received a greater portion of the design matrix score compared to last semester. This semester, only modifications are being made to the design. A brand new design is not necessary and, as a result, aesthetics can become a higher focus. Instead, only small changes will have to be made, so aesthetics can be a larger focus. The final design should look professional, as it will be used in professional research. The Cufflink modification scored highest in this category due to the fact that it replaces the current, unprofessional looking push plate. The other two modifications do not alter this portion of the design.

Safety-

The safety of the client and the test subject is an important aspect of any design. It is assumed that any design considered will meet a certain standard of safety. The design will likely be stationary and will not in any way alter the subject, so there are not many safety concerns involved. The Bike Mod and the Crutch modifications received the highest scores due to their stability. The location where the patient is applying a force should be the sturdiest and the Cufflink modification does not provide a strong support system, as its two vertical supports are not connected and could wobble perpendicular to the corner towers.

C. Final Design:

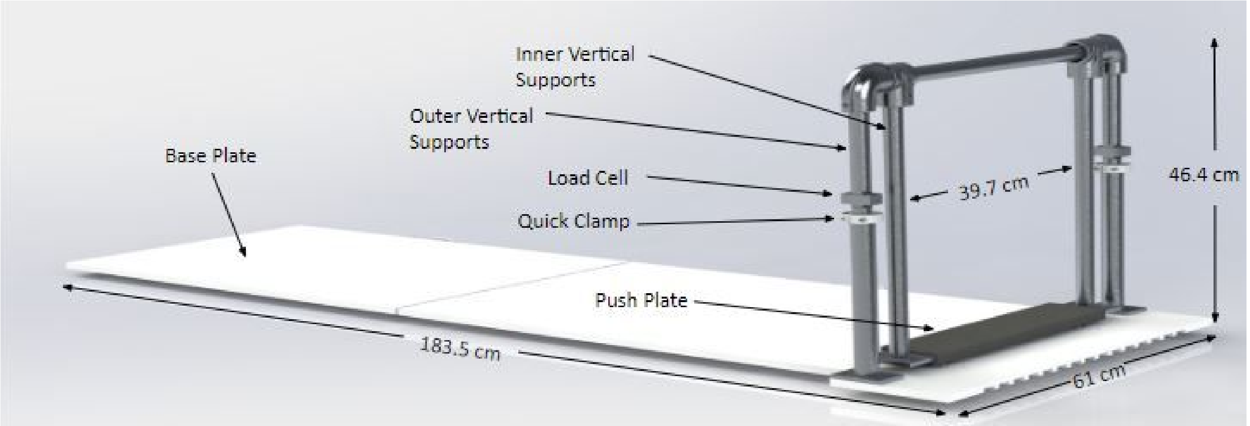


Image 15: *CAD model of final design.*

The final design for this semester included most of the components of the Bike Mod described above, along with a few other changes. The corner towers were fabricated in accordance with the Bike Mod summary, featuring hollow aluminum tubes welded to a bottom aluminum piece, allowing for fixturing to the existing base plate. The quick adjust shaft clamps were welded to the top of the corner towers to allow for easy, fast height adjustment of the vertical assembly. However, the bottom reinforcement plates were not added to the design as planned. This is because two industrial vacuum cups were attached to the bottom of the base plate. In total, they provide 210 lb-f of fixturing strength to an appropriately smooth floor surface, which is expected in most lab settings. Upon testing of the device to check stability, the vacuum cups held in place and prevented all base plate flexion. This ensures that data collection will be as accurate as possible, as all forces recognized by the load cells will be purely vertical.

Image 16 and 17: *A close up of the quick adjust shaft collar (left) and the finished LEST apparatus being used in step two of formal testing procedure (right).*

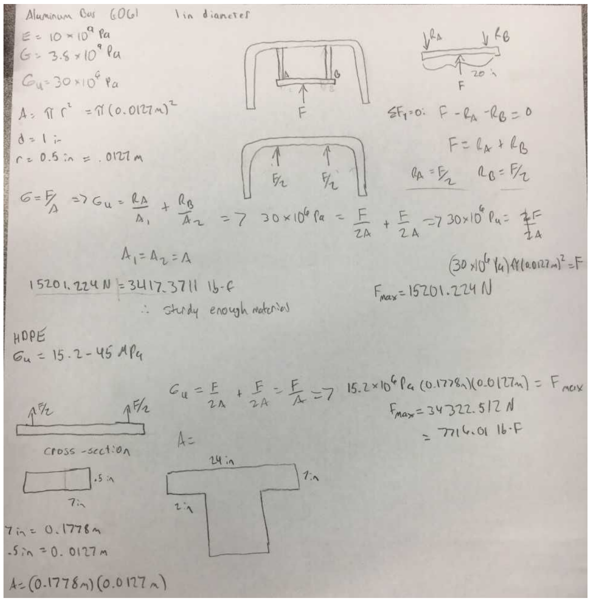
Handles were also added to the side of the base plate to allow for easier portability between testing locations. The final design was weighed on a scale and measured 34.6 pounds. At the beginning of the semester, the design weighed 47.4 pounds. In total, 12.8 pounds of material were removed from the design over the course of the semester while achieving significantly improved functionality. The goal was for the LEST to weigh beneath 40 pounds, and this goal was easily surpassed.

V. Fabrication/Development Process -

A. Materials

Various materials were used for the completion of last semester's prototype. The frame consists entirely of solid aluminum bar. Everything is fixed together with variously shaped connecting joints, which hold the frame pieces in place with set screws. The push plate is made out of an aluminum bar. The corner towers are also made out of aluminum bar and feature two handles with a threaded stud to allow the push plate to be raised and lowered. All of this is fixed to a sheet of high density polyethylene (HDPE) with a recycled yoga mat for padding on top. The HDPE sheet is cut into two pieces with three brass hinges on the bottom half to allow for folding and easier portability. Load cells are implemented into the uprights of the frame and these measure the forces in both tension and compression.

There are multiple new materials that were implemented on the modified design. Hollow aluminum tubes were used to replace the solid aluminum bar of the current corner towers. Quick adjustment shaft collars were also be welded on the corner towers to allow for easy height adjustment of corner towers. Handles were attached to the side of the base plate to allow for more efficient transportation and maneuverability, and industrial vacuum cups were fixed to the bottom of the base plate to allow for a more stable device. A detailed list of the materials used for this project and their cost can be found in the Appendix, section C- Current Semester's Materials List.


Aluminum Bar 6061   1 in diameter

$E = 10\times10^9$ Pa

$G = 3.8\times10^9$ Pa

$\sigma_u = 30\times10^6$ Pa

$A = \pi r^2 = \pi(0.0127m)^2$

d = 1 in

r = 0.5 in = .0127 m

$\Sigma F_y = 0: \; F - R_A - R_B = 0$

$F = R_A + R_B$

$R_A = F/2 \quad R_B = F/2$

$\sigma = F/A \Rightarrow \sigma_u = \frac{R_A}{A_1} + \frac{R_B}{A_2} \Rightarrow 30\times10^6\,Pa = \frac{F}{2A} + \frac{F}{2A} \Rightarrow 30\times10^6\,Pa = \frac{\cancel{2}F}{\cancel{2}A}$

$A_1 = A_2 = A$

$(30\times10^6\,Pa)\pi(0.0127m)^2 = F$

$F_{max} = 15201.224$ N

15201.224 N = 3417.3711 lb-f

∴ sturdy enough materials

HDPE

$\sigma_u = 15.2 - 45$ MPa

$\sigma_u = \frac{F}{2A} + \frac{F}{2A} = \frac{F}{A} \Rightarrow 15.2\times10^6\,Pa\,(0.1778m)(0.0127m) = F_{max}$

$F_{max} = 34322.512$ N

= 7716.01 lb-F

A =

7 in = 0.1778 m

.5 in = 0.0127 m

A = (0.1778m)(0.0127m)

Image 17: *Calculations showing maximum force(lbs-f) that can be exerted on the aluminum bar and HDPE*

Image 17 depicts the calculations required for the two materials that experience the most loading during testing. The aluminum bar in the above portion of the calculations experiences the direct force applied from the test subject. By looking up the mechanical properties of the 6061 aluminum bar and finding the maximum stress that can be applied, the maximum force without deformation was calculated. A similar process was done to determine the maximum force applied to the HDPE. As can be seen, the aluminum bar was the limiting materials based on the maximum force that can be applied without fracture. Based on calculations in the background section, the highest expected maximum voluntary contraction from test subjects is 59.53 lb-f. This equates to 264.8 N, which is significantly less than the maximum capable stress of 15,201.224 N of the aluminum bar. As such, the chosen materials are more than sufficient for this testing process.

B. Fabrication Methods

Fabrication of the existing prototype was completed last semester and a detailed explanation of all methods used can be found in Appendix D- Last Semester's Fabrication Methods. Additional changes to existing prototype were made based upon the features discussed in Section C of the Preliminary Design Evaluation section- Final Design. A detailed explanation of all fabrication methods performed for these changes can be found in Appendix E- Current Semester's Fabrication Methods. There are 3 new parts that were fabricated, including the corner tube, the corner tube base, and the remachined outer vertical supports. Additionally, a subassembly comprised of the corner tube, the corner tube base, and the quick-release clamping shaft collar was welded together. Finally, some small modifications were made to the base plate to fix both the handles and vacuum cups onto it.

C. Electronics

To obtain force measurements from the LEST device, an electrical system was implemented that consists of two load cells, an SST load cell transmitter, and the SST software. To begin, a force is first exerted upon the push plate of the design. This force is recognized by each load cell, which both are rated for a capacity of 300 lbs in tension and compression. The load cells each feature a wheatstone bridge, with one unknown resistance value that changes depending on the strain applied to the load cell. Changing resistance values will lead to differences in voltage across the bridge sensor, which is then outputted to the SST High Voltage Load Cell Transmitter. The excitation and output wires of the load cells are connected to the SST Transmitter as shown in Images 18 and 19. The SST Transmitter acts as a “middle man” between the load cells and a signal processor that will be described later on in this section.

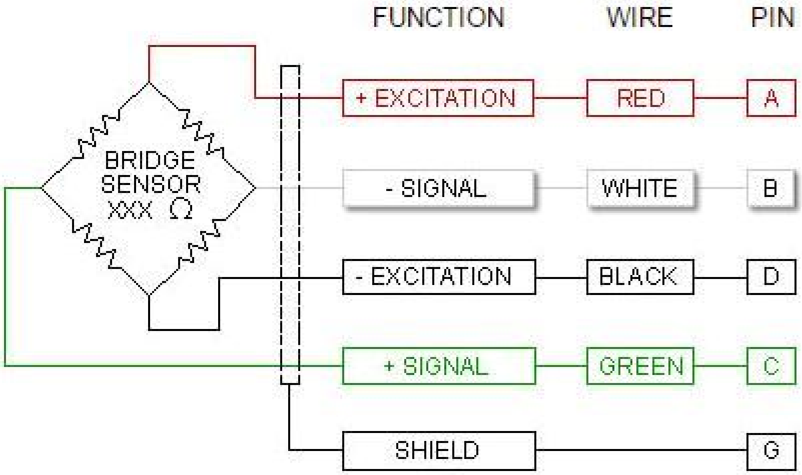


Image 18: *Wiring diagram for the MLP-300 Load Cell used in this design* [15].

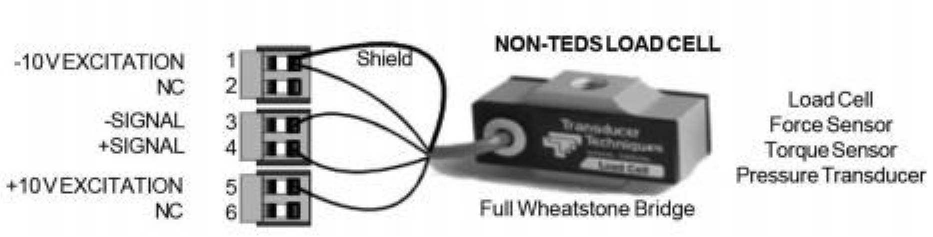


Image 19: *Wiring diagram detailing how the wires described in image 18 interface with the SST transmitter* [16].

One limitation of the SST is that it is only designed to take the input from one load cell. However, two load cells were used in this design. To provide a solution to this problem, like wires from each load cell were wired together along with one end of a third wire inside of a wire nut. Then, the opposite end of the third wire from each combined pairs of wire from the two load cells was hard wired into the appropriate terminal on the SST, as depicted in image 19. As a result of doing this, the effective capacity of the load cells was now 600 lbs.

Image 20 shows all of the pins on the SST Transmitter, that were interfaced with either the load cells, computer, or power source. An RS-232 "9-Pin" serial cable was what provided the connection between the SST transmitter and the computer that the software program was installed on. One end of the RS-232 cable was hard wired directly into terminals on the SST board, shown below:

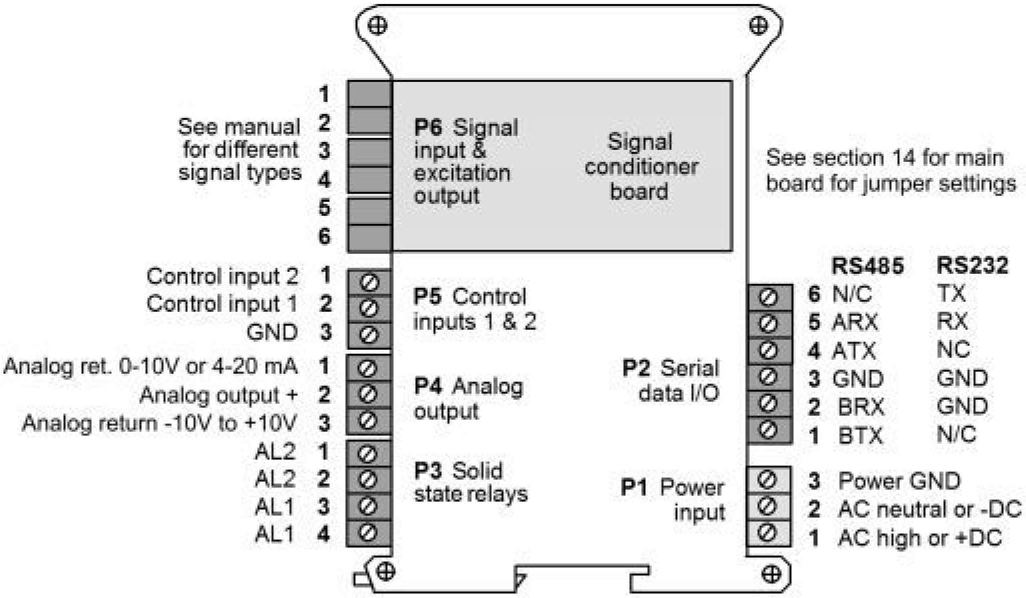
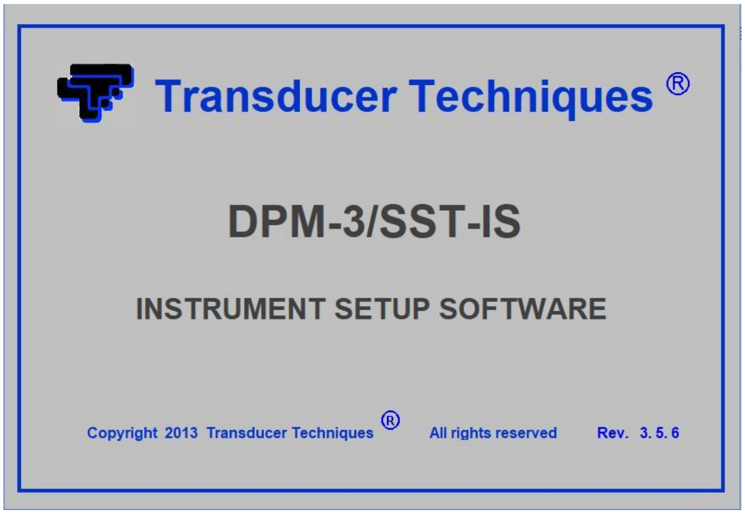


Image 20: *Wiring diagram detailing how all of the terminal designations for the SST transmitter* [16].

The correct connection to the terminals for the RS-232 cable are detailed in the "P2" section of the image. As can be seen, the "P6" section is what the load cells wire into. The "P4" section is where the analog output from the SST can be obtained. The "P1" section was dedicated to providing power to the SST and load cells from a 120 V power source. The power cable for the SST was included with the device and could interface directly with the terminals. The "P5" and "P3" sections were unused. The opposite end of the RS-232 cable was connected with a serial-USB adapter, as the laptop used for the electronics did not have a serial port.

In order to display force measurements on the computer, an SST signal processing software was used to interface with the hardware setup. The first step was to establish communications within the software. The connection type (RS-232) had to be selected, and the appropriate communications port that the serial-USB adapter was connected to had to be configured.



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DPM-3/SST-IS

INSTRUMENT SETUP SOFTWARE

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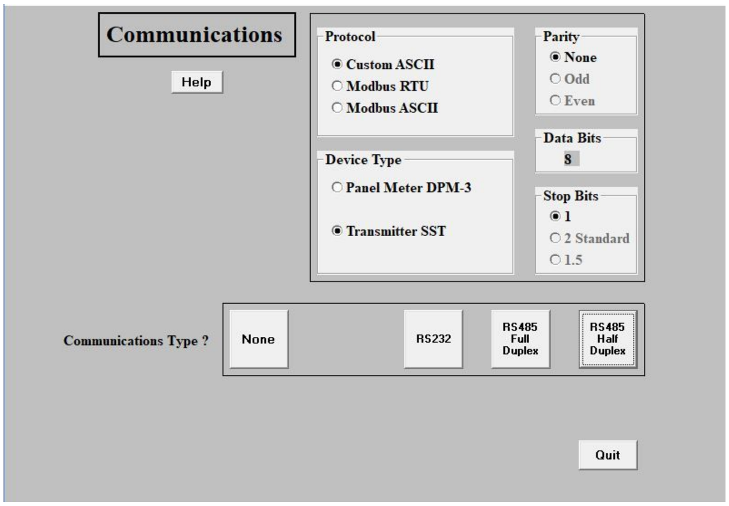
Image 21: *Setup screen of software program used to interface with SST Transmitter* [16].



Protocol
- ● Custom ASCII
- ○ Modbus RTU
- ○ Modbus ASCII

Parity
- ● None
- ○ Odd
- ○ Even

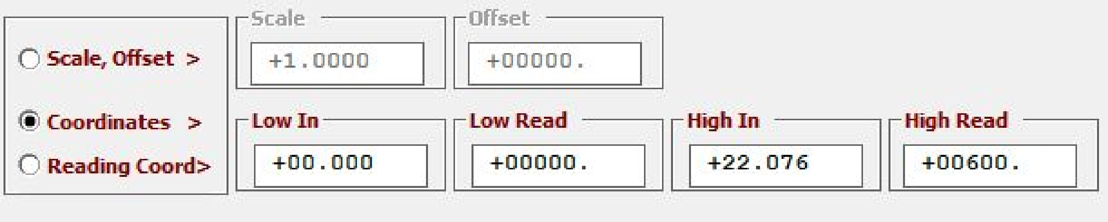
Data Bits: 8

Device Type
- ○ Panel Meter DPM-3
- ● Transmitter SST

Stop Bits
- ● 1
- ○ 2 Standard
- ○ 1.5

Image 22: *Communications establishment screen, used to select basic settings and communication type* [16].

After establishing a connection, settings had to be adjusted based on the voltage calibration values for the load cells. Within the "scaling" window, the low and high input values had to be set based on the range of voltage input values the SST would be receiving from the load cell. Additionally, the low read and high read values had to be programmed so that the force readings displayed on the SST software would be accurate. These values are shown in Image 23.



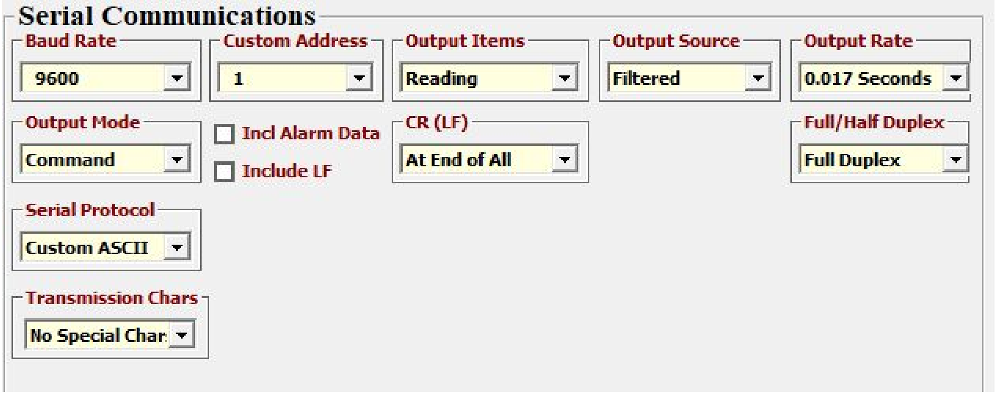
- ○ Scale, Offset >
- ● Coordinates >
- ○ Reading Coord>

Scale: +1.0000
Offset: +00000.

Low In	Low Read	High In	High Read
+00.000	+00000.	+22.076	+00600.

Image 23: *Scaling screen, within which the input and output readings of the SST Transmitter could be adjusted* [16].

Next, the communication settings had to be adjusted. The baud rate was set to 9600, the output rate set to 17 milliseconds, the data bits set to 8, and the stop bits set to 1.



Serial Communications

Baud Rate: 9600
Custom Address: 1
Output Items: Reading
Output Source: Filtered
Output Rate: 0.017 Seconds
Output Mode: Command
☐ Incl Alarm Data
☐ Include LF
CR (LF): At End of All
Full/Half Duplex: Full Duplex
Serial Protocol: Custom ASCII
Transmission Chars: No Special Char

Image 24: *Communications screen, within which the basic communication settings between the load cell and post-SST processor could be adjusted* [16].

With these settings applied to the SST Transmitter (settings can be applied by selecting Main Menu > DPM > Put Setup), accurate force measurements can be displayed through the software program. Image 25 shows an example of the Load Cell Transmitter Display with force displayed in pounds.

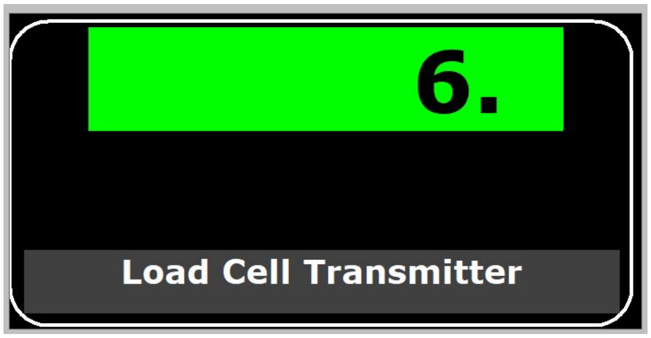
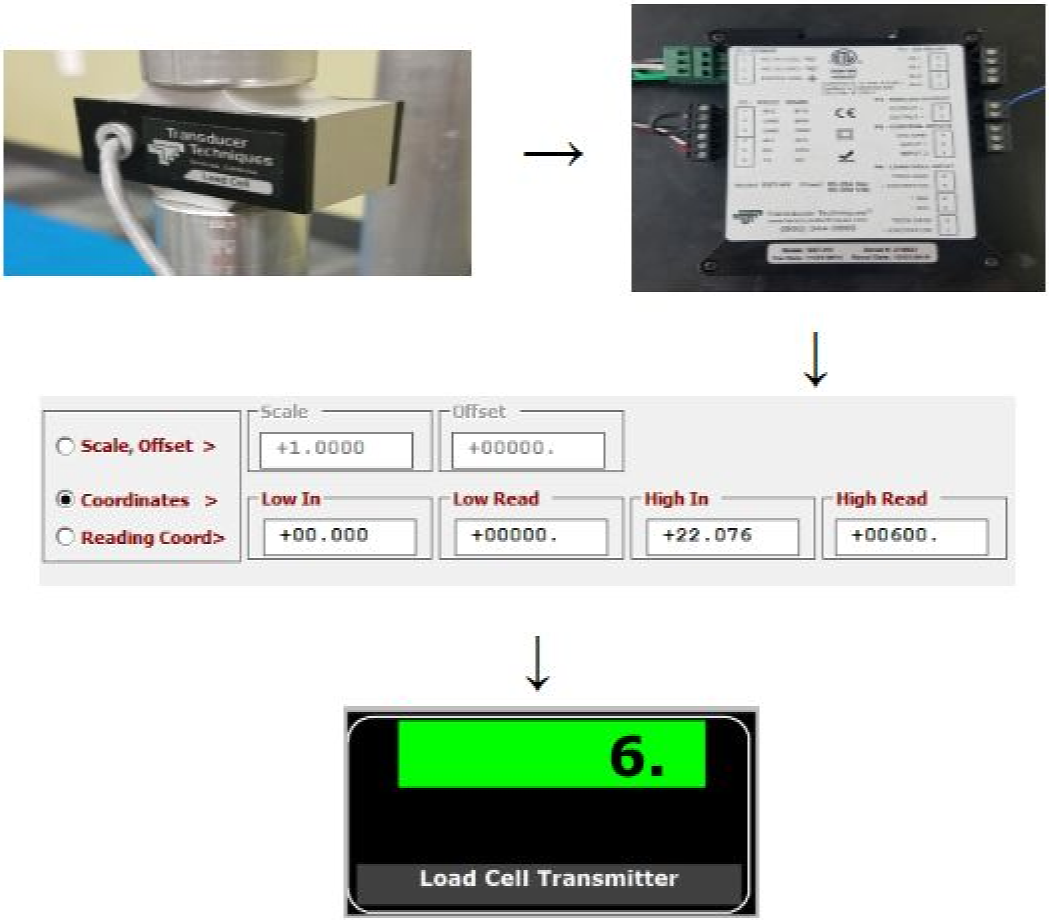


Image 25: The SST Transmitter displays the force measured by the load cells in pounds [16].

To summarize this electronic setup, Image 26 depicts a flowchart showing each component. Voltage output from the bridge sensor circuit in the load cell is sent to the SST Transmitter. The Transmitter is interfaced with the SST software in order to convert changes in voltage to changes in force readings that are displayed through the software.



○ Scale, Offset >
● Coordinates >
○ Reading Coord>

Scale: +1.0000
Offset: +00000.
Low In: +00.000
Low Read: +00000.
High In: +22.076
High Read: +00600.

6.
Load Cell Transmitter

Image 26: A flowchart showing the hardware and software components of the electrical setup used to measure force applied to the LEST push plate.

Alternatively, the analog output ports on the SST Transmitter can be connected to an Analog to Digital Conversion board (AD board). In this way, the AD board can be interfaced with a custom software program, if the user wishes to collect and record data separately from the SST software. If the analog voltage output is used, the settings depicted in Image 27 must be used. These settings ensure that -600 lbs of applied force will correspond to a 0 Volt output, while +600 lbs of applied force will correspond to a 10 Volt output.


Analog Out

Analog Out Source: Unfiltered
Lo Range Reading: - 00600.
Range: 0-10V Voltage
Hi Range Reading: +00600.

Image 27: The SST software settings that are required for accurately measuring force, when using the analog output.

One example of this method would be collecting data using an Arduino board. The analog output from the SST would be run through a voltage divider in order to divide the voltage range in half, according to Equation 1 [17]. In this case, two resistors of equal resistance would be used.

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2} \tag{1}$$

The purpose of using the voltage divider would be to achieve the 0-5 V range that is required for analog input to the Arduino. This analog input could then be converted to force measurements using an Arduino software program. Sample code is provided in Appendix F.

E. Testing

Image 28: Testing being performed in the Shell for both compression (right) and tension (left) values, with a weight of 45 pounds being applied in both instances.

In order to sufficiently test the accuracy of the LEST's data collection, it was brought to the Shell for access to weight plates. These weights were placed directly on the push plate in 10 pound increments, starting at 5 pounds and going up to 45 pounds. The SST software was hooked up and measuring the forces on the load cells, with the recognized force being displayed on the software program on a laptop. Testing was first done in compression, with the LEST oriented as it normally would be and the weights on the top of the push plate as depicted in Image 28. Then, to measure forces in tension, the LEST was flipped over onto the table it was resting on with the vertical assembly hanging away from the table. In this way, the weights could be placed on the “bottom” face of the push plate as depicted in Image 28. The testing results can be seen below:

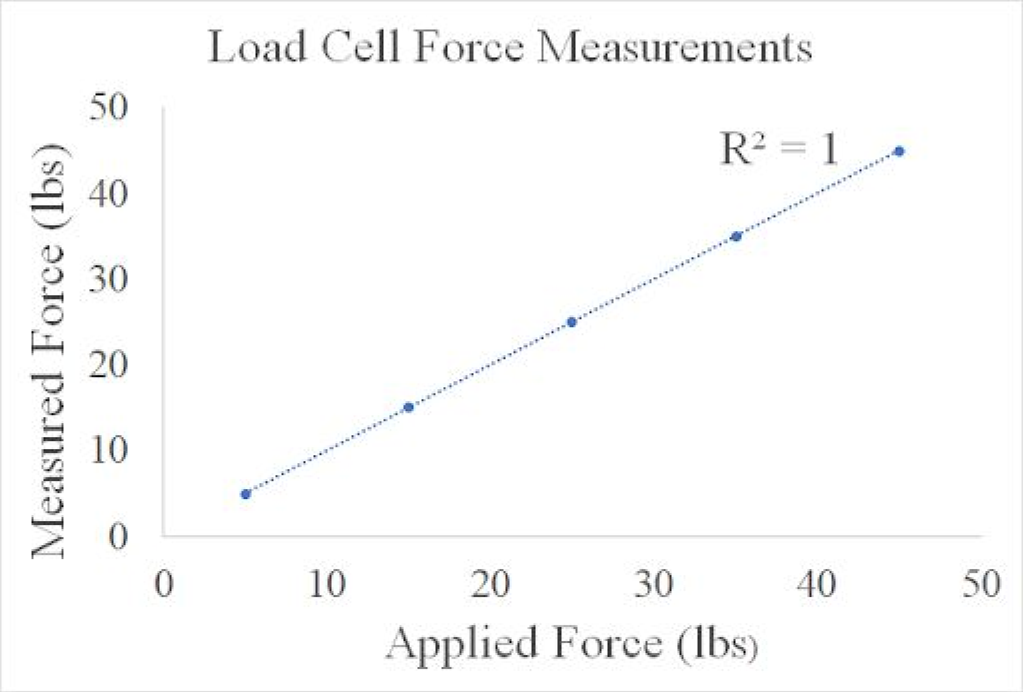


Image 29: Testing results for data collected in tension and compression.

The measured values on the SST software display exactly matched the weight being used for every 10 pound increment in both tension and compression. Both test series were plotted on the above graph but had exactly identical results, leading to their lines overlying each other and an R squared value of one. This demonstrates that our design is very effective and accurate in measurement of forces placed on the push plate. One concern is that the resolution of the SST software was very low, as it only displayed forces recognized to the nearest whole number. Because of this, future work for the project includes tuning the software to display numbers to a higher resolution, which would likely provide a better estimate of the accuracy of the device and more avenues for testing and improvement.

VI. Discussion

The team was able to meet key design specifications including reducing the weight of the device and obtaining accurate force measurements. With the replacement of the corner towers, 12.8 lbs of material was removed from the device, while maintaining the ability to adjust the height of the metal frame. With this decrease in weight and addition of handles to the sides of the base plate, the device will now be easier to transport between clinics. The struggles encountered while working on the electronic components of the design led to a failure to perform any sort of testing with the device last semester.

After extensive troubleshooting and rewiring, it was determined that the electronic problems stemmed from a problem with the SST transmitter. This semester, the SST was shipped back to *Transducer Techniques*, repaired, and then returned to the team. Using the load cells, SST, and the corresponding SST software program, the team was able to set up a functional electronic system that accurately measures (-) compressive and (+) tensile forces that are applied to the push plate of the device. Furthermore, vacuum cups were added to the bottom of the base plate to eliminate flexion during testing and reduce error in the measured force readings. Thus, the LEST device can be used in the research lab to start collecting quantitative data on hip flexor strength in patients with pelvic instability. While the quantitative data is accurate, the display does not read past the decimal point. This would cause errors in reading accuracy and low maximal voluntary contractions.

Ethical concerns are not a large concern for the device. However, there is always a possibility of injury while subjects are exerting their maximum forces in a straight leg raise. Efforts were made to increase the subject's comfort while using the device by adding padding to the base plate and push plate. The new corner towers were designed to limit excess movement of the metal frame, so that no adverse sudden movements will cause harm to the subject while they are applying force to the push plate.

VII. Conclusion

For this study, participants will be asked to lie on their backs in a supine position and perform a straight leg raise task while measuring their MVC (Maximum Voluntary Contraction) of the hip-flexors/knee-extensors in order to determine pelvic instability. The device needs to be light, quick and easy to assemble, comfortable, and able to withstand the strength of an adult female. The current device is physically and electronically functional After observing the progress made from the last semester on this design, the goal for this semester was to modify what has already been fabricated to better suit the client's requirements. The main focuses to meet this goal included reducing the overall weight of the design, reducing the flexion of the base plate during testing, and having the faulty SST transmitter fixed to ensure that all electronics are functional. Due to the successful reduced overall weight, reduced flexion of the base plate from the vacuum cups, and functional electronics, Dr. Deering will be able to begin obtaining quantitative results for her studies. This may be the first step in an accurate diagnosis of a common problem in women, pelvic instability.

A. Future Work

As with many new products, there are many ways to generally improve on how design specifications are met. The weight of the device was a variable that could be reduced in the corner towers, support beams, and base plate by using different materials and dimensions to cut down on unnecessary material. The HDPE sheet was $216.25 of the $511.86 spent last semester and found to be relatively easily flexed if the MVC test was implemented incorrectly. Since the HDPE had already been purchased and implemented, it was desired to add modifications to the HDPE that would allow it to be more rigid. Vacuum cups were the most efficient and cost effective way of enforcing HDPE rigidity. Another way that would have either coincided with, or replaced the vacuum cups was to apply a couple of thin sheets of more rigid material to the bottom of the HDPE. This would have ended up increasing the weight of our device and caused unnecessary complications in fabrication. The replacement of corner towers and other adjustments allowed the weight to remain under 40 lbs. To address these issues of weight and base plate flexion, all modifications included in the Bike Mod Design were made throughout the semester. This included removing the existing corner towers and replacing them with the hollow tubes and quick-adjustment shaft collars. Vacuum cups were added to the bottom of the base plate, in order to reduce flexion during testing.

Additionally, there are a number of other small adjustments that can be made to this device to make it more effective. Adding height measurements etched into the aluminum support beams, for one, would allow clients to easily adjust the push plate to specific heights for testing. Hollow tubing can also be used throughout the metal frame in order to reduce weight and provide a space for consolidating any wires. The device is currently set up to display force readings within the SST software; however, the analog output from the SST can also be connected to an AD board with a BNC cable connection for use in clinical research. This is the setup that is utilized by Dr. Deering and Dr. Heiderscheit. Ideally, the resolution of the display readings would be increased past the decimal point. Another goal would be to make the device more aesthetically pleasing to better suit a clinical setting. A few adjustments that can be made currently are to cover the push plate in a foam-like finish in order to expose as little of the HDPE as possible. One final adjustment can be made in transportability. Due to the still troublesome transportation of the device, the push plate and supports could be made detachable and the wiring could be kept in an attached box.

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VIII. Appendix

A. PDS

LEST (Lower Extremity Strength Tester)

Product Design Specifications
Client: Dr. Bryan Heiderscheit and Dr. Rita Deering
Team: Sam Parmentier, Dan Wildner, Eric Arndt, Hayley Raj
2/8/2019

Function:

During and after pregnancy, it is common for women to experience a loss of strength in the muscles of the pelvic girdle that can lead to pelvic instability. This can cause pain and discomfort, and new methods are continually being researched to relieve women of this condition during their pregnancy and the months afterwards. Currently, to determine if a patient has pelvic instability, a doctor has them perform a straight leg raise and rate the difficulty of doing so on a scale of 0-5, with a 5 being the highest difficulty. If the patient gives a rating of anything other than zero, the doctor then compresses the hips at the sides and has the patient try the straight leg raise again. If the extra pressure from the doctor makes the straight leg lift easier, this is indicative that the patient may have pelvic instability. One of our clients, Dr. Rita Deering, has performed comprehensive research that concluded that pregnancy has a significant impact on the strength of the pelvic girdle muscles. Presently, she is trying to quantitatively analyze the extent of the effect it has. Therefore, a device is needed to assess a maximal voluntary contraction (MVC) of the hip flexor (iliopsoas) and knee extensor (quadriceps, rectus femoris) muscles during a straight leg raise task to assess the loss of strength in the lower extremities of women both during and after pregnancy. This device will be completely portable and will have load cells implemented into the support posts to allow for the measurement of this MVC during testing.

Testing Procedure:

While laying down with their feet inside the area of the device labeled below, the subject will first perform an unassisted leg raise with one leg until fatigue. The push plate will be in its lowest position (as shown), and both feet will be within the bars of the push plate, while one leg uses the area in between them to perform the fatiguing task. The leg not performing the fatiguing task will remain on top of the push plate so that the load cells can record in compression how much force that foot pushes down with. This fatiguing task will be performed until failure, which is achieved once the foot drops beneath 10 cm or excessive lumbopelvic motion occurs (measured by an air bladder underneath their lower back). Then, the push plate will be raised to an appropriate height and the fatigued leg will immediately(within ~1 min) perform a straight leg lift. The MVC produced by that leg will be recorded near the ankle of that leg. The leg that did not partake in the fatiguing exercise will rest on the bottom plate of the design, which does not interact in any way with components fixed to the load cells. This process will then be repeated with the opposite leg on a separate day.

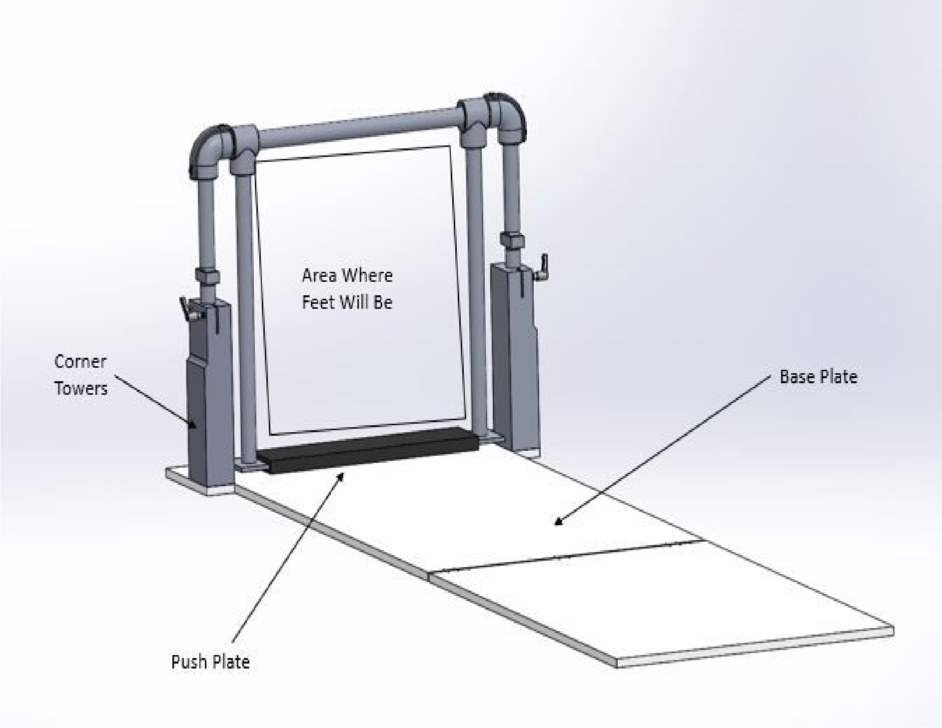


Figure 1: *Diagram of LEST Apparatus.*

Client requirements:

- Design must be completely portable in order to use in multiple research and clinical settings.
- Device should weigh under 40 lbs.
- The device must be strong enough to withstand the force of an MVC from an adult female performing a straight leg lift without breaking or losing function.
- The device must be in place and ready to use within one minute after the subject's fatiguing task to prevent muscle recovery.
- Comfort (or a lack of) of the test subject must not limit the amount of force able to be produced.
    - Primary points of comfort include the base plate the subject will be laying down on and the push plate the subject will be both resting their feet on and pushing up against.
- A budget of $1000 must be kept; $488.16 is currently available after the first semester of design.
- The device must be designed so that it can be used when the patient is in a supine position.
- The subject should not be able to hold onto the device in any way, and secondary help from a doctor or different test subject should not be required to hold the device in place.
    - To prevent the design from flexing and disrupting data collection, suction cups will be used to help hold the apparatus to the floor along with metal sheets.
- Load cells integrated into the design will be used to measure the MVC of the subject.

- All electronics shall be neatly organized and stored within the device so as to maintain an aesthetically appealing look and so that no wires/components disrupt the testing process.
- The surface of the design that the subject will press against with their ankle must not be uncomfortable to the point of causing pain, but must also not be too soft as to absorb the force of the MVC.
- The device must be conducive to the specific testing procedure detailed above.
- The design must completely integrate with the technology setup featured in the testing environment.
    - The Load Cell SST must be compatible with an A to D board and BNC cable.

Design requirements:

1. Physical and Operational Characteristics

a. Performance requirements:

- The device must have load cells integrated into it in order to accurately record the MCV of the test subject.
    - The load cells recognize forces from 0-300 N.
- All appropriate connections for the load cell to the data collection setup (SST, BNC cable, A to D board, Transducer Techniques software program) must be available during testing.
- The device will be used in UW-Health Research Park as well as other lab setting locations during the lifetime of the research project, and therefore must be completely portable.
- The device must not require any fixturing specific to a certain research location.
    - The weight of the test subject and suction cups will be used to hold the design in place.
- Must be able to withstand the force of a straight leg raise at maximum effort for an adult female.
    - This maximum force is estimated to be 264.8 N for a 30-year old female. [1]
    - Muscles involved: iliopsoas, quadriceps, and rectus femoris.
- The device must help to consistently and accurately measure the force of a lower body MVC (integrated load cells will measure the force produced).
- There must be adequate room within the device for the fatiguing task to be performed.
    - Both feet must be able to feet comfortable between the vertical supports holding the push plate in place. The subject will presumably hold their feet at hip width.
        - The average hip width of the adult American female is 12.16” [2][3]
- All portions of the device must be fully compatible with the specific testing procedure detailed above.
- Adjustment of the device (height of the push plate) must be fast and effective. Adjustable-position handles will be used on the corner towers to accomplish this.

b. Safety:

- Comfortable for patients to exert force without pain
- Able to easily accommodate patients of varying sizes, with the lower body size being of particular concern.
- Sturdy enough to avoid collapse and/or fracture from a lower body maximal muscle exertion of an adult female.
- No sharp or rough edges or protruding parts that could injure subjects as they use the device or the clients as they put the device in place.

c. Accuracy and Reliability:

- The device needs to contribute to an accurate reading from the force plate over multiple tests with varying patients (within 5% accuracy). This may require the ability to adjust on a per patient basis (in terms of height of apparatus).
- Testing of the device accuracy must be performed with weights that have been accurately measured. The force the weights exert on the push plate will then be measured in compression to ensure accuracy.
- The device should limit the area the patient can be situated in in order to maintain the position of the straight leg lift.

d. Life in Service:

- The two main locations the apparatus will be used are in UW-Health Research Park Clinic and the Badger Athletic Rehabilitation Training Center. However, it may be used in additional clinical settings.
- Needs to be available at any time of the day for extended periods of time. The number of cycles of MVC measuring is still yet undetermined.

e. Operating Environment:

- The device will be used and stored in a clinical setting.
- The largest chance for damage will likely occur during transport between clinics or while under stress from force applied by patient.
- Possible causes of failure could arise when subject is trying to get inside the apparatus and their leg/body collides with the apparatus in some way.

f. Ergonomics:

- Must be strong enough to easily withstand maximum contraction of hip flexor and knee extensor muscles of an adult female.
- Must allow a wide range of adult females to place feet into device
  - The interacting force bar needs to have enough space to accommodate a wide range of adult female ankles
    - Average ankle height = 3.058” [4][5]

g. Size:

- The apparatus must be wide and high enough to comfortably fit the lower legs/feet of any size adult female between its frame.
    - Average female hip width = 12.16”
        - Subjects will not have to hold their feet wider than hip width, so the vertical supports should be at least this width away from each other.
- The frame of the device will largely be sized based upon anthropometric data regarding the hip width and body length of the average American adult female.
    - The average hip height of the adult American female is 33.76” [2][3]
        - To ensure that the rear end of the subject holds down the entire apparatus, the folding joint of the base plate must be at least 33.76” from the end of the base plate the load cell apparatus is fixed to.
        - In this way, the rear end of the subject will pin the base plate to the ground.

h. Weight:

- The maximum weight of the device is 50 lbs, as it will need to be lifted and transported by one person between locations.
    - Weight reduction will be critical for ensuring the ease of use of the design.
    - Currently, the design weighs 47.41 pounds. The goal for this semester is to reduce the design to lower than 40 pounds.

i. Materials:

- No materials restrictions have been placed on this project as far as incompatibility with other equipment being used during the testing procedure.
- The frame is composed of aluminum rod with aluminum couplings at the corners.
- The base plate is made of HDPE with a foam mat on top for comfort.
    - The HDPE base plate was able to flex when an MVC was applied to the testing apparatus. This flexion should be reduced or gotten rid of by use of structural supports or alternative materials.
- The part of the device interacting with subject needs to be comfortable but not so soft that it absorbs the force of their MVC. A harder rubber material will likely be used.

j. Aesthetics, Appearance, and Finish:

- All seams, joints, and welds should be neat and aesthetically pleasing.
    - Professional looking coverings that accurately fit the dimensions of the design should be used, i.e. the yoga mat covering the base plate.
- There should not be any unfinished edges or contact points.
- No extraneous materials should be hanging down, protruding from, or in any way seen on the device.
    - All electronics (components and wires) must not impede the accuracy of data collection or interfere with the test subject in any way.

- The device's appearance should be comparable to the professional exterior of exercise equipment.

2. Production Characteristics

a. Quantity:

- One LEST will need to be produced.

b. Target Product Cost:

- A budget of $1000 dollars for this project has been set. Other competing designs have a cost of around $1000 dollars, so it would be preferred that our design does not reach that cost level.
  - $488.16 remain in the budget for improvements during the second semester of work.

3. Miscellaneous

a. Standards and Specifications:

- No FDA approval is required.
- No specific lab standards need to be met by the design, but it must be safe to use and prevent injury of the test subjects.

b. Customer:

- This design is not intended for commercial sale. For concerns of subjects utilizing the designs, please look below to "patient related concerns."

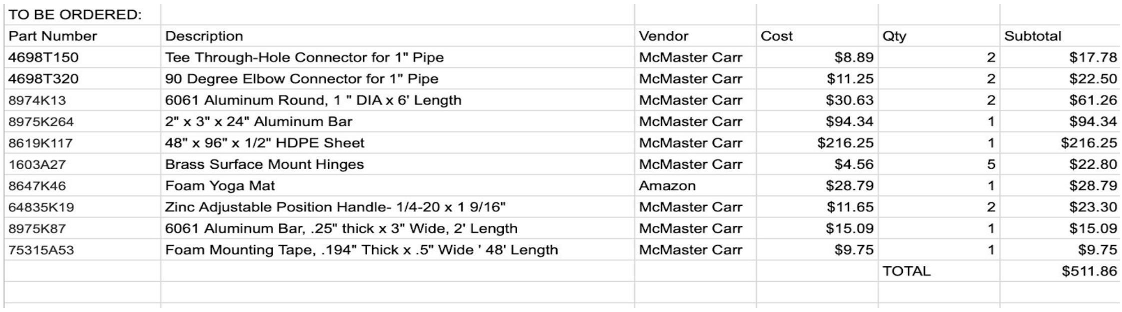
c. Patient-related concerns:

- Patient data confidentiality must be considered. The numerical value of MVC's of patients will be recorded, which is private information between the patient and the doctor performing tests.
- This device will be used for pregnant and postpartum women, so comfort is a major concern.
  - Subject must easily be able to perform the MVC test quickly after completing a fatiguing exercise.
- The testing of the apparatus involves creating a maximum force with certain muscles, so we want any surface of the device that a subject is pressing against to not cause them any pain or discomfort.
- All surfaces of the design must be relatively easy to clean between patient usage, in particular the mat covering the base plate.
  - No absorbent materials should be used.

d. Competition:

- MICROFET 2 MANUAL MUSCLE TESTING (MMT) HANDHELD DYNAMOMETER - $1,054
    - The Microfet 2 is an ergonomically-designed dynamometer that accurately measures the force produced by a certain muscle.
- Doctor's test-
    - A simple test that doctors use to measure if a patient has pelvic instability is to press against the sides of their hips and ask if that makes it easier for them perform the leg lift. If they say it does, they are considered to have pelvic instability.
- Training of whole leg waist abdominal muscle of lying on back power and test system - CN # 201520291327
    - This patent seemed to describe an apparatus that measured forces created similar to the ones in our testing procedure.

B. Last Semester's Materials List



TO BE ORDERED:					
Part Number	Description	Vendor	Cost	Qty	Subtotal
4698T150	Tee Through-Hole Connector for 1" Pipe	McMaster Carr	$8.89	2	$17.78
4698T320	90 Degree Elbow Connector for 1" Pipe	McMaster Carr	$11.25	2	$22.50
8974K13	6061 Aluminum Round, 1 " DIA x 6' Length	McMaster Carr	$30.63	2	$61.26
8975K264	2" x 3" x 24" Aluminum Bar	McMaster Carr	$94.34	1	$94.34
8619K117	48" x 96" x 1/2" HDPE Sheet	McMaster Carr	$216.25	1	$216.25
1603A27	Brass Surface Mount Hinges	McMaster Carr	$4.56	5	$22.80
8647K46	Foam Yoga Mat	Amazon	$28.79	1	$28.79
64835K19	Zinc Adjustable Position Handle- 1/4-20 x 1 9/16"	McMaster Carr	$11.65	2	$23.30
8975K87	6061 Aluminum Bar, .25" thick x 3" Wide, 2' Length	McMaster Carr	$15.09	1	$15.09
75315A53	Foam Mounting Tape, .194" Thick x .5" Wide ' 48' Length	McMaster Carr	$9.75	1	$9.75
				TOTAL	$511.86

C. Current Semester's Materials List

TO BE ORDERED:					
Part Number	Description	Vendor	Cost	Qty	Subtotal
6174A200	Bend-Preventing Vacuum Cup	McMaster Carr	$39.07	2	$78.14
1645A100	Oval Grip Pull Handle with Unthreaded Through Holes	McMaster Carr	$1.77	2	$3.54
9056K77	6061 Aluminum Round Tube- 2 Ft	McMaster Carr	$33.77	1	$33.77

89015K19	6061 Aluminum Sheet, 0.25" Thick, 2" x 48"	McMaster Carr	$7.35	2	$14.70
1511K220	Quick-Release Clamping Shaft Collar	McMaster Carr	$29.60	2	$59.20
				TOTAL	$189.35

D. Last Semester's Detailed Fabrication Process

The following parts are final sized parts that need to be fabricated for the assembly of the LEST apparatus:

1" DIA Aluminum Round- 6.125" Length (Bottom Vertical Support)			2
1" DIA Aluminum Round- 9" Length (Top Vertical Support)			2
1" DIA Aluminum Round- 20" Length (Top Horizontal Support)			1
1" DIA Aluminum Round- 17.125" Length (Push Plate Support)			2
.25" x 3" x 19" Aluminum Bar- Push Plate			1
2" x 3" x 10" Aluminum Bar- Corner Tower			2
.5" x 24" x 40" HDPE Sheet- Front Base Plate			1
.5" x 20" x 32" HDPE Sheet- Back Base Plate			1
Foam Padding to match above base plate pieces			1

The methods for creating each part will be described in detail in the order they are presented above:

1" DIA Aluminum Round- 6.125" Length (Top Vertical Support)- x2

1. On drop saw, cut a 6.25" length off of 6' stock material.
2. On lathe, face one end and file the edges. Measure overall length, flip piece around, touch off on rough face, and enter measured length into DRO. Face part down to finished length of 6.125".
3. Turn end down to ⅜" DIA with a depth of .3125".

4. Thread ⅜” stud along the full .3125” length using a ⅜-24 NF die.
5. Break sharp edges.

1” DIA ALuminum Round- 9” Length (Bottom Vertical Support)- x2

1. On drop saw, cut a 9.125” length off of 6’ stock material.
2. On lathe, face one end and file the edges. Measure overall length, flip piece around, touch off on rough face, and enter measured length into DRO. Face part down to finished length of 9”.
3. Turn end down to ⅜” DIA with a depth of .3125”.
4. Thread ⅜” stud along the full .3125” length using a ⅜-24 NF die.
5. Break sharp edges.

1” DIA Aluminum Round- 20” Length (Horizontal Support)- x1

1. On drop saw, cut a 20.125” long piece off of 6’ stock material.
2. On lathe, face one end and file the edges. Measure overall length, flip piece around, touch off on rough face, and enter measured length into DRO. Face part down to finished length of 20”.
3. Break sharp edges.

1” DIA Aluminum Round- 17.125” Length (Push Plate Vertical Support)- x2

1. On drop saw, cut a 17.25” long piece off of 6’ stock material.
2. On lathe, face one end and file the edges. Measure overall length, flip piece around, touch off on rough face, and enter measured length into DRO. Face part down to finished length of 17.125”.
3. On same face, make a pre-drill indentation using a #2 center drill.
4. Drill a 1” deep hole using a size I drill bit.
5. Countersink the hole.
6. Tap the hole to its maximum depth using a ⅜-16 NC tap.
7. Break sharp edges.

.25” x 3” x 19” Aluminum Bar- Push Plate- x1

1. On drop saw, cut a 19.125” length piece off of .25” x 3” x 24” stock material.
2. On mill, touch off on one rough face and face it off. Measure the overall length. Touch off on the opposite face and input the measured length. Mill the piece to the finished length of 19”.
3. Using an edge finder, locate the X and Y directions on the front left corner of the part.
4. Beginning with a #2 center drill, make a small pre-drilling hole in the piece at 1.5” in the y direction and 1.1875” in the x direction. Make an additional indentation at 1.5” in the y direction and 17.8125” in the x direction.

5. First using a ¼” twist drill, drill through the plate at both of these locations. Do so again using a letter X drill bit.
6. Deburr all sharp edges.

2” x 3” x 10” Aluminum Bar- Corner Tower- x2

1. To first create the left side tower, on drop saw, cut 10.125” long piece from 2”x3”x24” stock.
2. With the long edge of the part laying horizontally in the vice of a mill, touch off on one face and completely face it off. Measure the overall length of the bar. Then, touch off on the opposite face and enter the measured length into the DRO. Mill the part down to the finished 10” length.
3. Attach an angle plate to the mill table and indicate it using a dial indicator. With the long edge now vertical and the 3” face touching the angle plate, sandwich the part between the fixed angle plate and an additional free angle plate using a C-clamp. Place a large vice stop on the fixed angle plate so that it is flush with the edge of the part.
4. Program the mill to move to four separate hole positions. Assuming the origin is at the front left corner, the hole locations are (.5”, .5”), (1.5”, .5”), (1.5”, 2.5”), and (.5”, 2.5”). Program three additional repeat cycles after programming the hole positions for drilling, countersinking, and tapping.
5. Using an edge finder, locate the the x and y faces of the part, making the origin at the front left corner.
6. Begin the CNC program, first using a #2 center drill. Make a pre-drilling indentation at each of the four locations. Continue moving through the program, progressively using a #7 twist drill to drill a hole depth of 1.2”, a countersink, and a 1/4 -20 NC tap.
7. Position the quill over the (1”, 1.5”) location of the part. Use a #2 center drill to make a pre-drill indentation.
8. Beginning with a ¼” twist drill, drill a hole to the maximum depth allowable by the drill bit. Repeat using a ⅜” drill bit.
9. Using a morse taper adapter for the quill, again drill as deep as possible using a ¾” drill bit, and then a 1” drill bit. The hole should be just past 5” deep.
10. Loosen the part from the angle plate and flip it over, making sure it is flush with the fixed angle plate and the vice stop. This will ensure that no additional locating will be necessary.
11. Again, position the quill over the (1”, 1.5”) location of the part. Repeat steps 8 and 9 so that the 1” drill bit breaks through and a complete 1” hole is made throughout the tower.
12. Using a 1.001” reamer, ream the 1” through hole completely.
13. Using a 3/16” end mill, create a relief cut centered on the 2” face of the part, extending from the edge to the center hole on both sides. The relief cut should be 1” deep.
14. Place the part back in the vice, with the long edge again horizontal and the relief cut on the front right side of the vice. Edge find on the front right corner of the part.
15. First using a #2 center drill, create a pre-drill indentation at (-1”,1”). Drill to a depth of 1.6875” using a #7 twist drill.

16. Create a clearance hole at the same location with a letter I drill bit, drilling deep enough so that the clearance hole reaches the relief cut.
17. Using a ¼-20 NC tap, tap the #7 DIA hole on the opposite side of the relief cut.
18. Repeat this process at a location of (-1,2”) to create a second hole.
19. With the 2” wide face of the tower flat on the table of a bandsaw, line the blade up with the center of the relief cut and extend it to be 3.5” deep total.
20. In the vice of the mill, place either of the 2” faces down against the bottom of the vice. Extend the end of the tower with the relief cut far enough out to the right of the vice that a 5/16” through hole can be drilled at the bottom of the relief cut. This will be done for stress relief to reduce the propagation of cracking.
21. Begin with edge finding the part on the front right corner, and make a small indentation with a center drill at the (-3.5, 1) position after doing so.
22. Without moving the table, drill through the tower with the 5/16” bit.
23. Using a 1” four flute end mill with a 3” LOC, position it against the Y face of the right end of the part. Zero the DRO.
24. Now, position the end mill against the front X face of the part. Zero the DRO.
25. Using the “GO TO” feature, program the mill so that you can’t go past (-3.5”, .25”)
26. Begin milling down the face of the part with the clearance holes, NOT the tapped holes. Take .300” off each pass until a depth of .25” is reached in the Y direction, going all of the way to -3.5” in the X direction every time.
27. To create the right side tower, this entire process should be followed until step 13. In this step, the relief cut should again be placed on the right side of the vice but should be facing the BACK of it. Then, the following steps can again be followed. In this way, the clearance hole and tapped hole will start on the opposite side of the tower, so that the left and right towers are mirror images of each other.

.5” x 24” x 40” HDPE Sheet- Front Base Plate- x1

1. On panel saw, cut a 25” x 48” piece out of an 8’ x 4’ sheet of ½” thick HDPE.
2. On a table saw, cut the width down to the finished 24” and the length down to the finished 40”.
3. Make a mark 2” from each edge of the 24” width and 7” from one end of the part. Using the table saw with the blade high, cut out the 2” x 33” section on each side of the board.
4. On the mill, write a program to mill out three 2.0625” x .75” profiles that are all .1875” deep. One should be centered along the 20” side of the board, and the other two are exactly 5.875” away on each side of the centered profile.
5. Also program three holes to be drilled, all .21875” from the edge of the board, .9375” apart, with the center hole being in the center of the profile.
6. Remove the vice and fixture the board to the table of the mill, with the long edge running parallel to the table. Edge find the X and Y faces and set the origin at the extreme right edge of the board, in the center of the 20” length. Run these programs to mill out the three profiles and drill three holes in each profile, all using a #37 twist drill.

7. Write an additional program to drill 8 more holes. Assuming the origin will be at the front left corner of the left fin, the hole locations will be (.5” , .5”), (1.5”, .5”), (22.5”, .5”), (23.5”, .5”), (23.5”, 2.5”), (22.5”, 2.5”), (1.5”, 2.5”), (.5”, 2.5). Program two repeat cycles for drilling and countersinking.
8. Place the long 24” length of the board along the length of the table. Edge find and set the origin at the front left corner of the left fin. Run the program and drill using a letter I drill bit. Countersink deep enough to accomodate the head of a ¼-20 flat head socket head screw.

.25” x 20” x 32” HDPE Sheet- Back Base Plate- x1

1. On panel saw, cut a 21” x 48” piece out of an 8’ x 4’ sheet of ½” thick HDPE.
2. On a table saw, cut the width down to the finished 20” and the length down to the finished 32”.
3. On the mill, write a program to mill out three 2.0625” x .75” profiles that are all .1875” deep. One should be centered along the 20” side of the board, and the other two are exactly 5.875” away on each side of the centered profile.
4. Also program three holes to be drilled, all .21875” from the edge of the board, .9375” apart, with the center hole being in the center of the profile.
5. Remove the vice and fixture the board to the table of the mill, with the long edge running parallel to the table. Edge find the X and Y faces and set the origin at the extreme right edge of the board, in the center of the 20” length. Run these programs to mill out the three profiles and drill three holes in each profile, all using a #37 twist drill.

E. Current Semester’s Detailed Fabrication Process

The following parts are final sized parts that need to be fabricated for the assembly of the LEST apparatus:

Part Number	Description			QTY
8974K13	1" DIA Aluminum Round- 9" Length (Top Vertical Support)			2
022419-002	Corner Tube Base Plate (1/4" x 2" x 3.25" 6061 ALMNM BAR)			2
9056K77	10" LNGTH x 1.084" ID 6061 ALMNM TUBE (Corner Tube)			2
022419-001	Corner Tube Subassembly			2

The methods for creating each part will be described in detail in the order they are presented above:

1” DIA ALuminum Round- 9” Length (Bottom Vertical Support)- x2

1. On drop saw, cut a 9.125” length off of 6’ stock material.

2. On lathe, face one end and file the edges. Measure overall length, flip piece around, touch off on rough face, and enter measured length into DRO. Face part down to finished length of 9”.
3. Turn end down to ⅜” DIA with a depth of .3125”. 4. Thread ⅜” stud along the full .3125” length using a ⅜-24 NF die. 5. Break sharp edges.
4. Turn entire length to a diameter of .997” using a tailstock.

Corner Tube Base Plate- x2

1. On dropsaw, cut 3.25” length off of 89015K19- McMaster Carr.
2. On Mill, place length on parallels with one end hanging outside of the vice. Make a rough pass on one end of the length.
3. Flip the the part around so that the opposite end hangs out of the vice. Edge find the left edge nearest you. Mill down the part to finished length (3”), making sure to cut the rough end.
4. Using a #2 center drill, predrill four holes at (.5,.5), (2.5,.5), (1.5,.5), and (2.5,1.5).
5. Drill through holes at the same locations using a #7 twist drill.
6. Tap through at all four locations with a ¼-20 tap.
7. Create a CNC program on the mill to first mill out a 1.25” DIA hole to a depth of .167” and to then mill a through with a diameter of 1.167”.
8. Deburr all sharp edges.

Corner Tube- x2

1. On a drop saw, cut 10” length off of 9056K77- McMaster Carr.
2. Deburr all sharp edges.

Quick Adjust Shaft Collar Modification- x2

1. Using a belt sander, sand of the anodized finish on the bottom face of each shaft collar.
2. Clamp the collar onto the end of a 1” shaft with half of the depth of the collar open on the inside face.
3. Place this setup inside the lathe chuck.
4. Using a boring bar, bore out a hole with a diameter of 1.27” to a depth of .06”.

Corner Tube Subassembly- x2

1. With the bottoms of the 10” corner tube and the corner tube base plate flush, weld around the corner between the top of the corner tube base plate and the side of the corner tube. Make sure the countersinks are on the bottom face of the corner tube base plate.

2. Weld 1511K220- Quick Release Clamping Shaft Collar to top of 10” corner tube. Weld only halfway around the quick release clamping shaft collar.

Front Half Base Plate Modifications-

1. Remove the vise from the table of the mill and use table clamps to fix the base plate to the table of the mill, making sure the bottom face is facing upwards.
   a. Use a machinist square to ensure that the base plate is square on top of the table.
2. Use an edge finder to located the short edge of the base plate. Reset the zero point in the x direction to 2.75” away from that edge.
3. Edge find the long edge of the base plate and set a zero 5.25” away from that edge.
4. Mill out a pocket to a depth of .35” that is 4.375” long in the x direction and 1.375” long in the y direction.
5. Mill a pocket all of the through the base plate from (4.25”,5.25”) to (5.25”, 6.625”).
6. Turn the base plate around and reclamp and square it.
7. Repeat steps 2-6 to mill out another two pockets.

F. Arduino Code

```
int loadcellPin = A0;    // input pin for load cell

float sensorValue = 0;  // variable to store the value coming from the sensor

//float voltage = 0;

float force = 0;

void setup() {

  // initiate serial communication

  Serial.begin(9600);

}

void loop() {

  // read the value from the sensor:
```

```
  sensorValue = analogRead(loadcellPin);

  force = (sensorValue * (1200.0/1023.0)) - 600;



  Serial.print("force: ");

  Serial.println(force);

  //Serial.print("sensor value: ");

  //Serial.println(sensorValue);

}
```

G. CAD Drawings

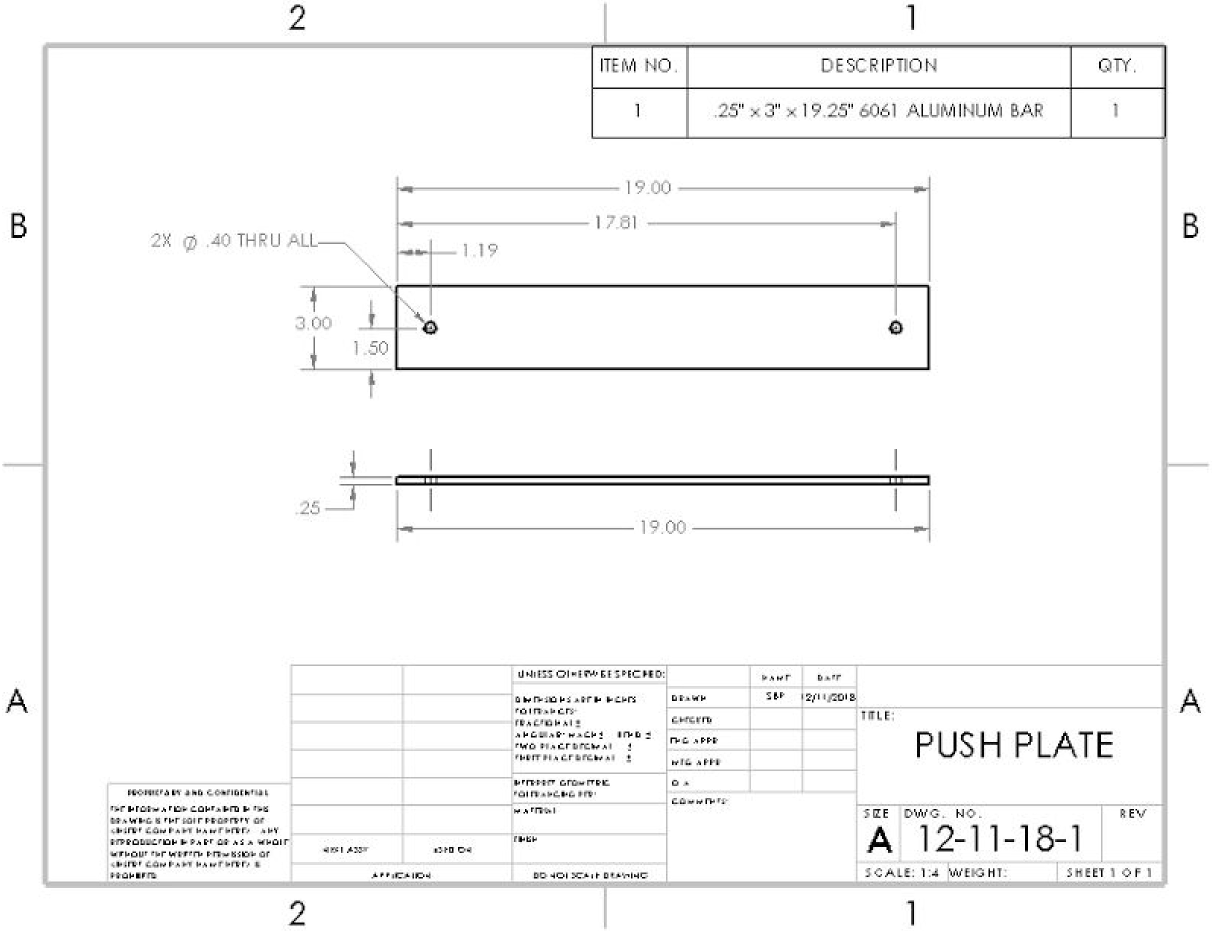
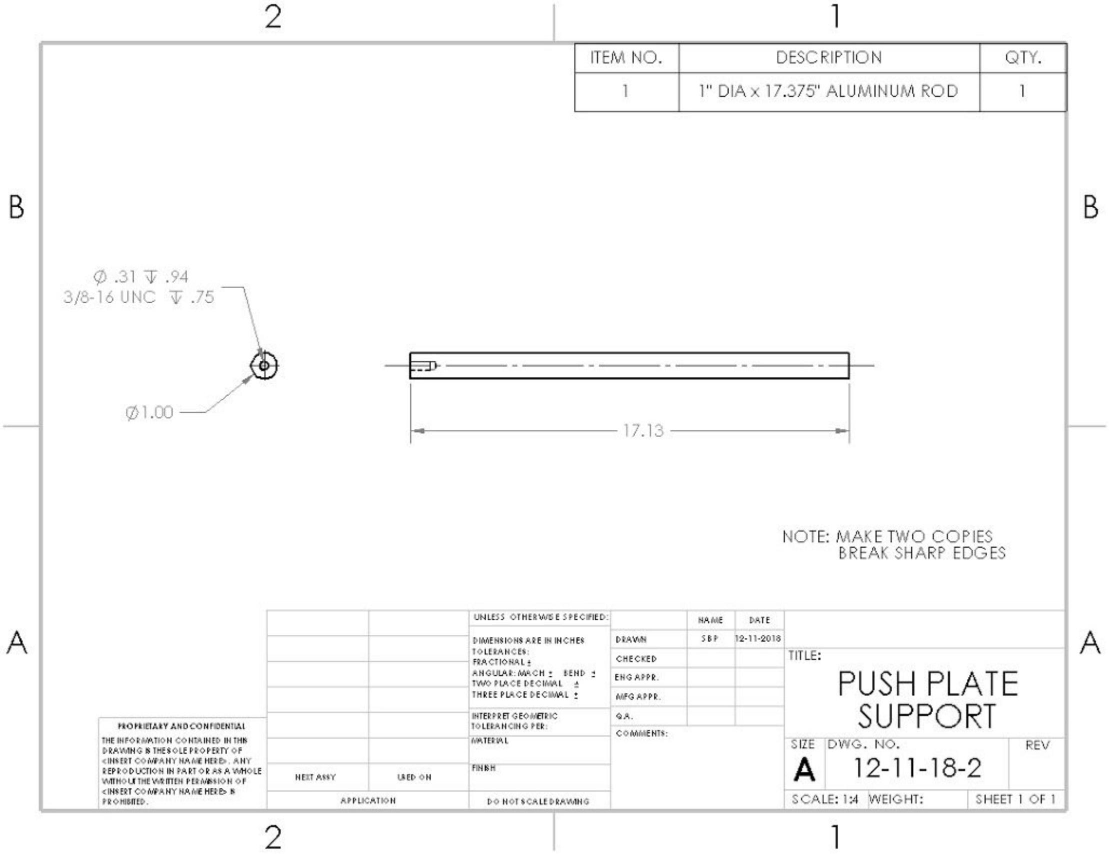


Image 1: *Detailed drawing of the Push Plate (part 12-11-18-1).*



ITEM NO.	DESCRIPTION	QTY.
1	1" DIA x 17.375" ALUMINUM ROD	1

NOTE: MAKE TWO COPIES
BREAK SHARP EDGES

	NAME	DATE
DRAWN	SBP	12-11-2018

TITLE: PUSH PLATE SUPPORT
SIZE A
DWG. NO. 12-11-18-2
REV
SCALE: 1:4
SHEET 1 OF 1

Image 2: *Detailed drawing of the Push Plate Support (part 12-11-18-2).*

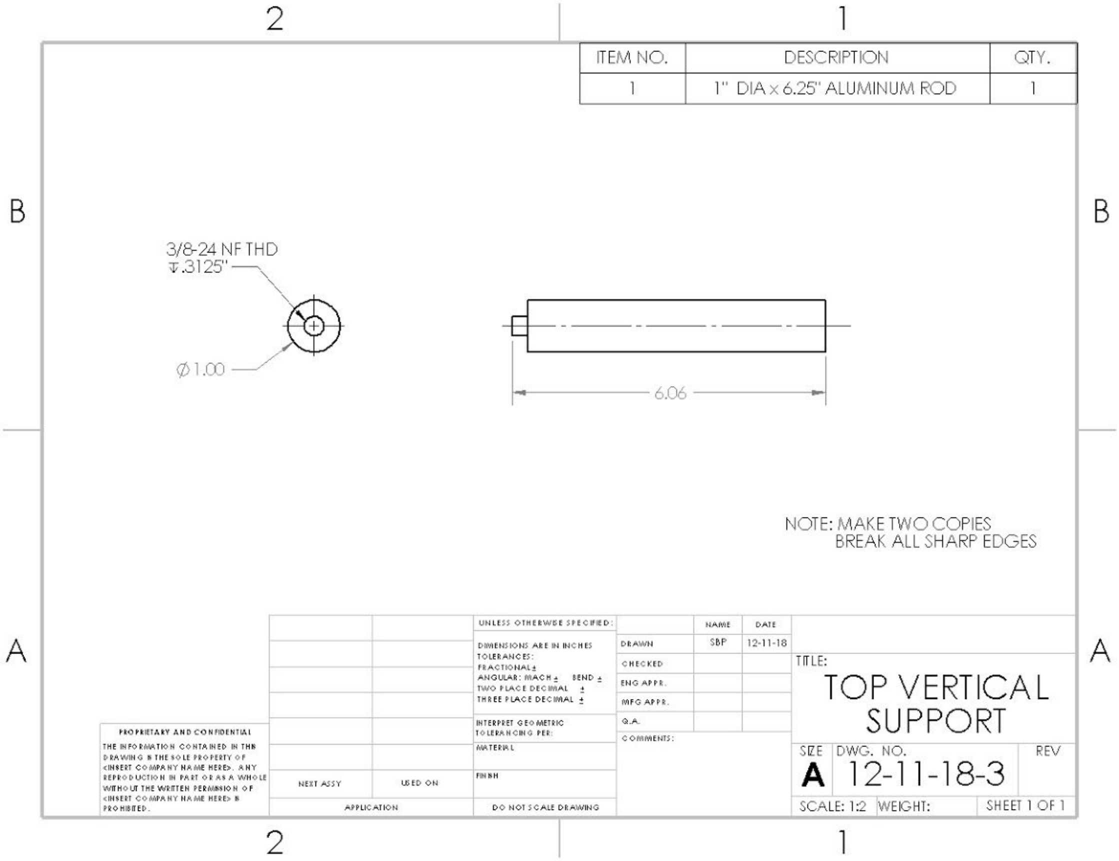


Image 3: *Detailed drawing of the Top Vertical Support (part 12-11-18-3).*

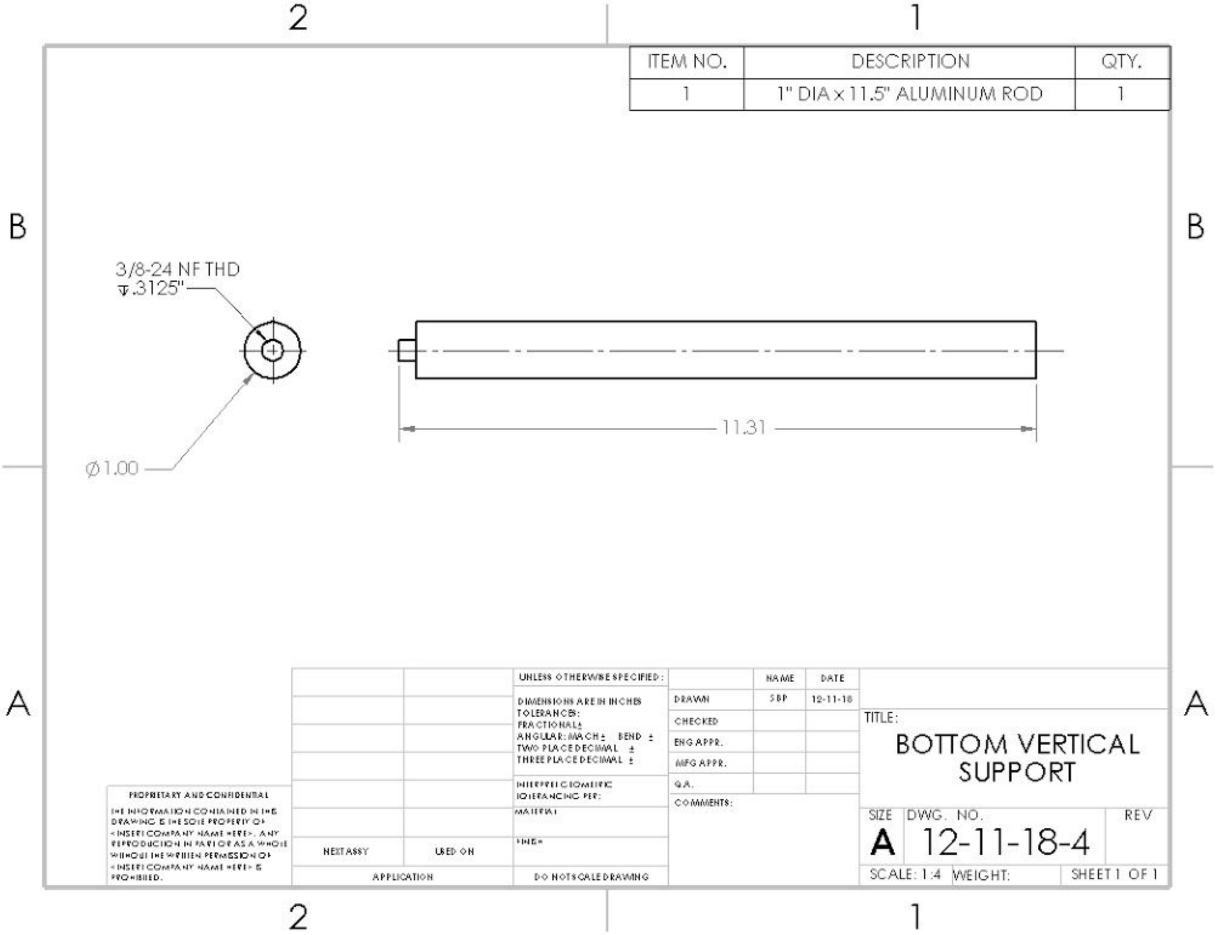


Image 4: *Detailed drawing of the Bottom Vertical Support (part 12-11-18-4).*

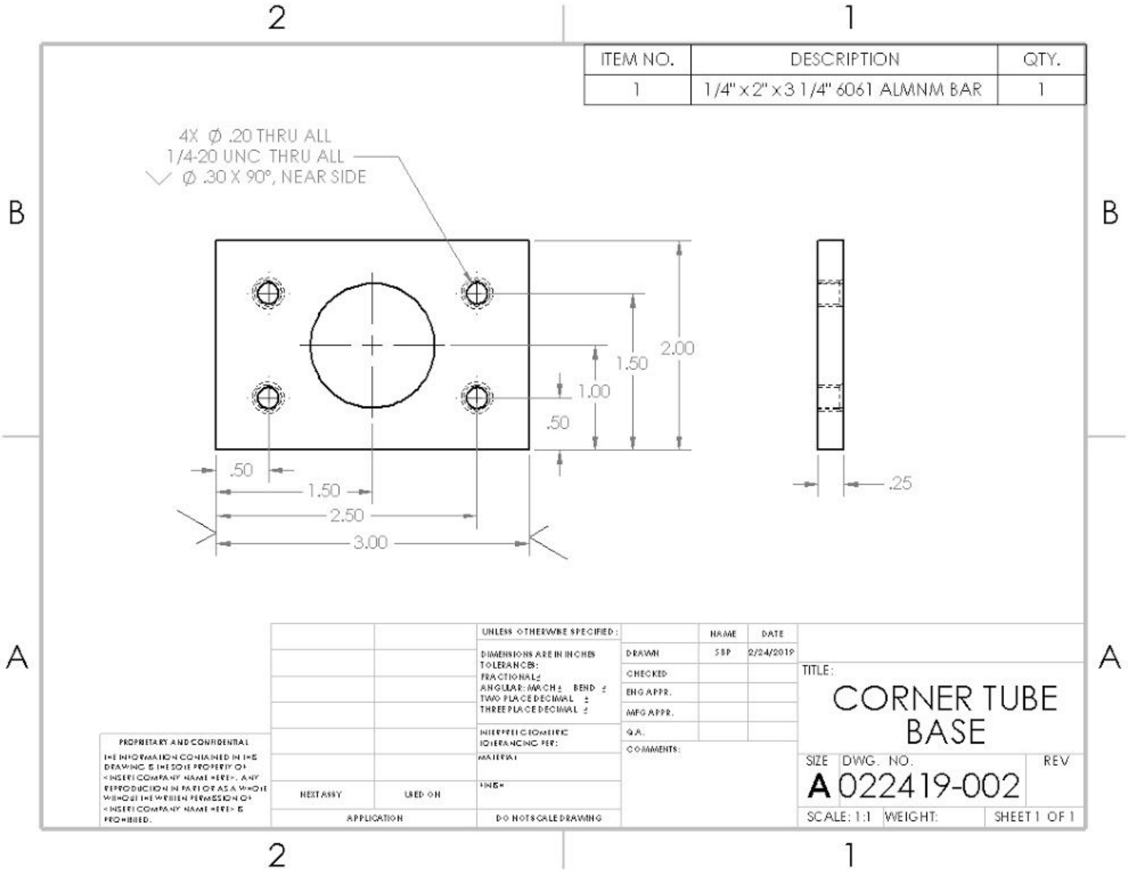


Image 5: *Detailed drawing of the Corner Tube Base Plate (part 022419-002).*

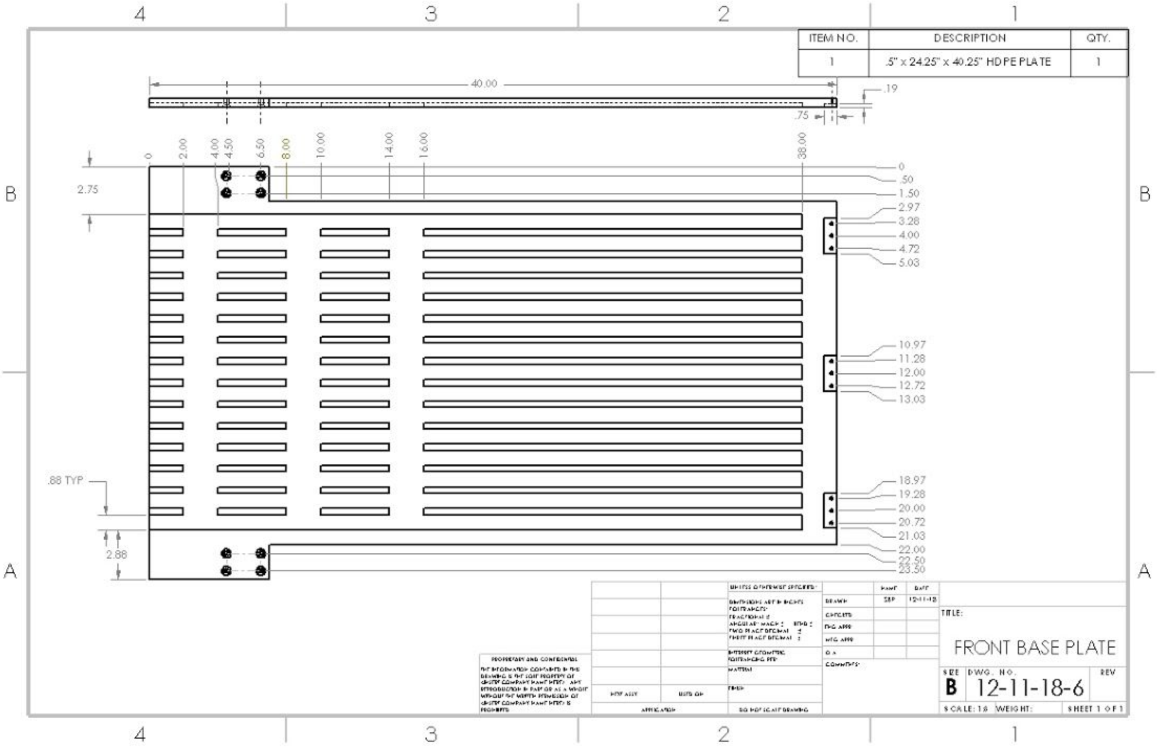


Image 6: *Detailed drawing of the Front Base Plate (part 12-11-18-6).*

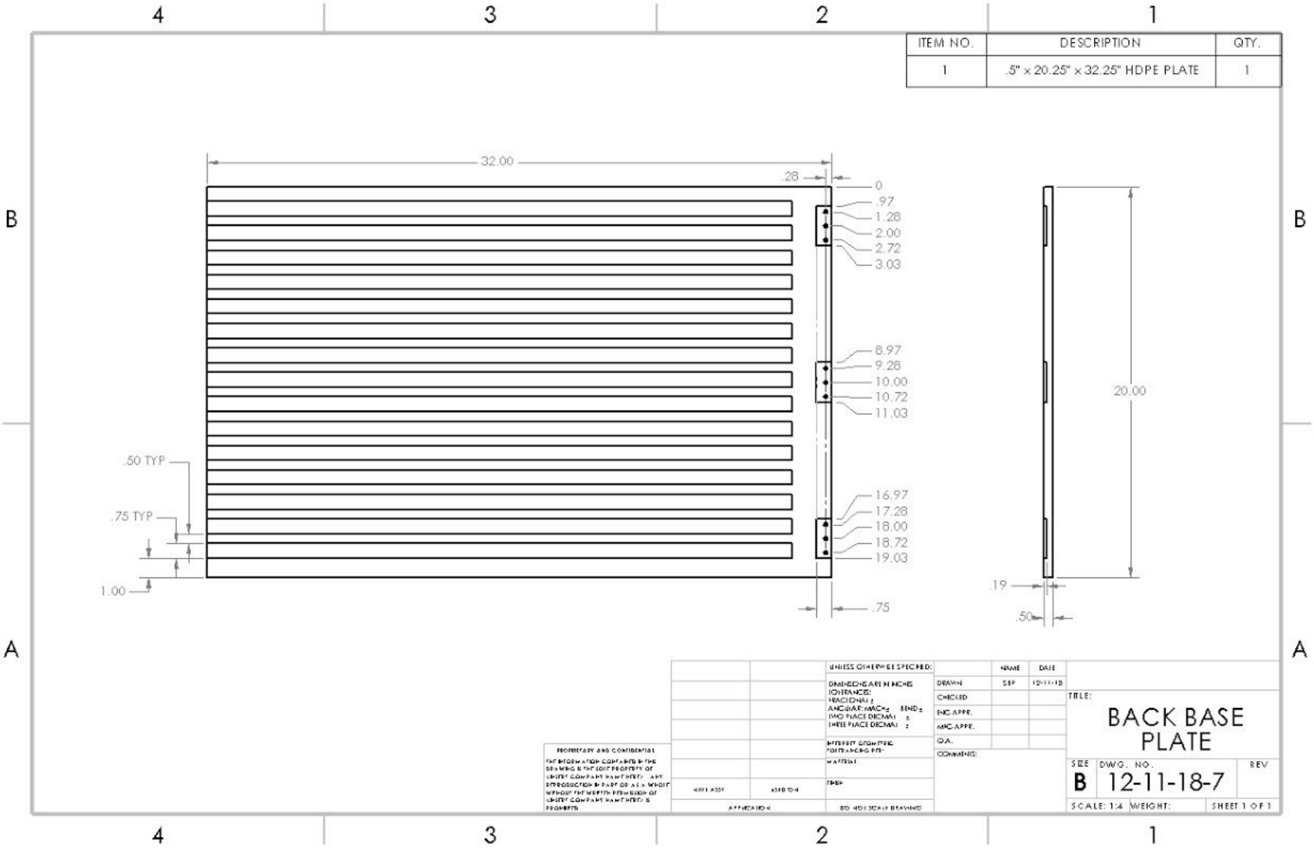


Image 7: *Detailed drawing of the Back Base Plate (part 12-11-18-7).*

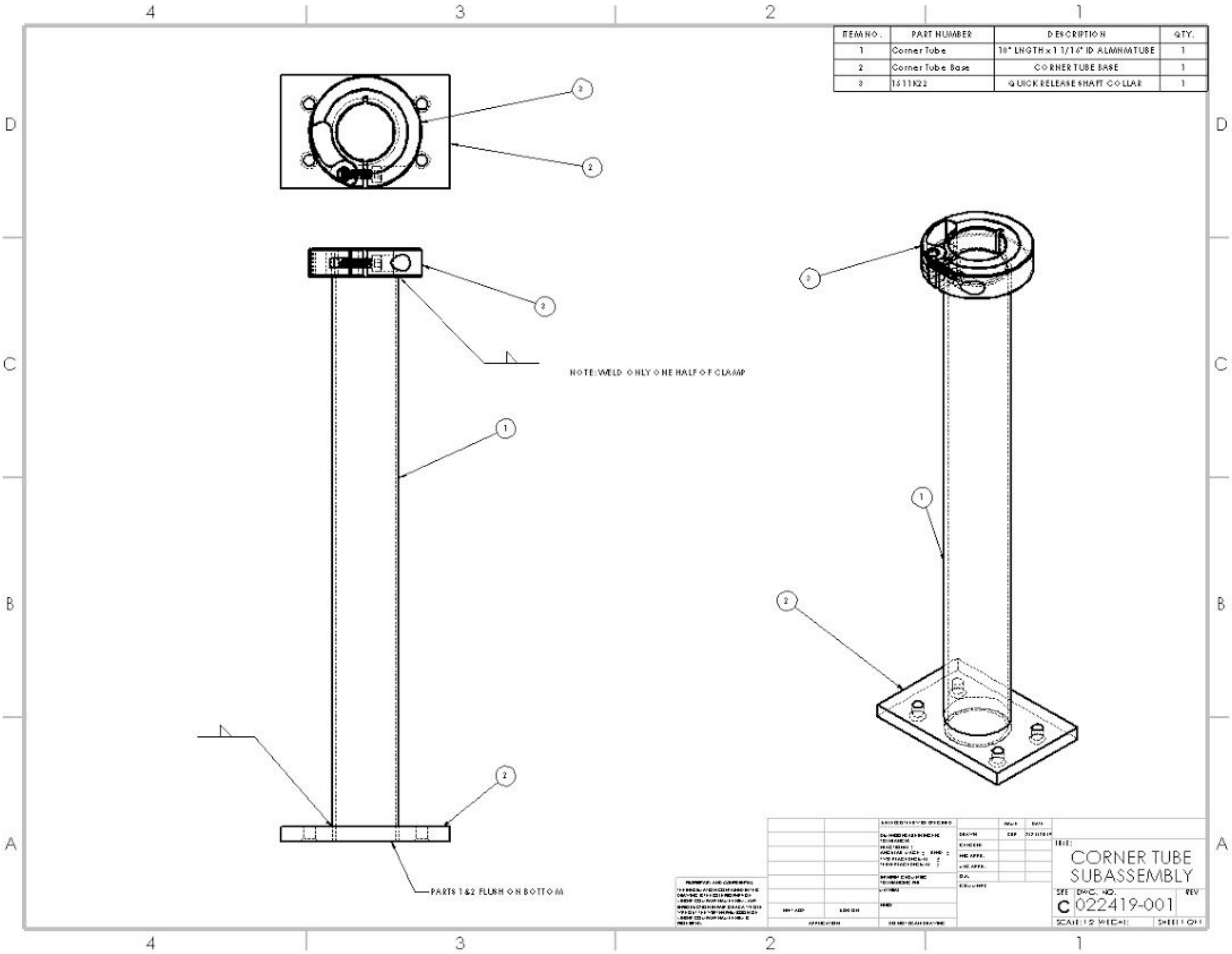


***Image 8:** Detailed drawing of the Corner Tube Subassembly (part 022419-001).*

H. Testing Protocol

Testing Location: The Shell

Conducted By: All team members (Hayley, Eric, Dan, Sam)

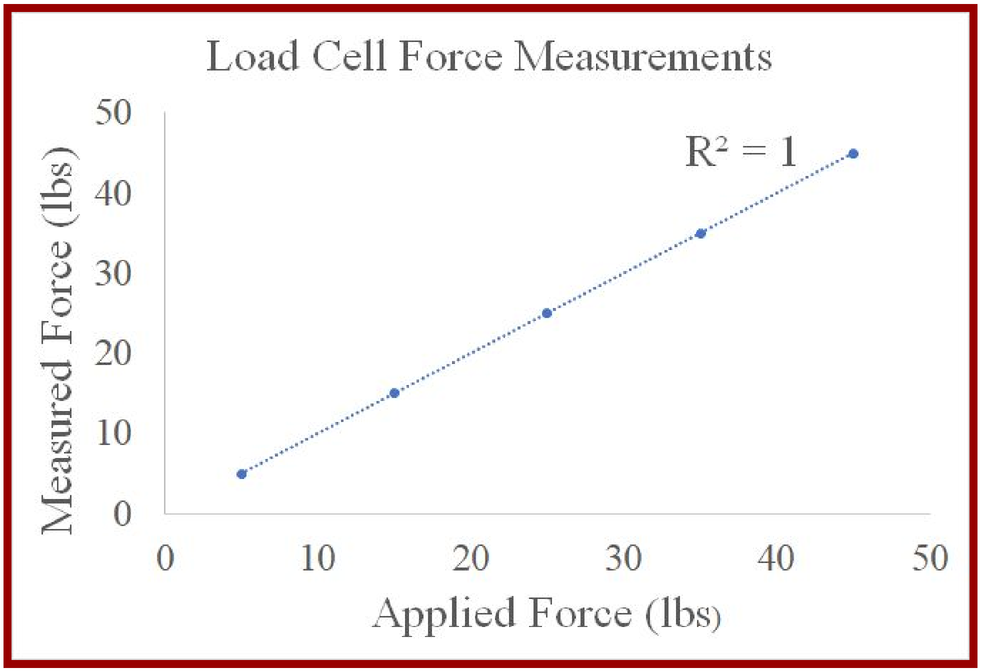
Testing Process:

1. Begin with the LEST upright in its normal position, resting on a table. Weights will be placed on the top face of the push plate to measure forces in compression with the load cells and SST software.
    a. First tare the SST display, ensuring that it reads 0.
    b. Begin by placing the first weight (five pounds) on the top of the push plate. Record the force recognized by the SST software.

   c. Increase the weight increment by 10 pounds, again recording the force displayed on the SST software.
   d. Repeat this process until a weight of 45 pounds is reached.
2. Flip the LEST over so the base plate rests on the table and the vertical assembly hangs over the edge. In this way, weights will be placed on the bottom face of the base plate to measure forces in tension with the load cells and SST software.
   a. First tare the SST display, ensuring that it reads 0.
   b. Begin by placing the first weight (five pounds) on the bottom face of the push plate. Record the force recognized by the SST software.
   c. Increase the weight increment by 10 pounds, again recording the force displayed on the SST software.
   d. Repeat this process until a weight of 45 pounds is reached.

Testing Results:

The testing was completed at the Shell following the above procedure. For each weight increment, the number on the display exactly matched the weight being measured. Pictures of testing can be seen below:



The above graph depicts our testing results, comparing the measured force to the applied force. The data had an R squared value of 1.