Johnson Health Tech: EMG Sensor Holder for Heels and Center of Mass Approximation

Biomedical Engineering Design 400
University of Wisconsin-Madison
Department of Biomedical Engineering
Final Design Report
December 9, 2020

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Abstract

Johnson Health Tech uses Delsys Trigno sensors to collect data on a runner's center of mass and step force. To do so, they use the sensor's inertial measurement unit to collect acceleration data and convert it into force using the subject's mass. The current method of attaching the sensors to the back of the shoe with athletic tape often causes the sensor to move and the tape to roll up. This is less than ideal since the sensor movement adds excess noise to the data making it harder to process and uncomfortable for the runner. They do not currently have a device to hold the third sensor to the user's chest and are looking for a design to do so. Two shoe sensor holders were created and tested for stability while one chest band was tested. Currently, all three designs seem stable and are viable options for a final product.

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I.Introduction

A. Motivation

The use of accelerometers to determine the forces on and velocities of different body segments eliminates the need for a force plate to measure reaction forces. This allows for the collection of movement and force data in situations when using a force plate is not possible or not ideal. The vertical ground reaction forces calculated from the accelerometers on the user's shoe, coupled with the step rate estimated from data collected by the sensor at the user's center of mass, can be used to assess the risk of injury for runners and other athletes on a variety of surfaces [1]. Johnson Health Tech currently implements this idea of using accelerometers for some of their research, but the method they use to attach the accelerometer sensors to the user’s shoe causes issues that can affect their data collected. There is a need to create easily applied sensor holders that will remain stable and not impede the user's natural gait cycle throughout use. This will result in increased accuracy of movement, acceleration, and force values collected. This data can then be extrapolated to better assess the conditions and stresses the runner's body undergoes. Johnson Health Tech uses these sensors to help design and compare different exercise equipment such as treadmills and to collect data on body kinetics to limit injury.

B. Existing Models

Multiple commercial systems currently exist for strapping different motion sensors to the chest and the heel/ankle region of the user. Johnson Health Tech also has an existing model that they use, but the current models used have issues that must be addressed.

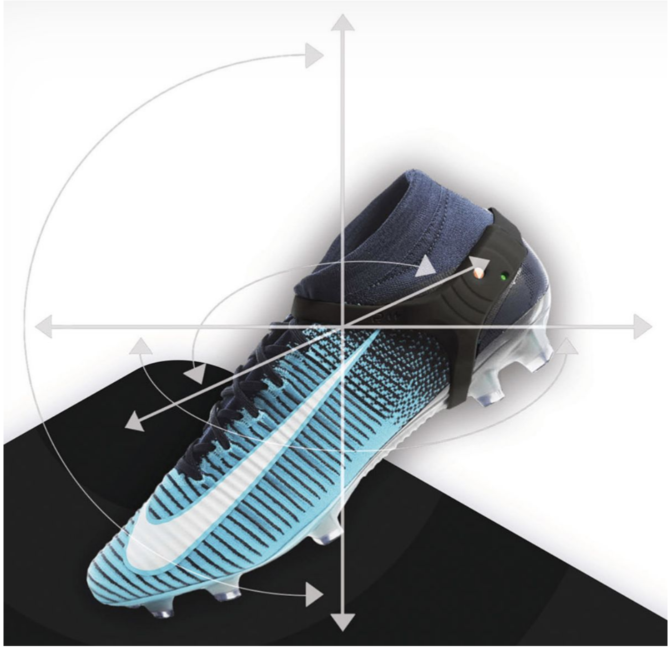


Figure 1: The Playmaker motion sensor shown on a cleat [2].

Playermaker, an athlete performance tracking platform, fabricates a smart motion sensor with a strap system to attach it to the user's cleat. The sensor system is usually used while playing soccer where it gives the user insights on many different variables such as load and gait analysis [2]. The strap system uses a rubber material that wraps around the top and bottom of the cleat while securing the motion sensor to the outer heel of the user as seen in Figure 1. The placement of these straps works well for cleats but not for regular running shoes. It uses the cleat to secure the sensor in place, therefore on normal running shoes it would slide off. Since this design is made of a rubber material there is some adjustability.

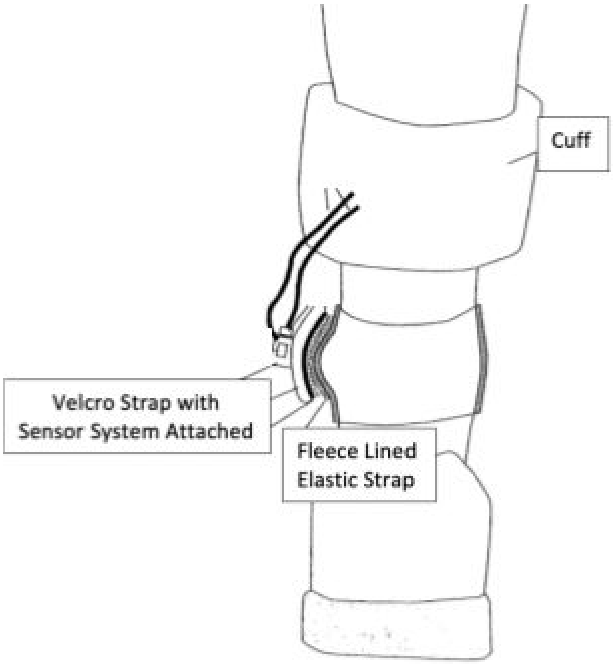


Figure 2: A view of the Xybermind sensor and cuff from the back of the shoe. The device is attached to the outside of the ankle using velcro straps [3].

Xybermind, a German company that develops small devices for the sport and fitness markets, has a patented device used to evaluate displacement angles using three different sensors [3]. The sensors are secured to the ankle region of the user using a velcro strap over a fleece elastic strap in conjunction with a cuff higher up on the ankle of the user as seen in Figure 2. While this strap mechanism has proven to work in the company's studies, this design does not secure any of the sensors used onto the heel of the user. Having the sensors centered on the back of the user’s heel is important to Johnson Health Tech since this location of the sensor is most representative of the ground reaction force that is being experienced and it allows them to make generalizations about total body movement.

Figure 3: The Polar H10 heart rate sensor modeled on a user [4].

Many different companies create chest straps to secure different types of sensors to the user's chest. One example is Polar, a company that specializes in a wide range of sports training computers. They have multiple heart rate monitors that utilize a chest strap to be secured to the user. One of their strap designs uses a soft textile material with silicone dots on the inside to prevent slipping and it is secured with a buckle [4]. The strap is made to go around the chest of the user and is in direct contact with their skin as seen above in Figure 3. The chest sensor used by Johnson Health Tech does not need to be in direct contact with the user's skin, but it is important for the sensor to have minimal movement from its starting position during physical activity.

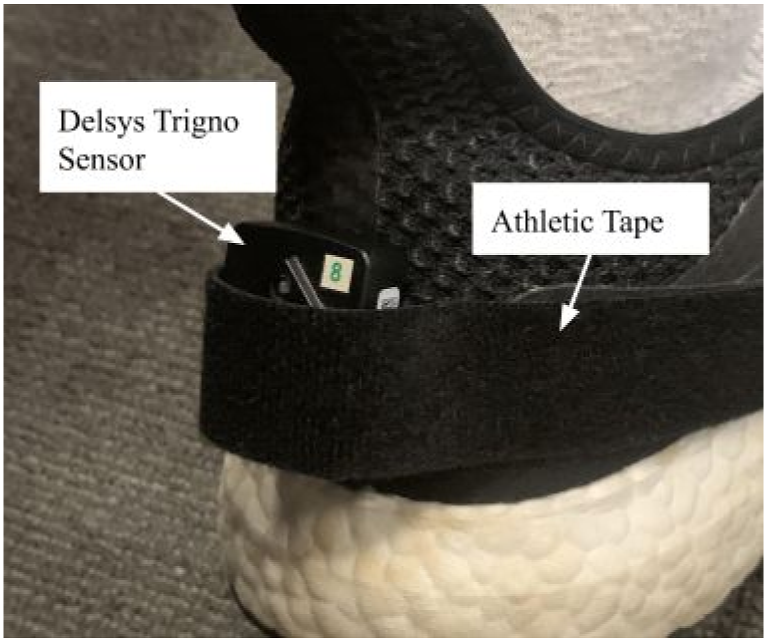


Figure 4: An image of the existing design used by Johnson Health Tech. Shown is the athletic tape that wraps around the sensor at the heel. Additional tape is used that is not depicted. The tape is wrapped around the heel to hold the sensor in place and then around the arch of the foot and over the laces [5].

In the current method used by Johnson Health Tech, the shoe sensor is secured to the back of the user's shoe using athletic tape, as seen above in Figure 4. It is further wrapped in tape that goes across the laces and under the sole. This method is time-consuming to set up and the sensor often slips. The tape can also roll up, causing the runner to feel changes in their steps affecting the results collected by the sensor. Currently, Johnson Health Tech is not incorporating a center of mass chest sensor into their design. However, it is something they would like to incorporate into their testing going forward. Johnson Health Tech has reached out to determine other devices that can hold the Delsys Trigno Avanti sensors that they use to the back of the user's shoe and chest, allowing for different data to be collected during testing.

C. Problem Statement

Johnson Health Tech uses Delsys Trigno sensors placed at the base of the sternum and the back of the heels to collect acceleration data. Currently, they have no way to hold the chest sensor in place and run into problems with the sensors placed on the heels. They use athletic tape on the users' shoes that often rolls up under their soles causing the user discomfort and increasing the likelihood of them tripping. The sensor is easily jostled out of place which affects the accuracy of the data. This project's goal is to create a safer and more stable sensor holder to collect more accurate data without causing the users discomfort.

II. Background

A. Background Research

The Delsys Trigno Avanti sensor is an electromyography and accelerometer device. To collect the data it has a nine-axis inertial measurement unit so it can measure movement in any direction. It measures three degrees of rotational data and three degrees of linear movements. It can communicate wirelessly with a phone or a computer. The sensors use their own program to process data, however, raw data can be extracted to be processed on other platforms [6].

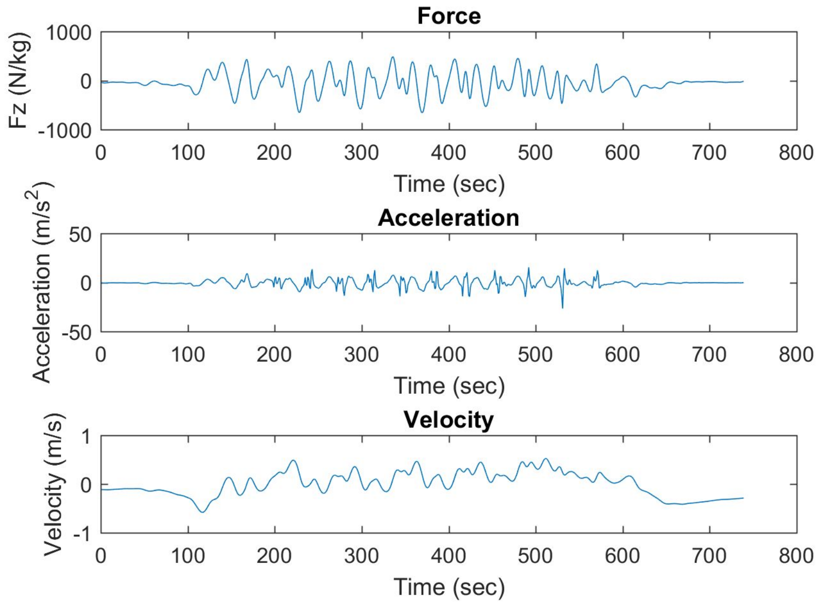


Figure 5: Shows sample data collected from a phone used as an accelerometer placed on the center of the chest. The force is from the vertical direction but both acceleration and velocity are defined as positive with the runner's movements. The increasing and decreasing acceleration corresponds to the runner's steps as do the spikes in velocity.

The acceleration data collected by the sensors can be converted into steps per minute and force per step. By looking at the changes in acceleration and force and counting the number of zeros for acceleration moving parallel to the sagittal plane, the number of steps can be obtained. This is because with each step the foot will switch directions causing it to have no acceleration. By calculating the derivative of the acceleration data, which is treated as a function of time, the velocity can be obtained. Using the acceleration and velocity in the vertical direction, the time of the shoe's impact can be determined. When looking at the velocity over time, the subject will have their foot on the ground when the vertical velocity hits zero. The acceleration value can then be found for that same time. Using Newton's second law, force equals mass times acceleration, the force of the step can be determined. The sensor located at the center of mass is used in addition to this data, allowing for generalizations of total body movement and a more accurate estimation of step rate.

The forces subject to the runner are another useful variable to track as they can relate to injury and running technique. Typical forces analyzed in a runner's gait include peak vertical ground reaction force, peak brake ground reaction force, and peak force along the tibia. These variables are obtained by taking the maximums of the acceleration data collected by the Delsys Trigno Avanti sensor at corresponding time intervals and relating them to the runner's weight in kilograms [7]. Additionally, these ground reaction forces can be used along with joint angle and loading rate, which is the speed at which forces are applied to the body, to characterize the running technique of the user. Because this typically requires the use of force plates and motion capture systems, the possibility of characterizing a runner's kinetics with only a few sensors is highly attractive [8]. With optimized algorithms for relating acceleration data to such variables, Johnson Health Tech would be capable of characterizing a runner's gait as well as detecting the risk of injury in a number of different environments if desired. Although their current testing environment is indoors in a controlled environment.

B. Client Information

Arrington Polman is an intern and Staci Quam is a project engineer at Johnson Health Tech. They have used Delsys Trigno® sensors in the past to estimate the force and velocity of the limbs and center of mass data and has noticed issues with their current method of securing the sensors to the user and hopes to make the testing process more comfortable for users and lower the chances of inaccurate data.

C. Design Specifications

The final design will consist of two sets of sensor holders consisting of two shoe holders, one for each shoe, and one chest holder. The holders need to securely hold the 26.85 mm by 37.00 mm by 14.75 mm Delsys Trigno Sensor. Each shoe holder should be compatible with running shoes women's size 5 to men's size 12, specifically 21.6 cm to 28.6 cm [9], and each chest holder should fit a chest circumference from 80 to 150 cm [10][11]. The shoe holders should also be durable enough to withstand forces of, at least, 2.28 to 2.64 kN [10][12]; to adjust for the majority of users, the sensor holders should be able to withstand up to 4 kN of force. Both types of sensors should also hold the sensor vertically to allow for proper data collection.

The shoe holder should not cause any slipping or tripping to the user and should not contain any hard parts that would be in contact to, or rub against the skin. The holders should also be minimally burdensome to the user and barely noticeable during usage. All of the holders should also have, at most, aminimal alteration to the gait of the user; the shoe holder should have a sensor displacement of less than 0.5 cm in any direction relative to the placement of the device on the heel, and the chest holder should not displace more than 2.0 cm in any direction relative to the placement on the chest. The sensor must be placed on the back of the heel with the indicator arrow facing upwards.

The sensors should either be reusable or inexpensive enough to be a one time use device. A reusable device is the preferred method. The holders should be easily washed and sterilized for maintaining a sanitary environment for the users.

III.Preliminary Designs

A. Chest Sensor Holders

1. Fanny Pack

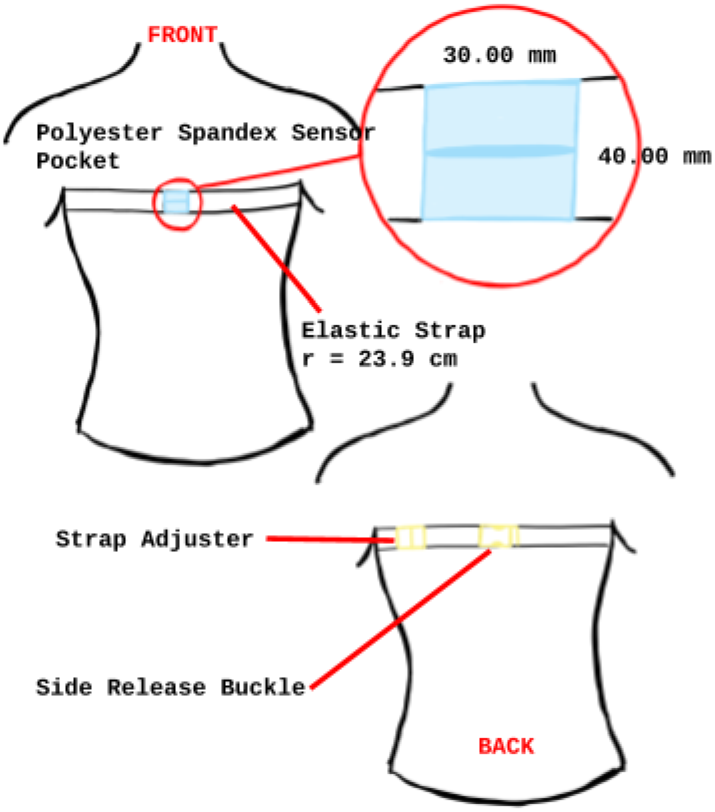


Figure 6: The Fanny Pack design for the center of mass sensor which is a singular strap with a fitted-pocket.

The "Fanny Pack," Figure 6, encompasses a singular elastic strap with a polyester-spandex pocket that is 30 mm by 40 mm. This will allow the 28.85 mm by 37.00 mm by 14.75 mm sensor to be stable during activity, as the elastic characteristic of the polyester spandex material will stretch around the thickness to maintain a tight junction with the body. The singular strap with the side release buckle for attachment and strap adjuster for the fit is simple and is similar to other active accessories such as a running fanny pack as the name implies. This resemblance allows for the assumption of comfort during activity. In terms of size, the circumference of the band without any adjustments will be approximately 150 cm or a radius of 23.9 cm. The average circumference of an adult male in the United States is approximately 100 cm according to the Centers for Disease Control [10]. The additional 50 cm of material accounts for larger subjects and, if necessary, the stretch property or a nylon expander can allow for larger subjects still. To account for smaller, particularly female, subjects it may be necessary to include an additional strap adjuster or shift the placement of the side release buckle. One possible obstacle of the fanny pack design is the movement in the vertical direction as the subject center of mass moves during the running gait. Proper, secure adjustment of the band is expected to minimize the potential bounce of the sensor. The sensor bounce could also arise from the deformation of the elastic material due to fatigue over time. The simplicity and low cost of the design would allow the user to replace the model when this occurs within reason.

2. Mounted Harness

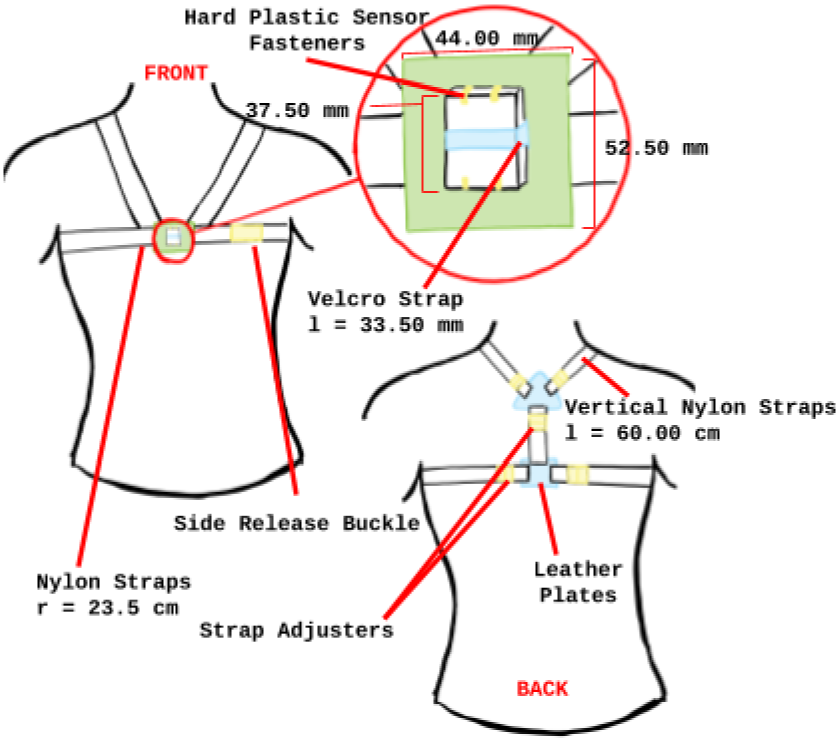


Figure 7: The Mounted Harness chest holder design that has vertical straps for stabilization and multiple adjustment points for subjects of various sizes.

Figure 7 is the "Mounted Harness" design which has both vertical and horizontal straps for supplementary stabilization of the sensor at the center of mass. The design has four separate nylon straps, one horizontal, and two halters connecting to a short vertical one on the back. The sensor is secured to a 44.00 mm by 52.50 mm plastic plate by L-shaped, plastic fasteners, and a velcro strap that measures 33.50 mms. Discomfort for the crisp edges of the plastic plate could arise; albeit, the sensor is anchored firmly in position. The horizontal strap is identical in design to the ‘Fanny Pack” in terms of the radius and width. The major differences are the anterior and posterior plates that create a disconnect in the nylon strap. To account for the various sizes of subjects, there are also strap adjusters flanking the posterior plate of the 150 centimeter band. The two identical vertical straps measure 60 centimeters and the one connecting the leather plates on the back is 12 centimeters. The harness needs to be compatible with all subject sizes, but if made too big it can create an excess of materials on the petite subjects which is not ideal. Furthermore, there is a possibility of irritation from the straps near the neck. Proper calculations of the strap angles would diminish the possibility of itch. The intricate design of the “Mounted Harness” provides securement of the sensor in all directions during activity but creates more chances of discomfort with the increase in design aspects.

3. Lederhosen

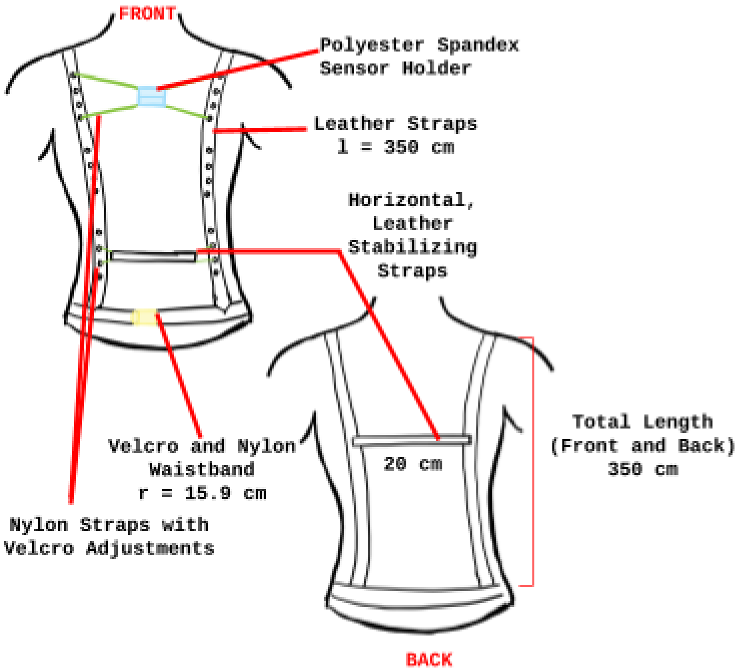


Figure 8: The Lederhosen center of mass holder that is based on the German Suspenders with two vertical straps supporting the sensor holder.

The “Lederhosen,” as depicted in Figure 8, is inspired by German suspenders. The design incorporates two leather straps measuring 350 centimeters each that attach to a nylon waistband that would measure 100 centimeters. The dimensions of this design are based on the average adult male in the United States. The suspenders' length was calculated from the average height of men, 175 centimeters, then doubling the approximate waist-length determined from anthropometric data [10]. The major flaw with this design is the lack of adjustability. It is perfect for the average man but would be ill-fitting for everybody else. Adjustments could be made to the design to better fit more subjects; although, other dilemmas are also present, such as the leather material and maintaining the waistband position. The leather material is necessary for the holes on the suspenders portion of the design as it is flexible, but also durable enough to maintain the proper hole dimensions. The holes are utilized in the mobility of the sensor position. The polyester spandex sensor pocket with velcro straps can be vertically relocated on this device for other applications. The sensor pocket is the same dimensions as the “Fanny Pack” at 30 mms by 40 mms and it has four velcro straps attached to it for secure positioning of the sensor. Although there is a possibility of the sensor being askew from the centerline as the adjustments to the velcro are man-made thus leaving room for human error. In addition to the sensor holder on the front, there is a horizontal leather stabilizing strap that also has velcro on either end. The strap is used to keep the suspenders relatively parallel. There is also another horizontal strap, this time fixed in width, on the back. This again creates a few issues with adjustability between users. Ultimately the “Lederhosen” is a unique interpretation of a center of mass sensor holder with some major design flaws that would need to be addressed before continuing.

B. Shoe Sensor Holders

1. The Clip

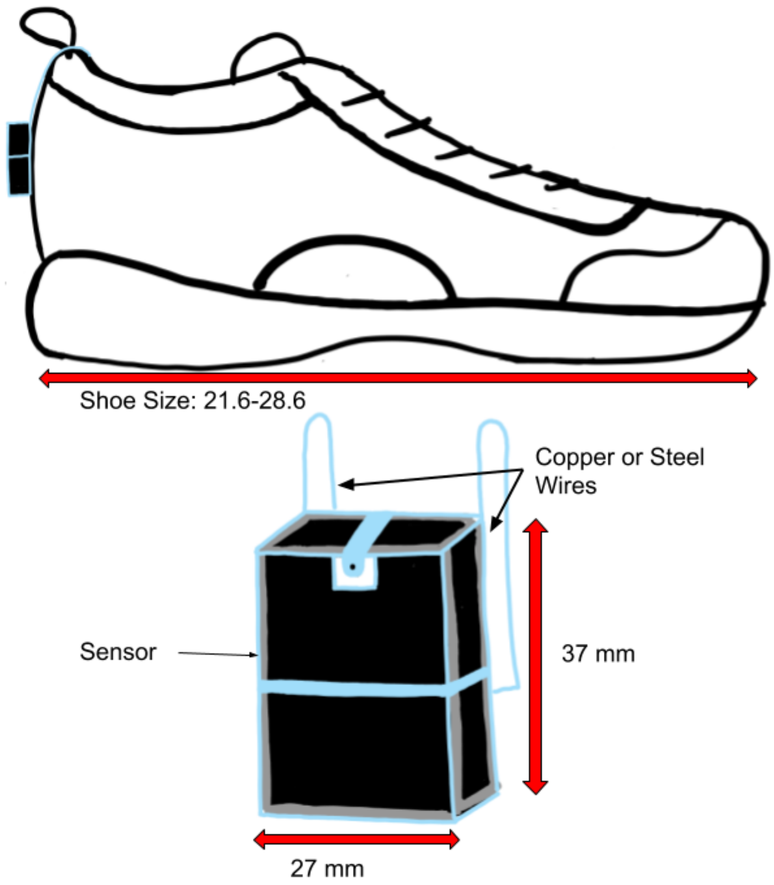


Figure 8: Shown here is "The Clip" design which uses wires that attach at the sensor holder and extend over the heel of the shoe and run down along the insides of the shoe.

The first design is "The Clip." It consists of a 3D printed sensor holder connected to wires as shown in Figure 8. The wire is bent into a clip shape that goes over the back of the shoe and inside adjacent to the sides of the heel of the user. The wires should be approximately 2 mm thick to minimize their effect on the user's gait while providing enough support so the Clip does not easily lose its shape. Stainless steel wire is the most likely material that will be chosen for this design because of its accessibility, malleability, and strong mechanical properties.

A perk of this design is that it is easy to apply and will fit all shoe sizes. It is not dependent on the width or length of the shoe so it can easily be clipped on from user to user without any adjusting. The plastic and wire are also easy to clean with any disinfecting spray or wipe. Additionally, it uses minimal material, making it lightweight, decreasing the chances that it affects the user's natural gait. One concern is that the user might find the wires inside the shoe uncomfortable to run or walk with. The strength of the stainless steel wires will also need to be tested to ensure that they can remain in shape during normal running stresses.

2. The Straps

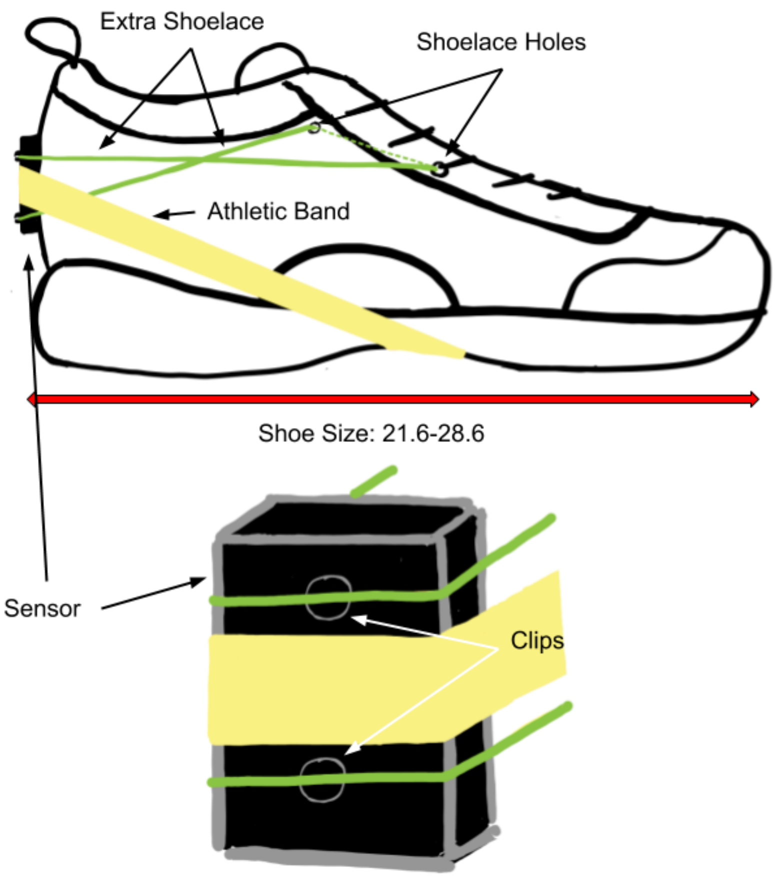


Figure 9: Shown above is one strap beneath the arch of the shoe and two smaller straps run through shoe lace holes all maintaining the proper sensor position.

This design incorporates the use of two different "straps" attached to the 3D printed sensor holder at the back of the shoe as shown in Figure 9. Each of these straps exerts a force in the x-direction, preventing the sensor holder from falling off the back of the shoe. The larger strap depicted above runs beneath the sole of the shoe to provide a force downward in the y-direction on the sensor holder, while the smaller strap provides counter-forces in the positive y-direction. Forces in the z-direction are equal and opposite because there are three straps on either side of the shoe.

Some advantages of this design include that it is lightweight, adjustable, and secure. The straps will be made of athletic band material (bottom strap) and nylon (upper strap). This will make it lightweight and not be cumbersome for the user. The straps will also be adjustable and capable of fitting shoe sizes 6 in women's to 12 in men's. Because of the balancing forces in the x, y, and z directions, this design will likely be secure, however, testing will need to confirm this. Possible downsides to this design include the stability of the bottom strap and the need to occupy two laces holes. In runners with high arches, and thus shoes with high arches, the athletic band strap will likely be secure. However, the concern is that the athletic band strap may slip when applied to runners with relatively flat shoes, possibly causing discomfort, injury, and loss of data. The other possible complication is that because this design requires the use of the top two laces holes of the user's shoe, there may not be room for both the nylon straps and the runner's laces. If this is the case, the runner would have a slightly different gait than normal, causing inaccuracies in the collected data.

3. The Goalpost

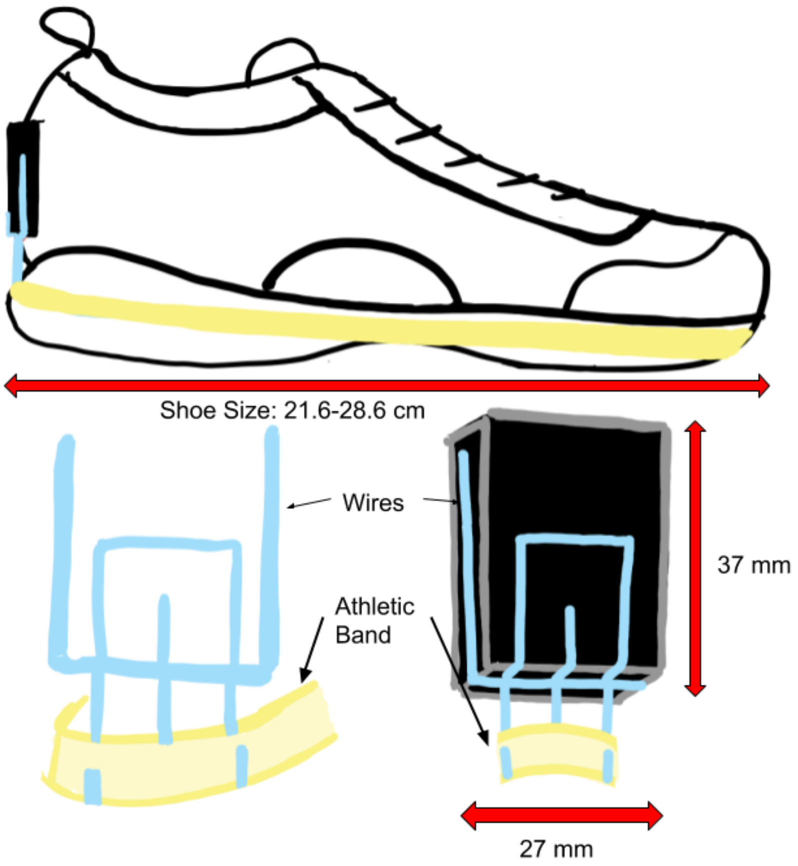


Figure 10: This image shows "The Goalpost" design in which an athletic band is wrapped around the base of the shoe. This band is connected to the 3D printed sensor holder via stainless steel wires.

This design utilizes an athletic wrap around the base of the shoe, avoiding any contact with the user as shown in Figure 10. Stainless steel wires adhered to the athletic band, either by glue or tape, will be connected to the 3D printed holder located at the back of the heel. The main advantage of this design is that its location is below where the user's foot would be placed. This means that the user will not be able to feel when the apparatus is attached and will therefore undergo their natural gait cycle. Although this is a very important characteristic, there are some drawbacks to this design as well. Because this design uses a fixed athletic band, it is not adjustable for multiple shoe sizes. It would be possible however to fabricate different sized models (small, medium, large) that could cover the specified requirements of 21.6 to 28.6

centimeters. Another negative of this design is that the elastic band surrounding the base of the shoe may slip off while the user is running. The stability of the band would have to be tested experimentally to accurately assess its function. Lastly, the stainless steel wires used to connect the elastic band to the 3D printed sensor holder need to be tested to ensure that they can withstand the stresses associated with a runner's movement over a prolonged period of about 20 hours.

IV. Preliminary Design Evaluation

The two components of this device each received their own design matrix. Both matrices have the same categories except for safety, which is only in the shoe design. The highest score in each category is highlighted. Each design is given a score out of five. Then using the weight is converted into a total score out of one hundred.

Predicted stability: How stable the predicted design is based on forces acting on and created by the design. It is an estimate of how well the design is predicted to resist slippage due to gravity and excess movement due to jostling and momentum. The importance of reliable data earned it the highest weighted score.

Comfort: Takes into account the user’s ability to notice the device and any pain it will cause. The goal is to have the device be unnoticeable by the user or, at a minimum, cause the least amount of discomfort. If the user is comfortable using/wearing the design, it should allow them to run more naturally. This is why it is weighted as the second highest.

Lack of Hindrance: A gauge of how the device impacts the runner’s natural gait. A higher score represents less hindrance. If the runner does not experience hindrance, then the data will be the most representative of their actual run, so it is also weighted the second highest.

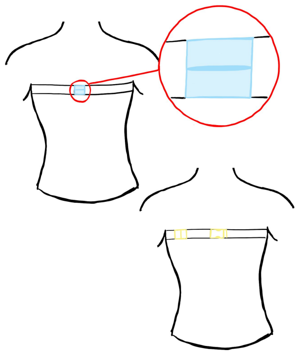
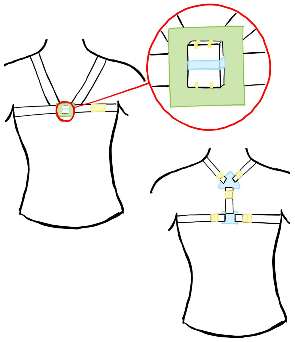
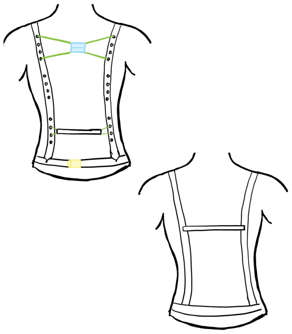
Safety: Category only for the shoe holder designs. Since the design is on the shoe, the design must not pose a tripping hazard.

Ease of Fabrication: How easy the device is to make. If something were to happen to the designs, it should be easy to replicate, so testing can continue. This earned it the third lowest weight.

Cost: A higher score represents a lower cost. Since the materials needed for each design are relatively low and equal-cost was weighted the lowest along with ease of use.

Ease of Use: How easy the device is to put on each user and clean after each use. Each design does not require any special skills or training to use and there are no predicted complications from using the designs, so it is also weighted the lowest.

Table 1: The chest holder design matrix utilized to rate the three preliminary models.

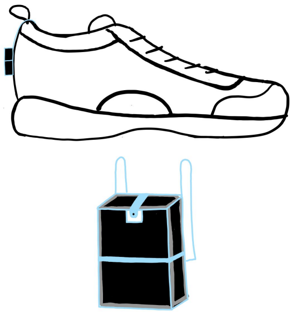
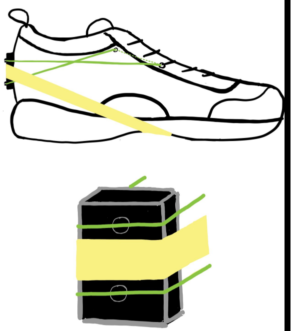
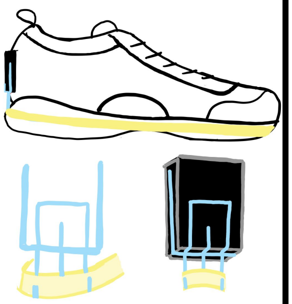
		The Fanny Pack		**The Mounted Harness**		**Lederhosen**	
							
	Weight	**Score Out of 5**	**Weighted Score**	**Score Out of 5**	**Weighted Score**	**Score Out of 5**	**Weighted Score**
Predicted Stability	25	3.5	17.5	4.5	22.5	4.5	22.5
Comfort	20	4.5	18	4	16	3.5	14
Lack of Hinderance	20	5	20	3.5	14	3.5	14
Ease of Fabrication	15	5	15	4	12	2.5	7.5
Cost	10	4.5	9	4.5	9	3.5	7
Ease of Use	10	5	10	4.5	9	3	6
Total			89.5		82.5		71

The "Fanny Pack" design scored the highest for comfort, lack of hindrance, ease of fabrication, cost, and ease of use. This is largely due to its simplicity in only having a single strap. The one strap will not impede the runner as much since it is similar to many existing heart rate monitors used by runners. It could be made to fit many sizes with a design similar to a belt or other sort of buckle. It does not have the highest predicted stability though since nothing would prevent it from moving up or down other than the forces of friction. The high scores in the other categories gave it the highest overall score.

The “Mounted Harness” scored the next highest overall tying with the “Fanny Pack” for cost and scoring highest in stability. The added straps over the shoulder are predicted to help counteract any jostling in the vertical direction which would add stability. However, these straps may be less comfortable to the runner and impede their natural arm movements while running. These factors caused it to score lower than the first design. They also would be more time-consuming to produce, decreasing the ease of fabrication.

Finally, the “Lederhosen” scored the lowest overall. It tied with the “Mounted Harness” for predicted stability since the large number of straps would prevent movement in all directions, but scored lower in the other categories. The large design covering most of the torso would be uncomfortable for running and the inelasticity of the leather straps would impede movement. It would also be the hardest to fabricate and use. There would be many different components to adjust, including the waist strap, and the sensor height. Other portions do not have an adjustable component such as the shoulder straps. All of which accounts for the much lower score.

Table 2: The design matrix for the three shoes sensor holder designs.

		The Clip		**The Straps**		**The Goal Post**	
							
	Weight	**Score Out of 5**	**Weighted Score**	**Score Out of 5**	**Weighted Score**	**Score Out of 5**	**Weighted Score**
Predicted Stability	20	4	16	2.5	10	1	4
Comfort	15	2.5	7.5	3.5	10.5	5	15
Lack of Hinderance	15	4	12	4	12	4.5	13.5

Ease of Fabrication	12.5	3.5	8.75	4	10	4	10
Safety	12.5	4	10	3	7.5	4.5	11.25
Cost	10	2	4	4.5	9	4.5	9
Ease of Use	10	4.5	9	3	6	3	6
Total			67.25		65		68.75

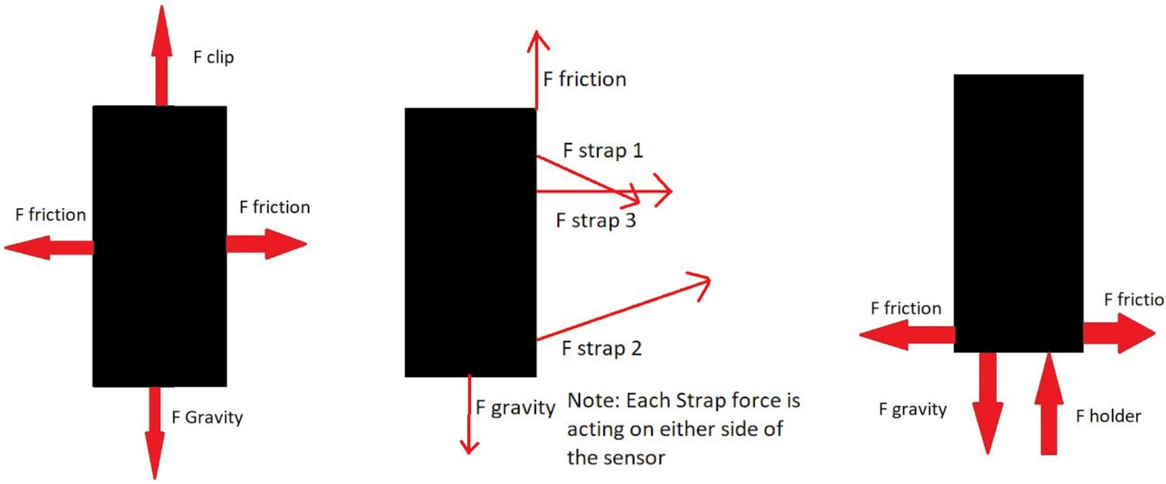


Figure 11: Force Body Diagrams of each shoe holder design. From left to right it is "The Clip," "The Straps," and "The Goal Post." "The Straps" View is from the side while the other two are from behind. Placement of the arrows is to indicate approximately where each force would be acting on the design. See page 50 of the appendix for calculations.

Overall, the sensor holders all scored within four points of each other with "The Goal Post" scoring the highest with 68.75 out of 100. The "Clip" scored the highest in predicted stability and ease of use. It has the highest predicted stability since it is the only design that can guarantee that the sensor will not slip downward on the shoe. It can also pinch tighter to resist side to side movements. The free-body diagrams of the "Clip" and the other two shoe sensor holders can be seen in Figure 11. It is also very easy to use because no size adjustments are needed to fit different shoes.

"The Straps" scored the highest in ease of fabrication and cost. Only the sensor holder would need to be constructed. The straps themselves would just need to be cut to size. This also lowers the estimated cost. Although the straps would be easy to adjust for any shoe size, it also has the potential to roll up like the tape and be time-consuming to put on and position correctly. The downward forces of the straps could also cause the sensor to slip down the shoe.

"The Goal Post" design scored the highest in all categories except predicted stability and ease of use. The strap going around the shoe could be very difficult to position in order to make sure it does not slip off while in use. The base of the holder is also far from the sensor, allowing it to potentially act like an inverted pendulum. Assuming that everything is positioned correctly and the strap does not come loose, it should be the most comfortable and hinder the runner the least since it does not go inside the shoe or wrap around the bottom. However, due to its low predicted stability and difficulty to use, it was not created.

V. Fabrication and Testing

A. Materials

Exercise Band: Used in one of the shoe sensor holder designs so that the user did not feel the material underneath their shoe while running. It was also the intent that the rubber would help to resist slippage on the shoe and the ground.

Copper Wire: One option for the "Clip" design wire. Chosen for its flexibility.

Steel Wire: Another option for the "Clip" wire. Chosen for its stiffness.

Spandex™: Picked to hold the sensor to the chest band. It will be able to stretch with the band and the stretch itself will allow a pocket to be formed that can securely hold the sensor without it bouncing around.

Elastic Band: The ability to stretch will make it more comfortable for the user to breath and run. This will also help hold itself up securely to the user.

B. Methods

1. The Chest Holder

Beginning with the pocket for the sensor, a first prototype was created by cutting a strip of fabric from a pair of Spandex™ running shorts and sewing it into a pocket shape to fit the sensor. As shown in figure 12, while this prototype was useful, it was too small to allow for easy removal of the sensor and the flap that covers the top of the sensor and prevents it from moving was unable to be secured in the correct place. With this known, future prototypes have to be created to allow for the sensor to fit more securely and have room to attach the pocket to the chest band.

Figure 12: The first prototype of the pocket for the Chest holder. This prototype was a proof of concept design that was of an incorrect size and was not used in the final prototype.

2. The Clip Design

In order to ensure feasibility of this design, a proof of concept model was created out of pipe cleaners as seen in figure 13. This preliminary model showed promise because the wires that run beneath the insole of the shoe could not be felt by the bottom of the user's foot. Therefore, this was a realistic method to ensure sensor holder stability without compromising user comfort. Another important finding that came from this model is that the wires can not be run directly up the back of the shoe. This led to significant user discomfort which would certainly alter the gait. It was determined that future models would have to be modified to ensure user comfort.

Figure 13: The proof of concept pipe cleaner model, showing the wires running directly over the heel of the shoe and beneath the insole.

The next step in the design process of the "Clip" was to fabricate a model that incorporated actual wire and avoided the discomfort problem from the pipe cleaner model. 18 gauge rubber coated copper wire was used as the material of choice because of it's flexible mechanical properties. In this model, wire is still run beneath the insole of the shoe but instead of running up the heel, it is directed up the sides of the shoe in order to minimize contact with the user's foot and ankle (figure 14A). The copper wire was taped to a tic tac box which was used to model the sensor because of it's relatively similar size and weight. This design was tested for comfort and durability over the course of a 3 mile run; the runner hardly noticed the presence of the wires, showing that the new wire shape was preferable over the previous one which ran the wires up the heel of the shoe. Additionally, the tic tac box had not moved from its original position following the run, however there was uncertainty about whether it was moving perpendicularly away from the shoe during the course of the run. Because of this, an additional material with greater mechanical strength would need to be evaluated.

Figure 14A and B: Figure 14A on the left shows the wire entering the side of the shoe, avoiding the discomfort seen with the pipe cleaner model. Figure 14B on the right shows the model outside of the shoe consisting of two wires bent in similar conformations.

Following the success of the tic tac model, the focus was set on evaluating a material with greater mechanical strength as well as fabricating pouches that secure the sensor and attach to the wire. A 16 gauge steel wire was bent into a similar shape as the copper wire used in the tic tac model, however instead of using two wires (as seen in figure 14B) it was made of just one (figure 15). Using one continuous wire makes the device more robust and easier to apply. The steel wire is attached to a polyester sensor holder which was fabricated by taking material from a cinch bag and super gluing the edges to make a pouch. This pouch also has a piece of plastic inserted at its back edge to stabilize the sensor. A separate sensor holder was constructed for the copper wire model so that multiple options could be evaluated. This sensor holder was made of duct tape wrapped around pieces of popsicle sticks which provided the pouches structure. Lastly, both the polyester and duct tape pouches had velcro patches applied to ensure that the sensor remains inside the pouch at all times.

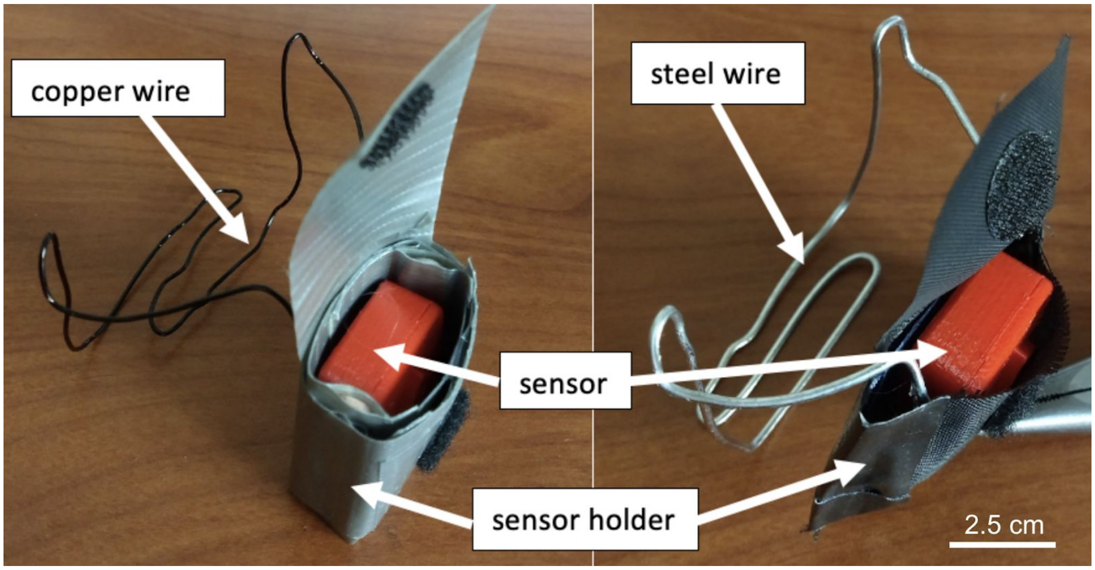


Figure 15: The left image is the copper wire model attached to the duct tape sensor holder. The right image is the steel wire model connected to the polyester pouch.

3. The Straps Design

The first prototype of the “Straps” design only used a latex workout band and twine, but as testing was carried out using this design it was discovered that the twine was not secured to the sensor in any way and needed to be better secured to the sensor since it kept slipping down. A way to oppose the downward force due to the exercise band that crosses under the arch of the shoe, as seen below in figure 16, needed to be found.

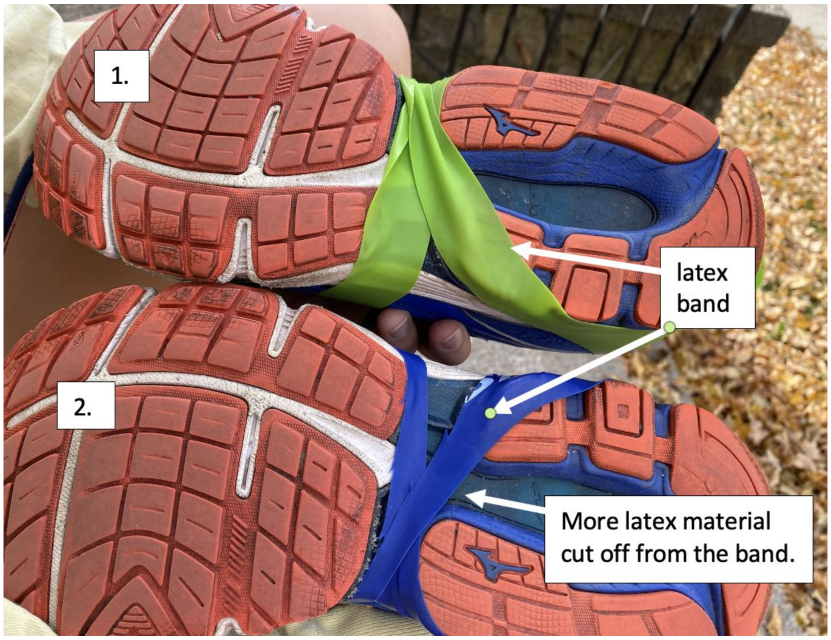


Figure 16: The latex bands cross under the arch of the shoe. The first prototype, after the proof of concept, is denoted with number one, and the final design is denoted with number two.

The next prototype of the "Straps" design with the green latex band included a cord holder and a shoelace instead of twine as seen in figure 17 below. The cord holder, which has 3M adhesive on the back, was attached to the back of the sensor near the top. This secured the shoelace that wraps around to the front of the shoe and is tied through the eyelets of the shoe. In this prototype some of the latex band from the part that crosses under the shoe was cut off in order to decrease the amount of material making it more comfortable for the user.

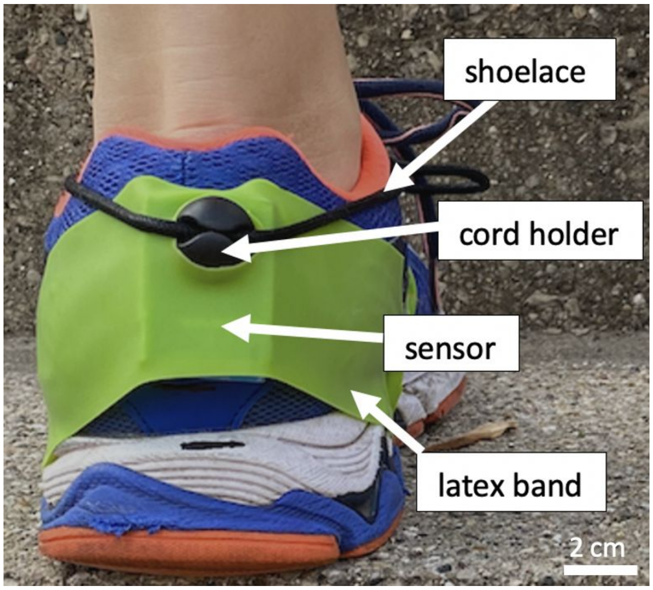


Figure 17. The first prototype after the proof of concept demonstrating the cord holder that was added.

When this prototype was tested the sensor still slipped. After inspection it was determined that this occurred because both the shoelace and the latex band experienced downward forces. The shoelace was at a downward angle as seen in figure 18.

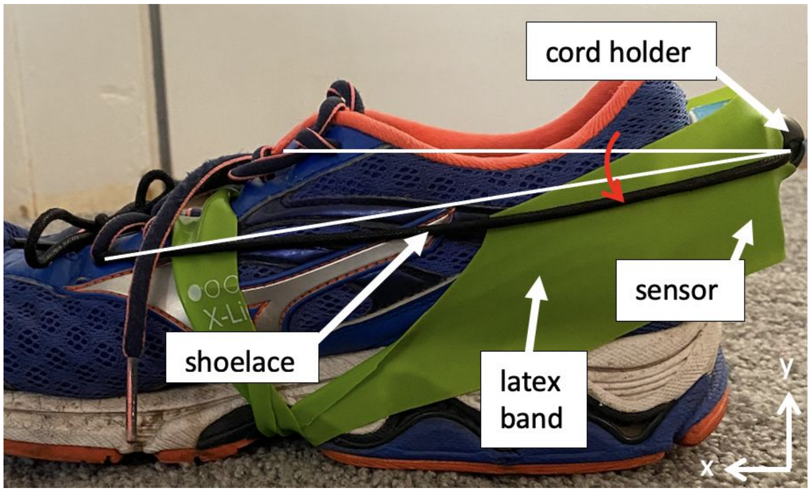


Figure 18: First prototype of the "Straps" design. This image demonstrates the downward angle created with the shoelace.

In the final prototype the cord holder was attached to the back of the sensor, specifically at the bottom to achieve the largest upward angle of the shoelace, as seen in figure 19, which provided more opposing force to the downward force created by the latex band. Even more of the latex band from the part that crosses under the shoe was removed so that the user cannot feel it when using the holder. In addition the latex band was cut so that you can tie it together on top of the laces after it crosses under the shoe. This allowed for more adjustability and made it easier to attach to the shoe.

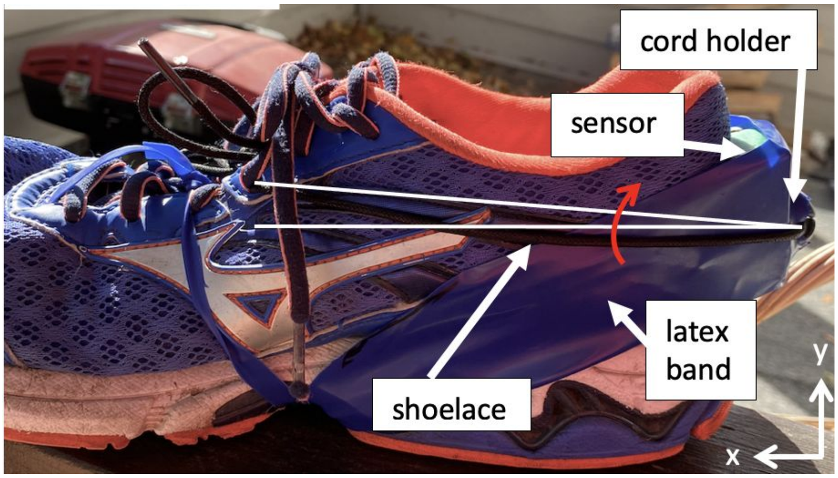


Figure 19: The final prototype of the "Straps" design with its improved shoelace placement to add a larger upward force.

C. Final Prototype

1. The Chest Holder

The final prototype for the chest holder consists of two pieces that have been attached together. This design mimics the design of the heart rate sensor from Polar shown in figure 3 and is an extension of the "Fanny Pack" design shown in figure 5.

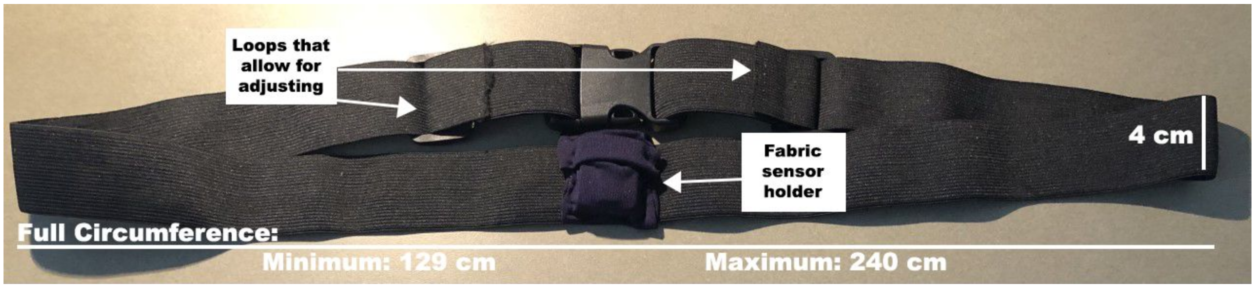


Figure 20: The final prototype of the Chest holder, showing both the sensor holder pocket and the adjustable mechanism, as well as the minimum and maximum circumferences of the band.

The first part of the prototype is the pocket that holds the sensor; this pocket was sewn from a single strip of fabric, cut from a pair of Spandex™ running shorts, to snugly fit the sensor as demonstrated in figure 21. The second part of the prototype is the band that wraps around the chest. The finished pocket was attached to the band with thread to prevent any extraneous movement (figure 22).

Figure 21: A progression showing how the sensor fits into the Chest holder pocket.

Figure 22: The backside of the Chest holder, showing how the pocket is attached to the strap.

2. <u>The Clip Design</u>

There are two final prototypes for the "Clip" design. The first consists of the 18 gauge copper wire which is attached to the duct tape sensor holder, the second is made of 16 gauge steel wire which attaches to the polyester sensor holder. Each of these models are shown inside of a shoe in figure 23 and isolated in figure 15. Each design's wire is configured to run beneath the insole of the user's shoe, up the sides of the inside of the shoe, and around to where it attaches to its respective sensor holder. This wire shape ensures overall stability by using the weight of the runner to maintain the wires position. The shape is also configured to minimize contact with the user's foot and therefore minimize discomfort.

For the sensor holders themselves, which secure the sensor and attach to the wire, two different materials were tested. Each of these sensor holders is configured in approximately the same way, consisting of a pouch that the sensor is placed in with a tongue extending up that covers the sensor by attaching to the body of the pouch via velcro as seen in figure 15. Both the duct tape and polyester materials successfully secured the sensor in place over the course of a 3 mile run. However, the duct tape is a more simplistic design which allows easier transfer of the sensor in and out, making this the preferred sensor holder material.

Two separate final designs were fabricated because each wire material excels in a certain requirement, and not enough testing has been done to accurately conclude that one is better than the other. The copper wire model proved to be more comfortable over the course of a 3 mile run, while the steel wire model showed that it maintained the sensor's position with more accuracy, which is further discussed in testing. If the Delsys Trigno™ sensors used by Johnson Health Tech are able to acquire accurate data with the copper wire model that would make it superior because of its comfortability. However, if these sensors are only able to acquire accurate data with the steel wire model, that would give that design the edge.

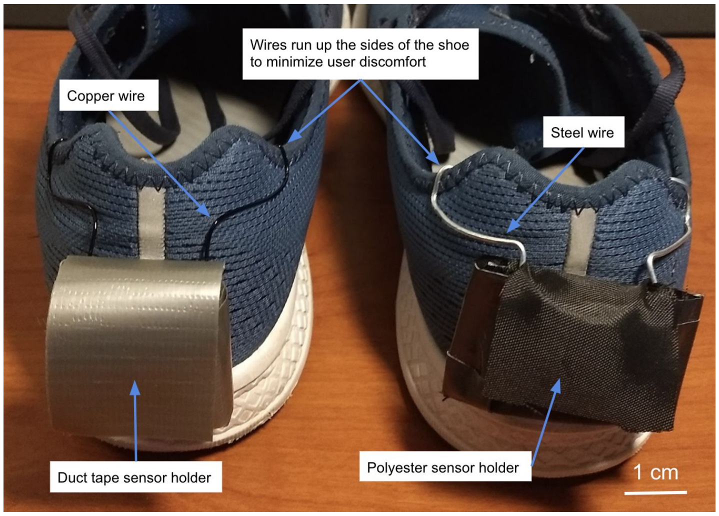


Figure 23: This image shows the final prototypes for the "Clip" model inserted as they would be during use. On the left is the copper wire model attached to the duct tape sensor holder and on the right is the steel wire model attached to the polyester sensor holder.

3. <u>The Straps Design</u>

The final prototype of the "Straps" design involves a latex band, shoelace, and cord holder as seen in figure 19. The latex band goes over the back of the sensor on the heel of the shoe and crosses under the arch of the shoe, as seen in figure 16, to reduce interference with the user's gait. The band then comes back on top of the shoelaces of the shoe after crossing under the arch. The latex band is tied on top of the laces of the shoe to secure it. This feature allows for more adjustability of the sensor holder. The cord holder is attached to the bottom of the back of the sensor, as seen in figure 24, to allow for the largest opposing force to the downward force created by the latex band. The shoelace is run through the cord holder, and wraps around to the front of the shoe on either side of the ankle where it is threaded through the eyelets of the shoe and tied on top of the original shoelaces. This can be seen in figure 25.

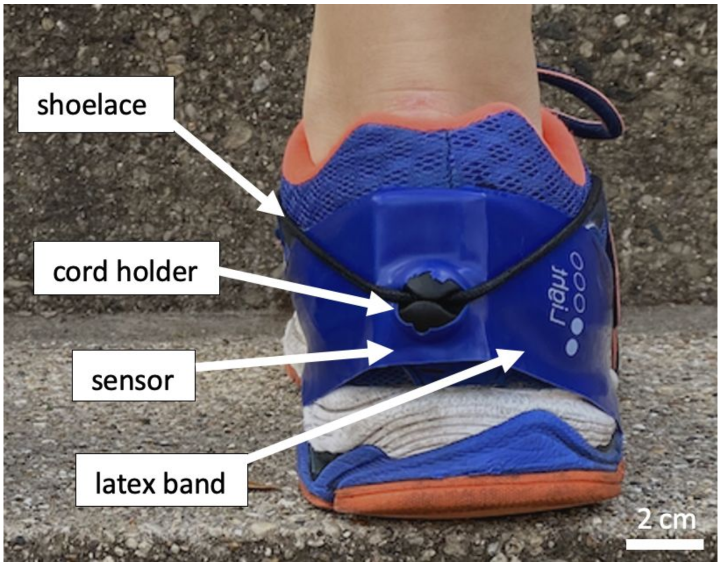


Figure 24: The back of the final straps prototype. Demonstrates the cord holder placement.

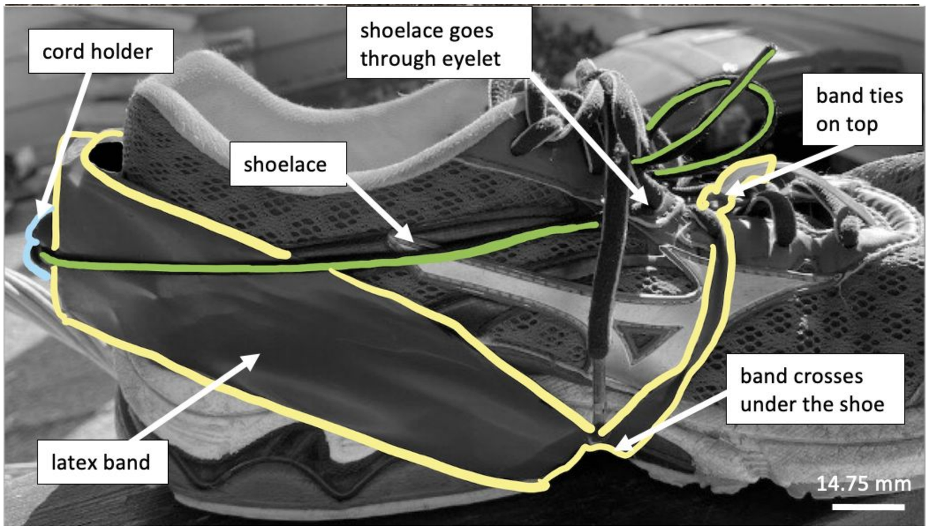


Figure 25: In the final prototype of the straps design the shoelace goes through the cord holder to the front of the shoe where it is tied on top of the original shoelaces.

D. Testing

The first round of testing that was done was used for the straps design prototype improvement. The straps sensor holder was put on a running shoe and the position of the sensor in the y-axis was marked on the shoe. The user then ran for one minute and the position of the sensor in the y-axis was marked again. A ruler was then used to measure the movement of the sensor, if any. This process was repeated for three trials for each of the straps prototypes. The fourth trial was slightly different as the second strap that went through the shoelaces was removed to determine the importance of it. This method of testing is not the most accurate, but it was sufficient for testing the effectiveness of each prototype and helped to make design decisions.

Phase two of testing was done with the motion capture software Kinovea. It works by placing markers on the user and filming them during the activity that needs processing. It can be used to measure movement, acceleration, and joint angles. To test the sensor holders, a marker of bright and contrasting color was placed on the sensor and on the shoe as shown in figures 26 and 27. The videos were then opened in kinovea where the markers were selected and the software can track their movements frame by frame. If Kinovea inaccurately tracked the movement, the marker was adjusted. Kinovea generated data for the position of the markers throughout the video.

Figure 26: Current method of filming the back of the shoe with three sensor placements. In certain trials only the bottom marker was visible.

Figure 27: The placement of the three markers on the shoe. They were all too close together to currently track all three.

After the data was run through Kinovea, the data was processed in MATLAB to calculate how the distance between the two markers changed throughout the testing period. It also calculated the change in X and Y distance from each other. The average movement was calculated for each trial.

Each shoe sensor holder went through four trials, two from the side and two from the back. This was to gain data on the vertical and lateral movement of the sensor while running. The trial lasted for 15 seconds. The chest strap went through similar testing with two trials recorded facing the front of the user. The markers were placed on the sensor and the users' sternum.

VI. Results

A. Chest Holder

Figure 28 depicts the average changes in the horizontal and vertical directions as well as the total change for the chest strap design (raw data found on page 60 of the appendix).

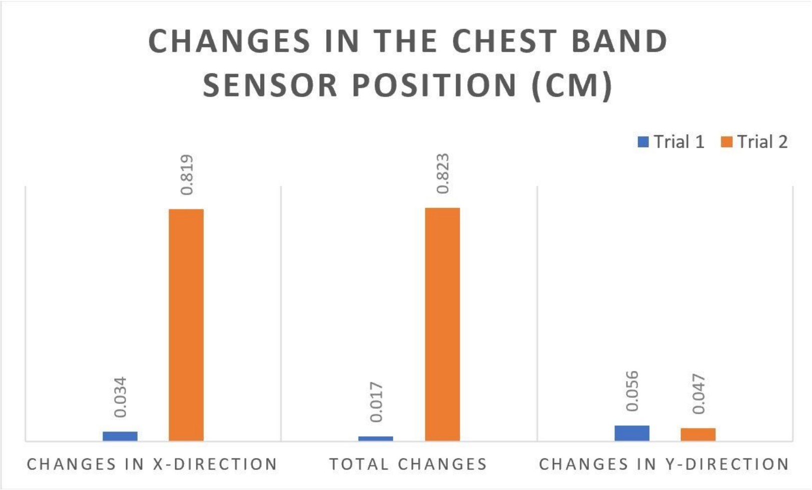


Figure 28: The change of position of the sensor in the chest band in the horizontal and vertical positions as well as the total change in position.

The chest holder design had large variations in the movement between the two trials, but the calculated changes in the vertical direction were minimal at 0.056 cm and 0.047 cm, which is promising. The x-direction clearly drives the large total change in distance for the second trial; however, both are within our desired maximum of 2 cm. Further testing needs to ensue to determine if either were outliers.

B. Shoe Sensor Holders

Two phases of testing were performed on the "Straps" design: the first one to determine if the updates to the initial prototype were beneficial and the second one to compare it to the "Clip" design. Figure 29 is the results from the first round of testing.

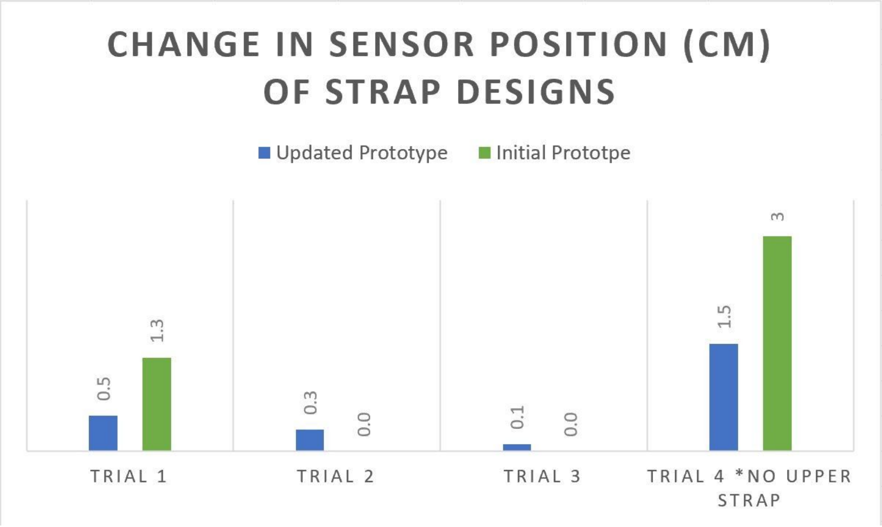


Figure 29: The change of position of the sensor of two "Straps" design prototypes from before and after a one-minute run.

The alterations made on the initial prototype are beneficial, even if it is not numerically evident. Through the first three trials, the average change was 0.33 cm and 0.30 cm for the initial and updated designs respectively. The fourth trial eliminated the top strap which proved to be detrimental; thus proving the importance of the two-strap design. The 1.3 cm vertical transformation of trial one for the initial prototype is an outlier (calculated with MATLAB and the code is on 52 in the appendix). The omission of the data point causes the average to diminish to 0.0 cm; although there was visible movement during testing of the initial prototype. The thicker straps underneath led to more discomfort for the subject and began to roll up. For these reasons, the second prototype was used in the second phase of testing.

Each of the final designs were analyzed with the Kinovea software and Figure 30 depicts the average change of overall distance per frame of two trials for the two "Clip" designs and the "Straps" design.

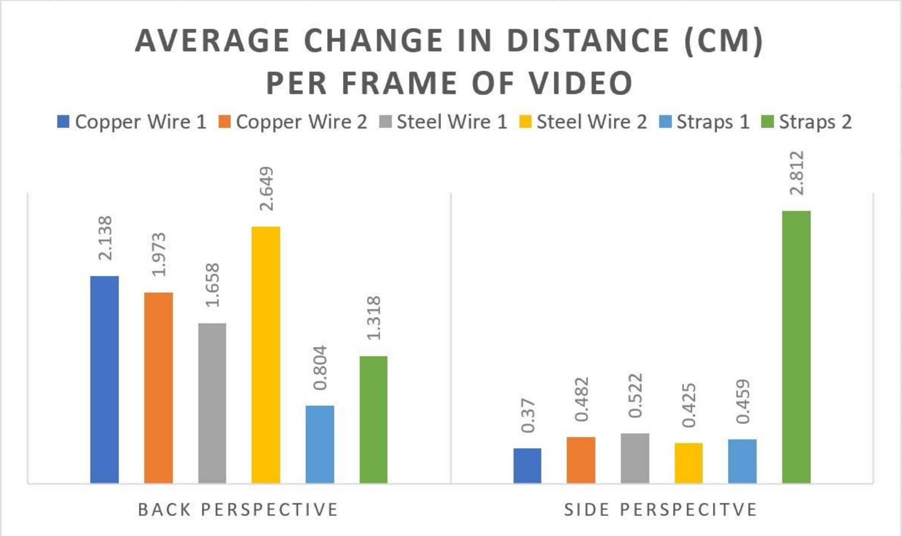


Figure 30: The average change in distance per frame of the shoe sensor holder prototypes.

The first "Straps" design trial was attached to a flat bottom shoe while the second trial was attached to a shoe with a center groove. A Student's t-test was performed with a desired value of 1.0 cm for the back perspective and 0.2 cm for the side perspective. The back has a larger value to account for the higher variability due to the software not accounting for the change in angle of the foot throughout the stride. Table three contains the calculated p-values for each trial (the code for the calculation is on page 61 in the appendix).

Table 3: The p-values along with the desired value for the data from the final testing.

	p-Value Back	**p-Value Side**
desired value	**1.0 cm**	**0.2 cm**
Copper 1	0.004	0.342
Copper 2	0.007	0.253
Steel 1	0.028	0.226
Steel 2	7.75×10^{-4}	0.296
Straps 1	0.250	0.270
Straps 2	0.141	5.87×10^{-4}

For the situation, a p value under the 0.05 level of significance is not desired as it means that the total distance is significantly higher than the desired value. The "Straps" design on the flat shoe is the only one to not hold significance for either perspective and is the only one to be below the desired value of 1.0 cm. Overall, the “Straps” design has the highest percentage of non-significance at 75% compared to the 50% of the “Clip” design. Although both show promise as each of the designs, more accurate testing will have to be performed to determine if the total change of difference can be less than the 0.5 cm of total change in distance over time compared to the current values which are in a 0.3 second frame.

VII. Discussion

The preliminary tests conducted indicate that all three of our current shoe holder designs show great potential in securely holding the sensors to the shoe. It is difficult to come to any conclusions about which design is the most stable with only two trials and one subject for each design. However, assuming that the second trial for the “Straps” collected data inaccurately, it appears to have the most stable data. After the initial measurement, the change in distance between the two markers appeared to remain relatively stable. Meaning that if the data was run through again starting with the initial measurement coming from a later frame, the change in distance may reflect those of the first trial.

Although the data provides a good starting point in the evaluation of the sensor holders, there are several sources of error that make definitive conclusions difficult. The first of which results from the test subject moving closer to or further away from the camera. Kinovea cannot take perspective into account, so it registers this change in distance as the marker's changing position. For tests that are looking at the angles of joints this would not be an issue, but since this tests relies on the initial distance between the sensors compared to that distance over time, it can cause inaccuracies in the data. If the user moves further away, the distance will appear to shrink which could cause any movement of the sensor to appear as normal such that the sensor was held in place. The opposite can be said for when the user gets closer to the camera. It is hypothesized that this is what happened during trial two of the “Straps” design based on the high movement average. Normal distances would be flagged as an increase and the sensor shifting down could be read as normal. To prevent this issue going forward, the user could mark the ground with an X as a target to step on.

Another possible source of error could be due to low camera quality and poor lighting causing the frames to be blurred. Kinovea often lost track of the markers and the traces needed to be manually adjusted to lie on the marker. Figure 31 is a screenshot of a frame in the Kinovea software.

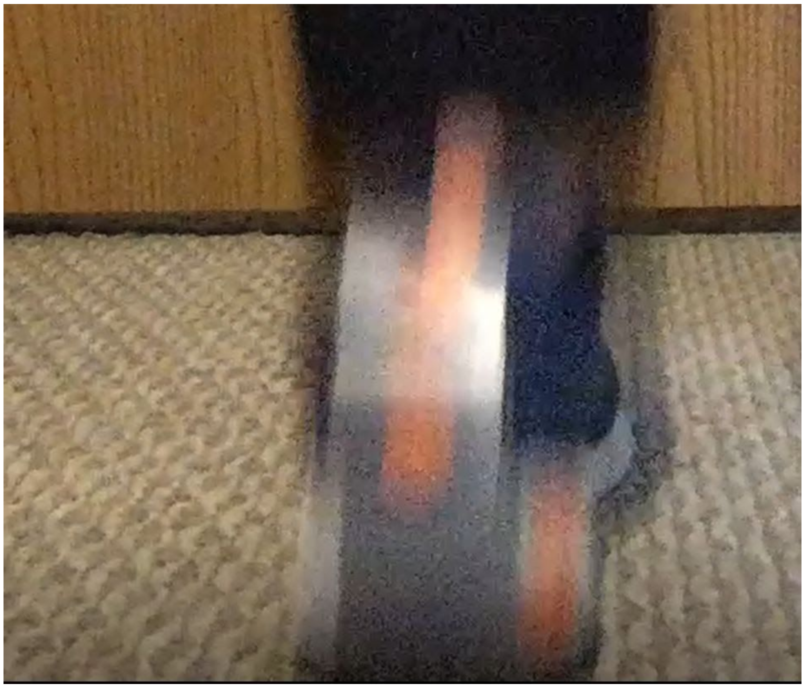


Figure 31: A blurry frame from one of the trial videos depicting the difficulty in placing the traces on the markers.

Often the markers appeared as a blur so the trace placement itself needed to be estimated. Higher quality video cameras with more recorded frames per second will reduce blur, making the videos easier to map.

Finally, the back view could inaccurately measure the vertical distance between the two markers due to the change in foot angle. This is evident in the data seeing that the change in distance from behind was three times greater than the side view in many of the trials. As the foot rotates, the plane that the markers are on becomes more horizontal which causes the camera to register the change in perspective as a change in distance. To eliminate this going forward, the back view can be used to only measure the lateral movement of the sensor. If the two markers are placed co-linearly. The overall distance between the two markers will not matter, only the difference between the X coordinates of the two markers.

A source of error during the chest holder trials is that sometimes the subject's hand moved in front of the markers. Going forward it will be important to ensure that the test subject is cognizant of where their hands are. If they swing their arms more parallel to their body, there should be no obstruction of the markers and minimal disruption to their gait.

VIII. Conclusion

Due to the variability of the current testing, the additional testing will determine which of the two designs is superior or if a combination of them is. For both designs there are still improvements to be made to optimize the comfort, ease of use, and securement of the sensor.

Future testing needs to be done in order to gather more accurate information on the movement of the sensors. This will include more trials on more users. Again, these tests will consist of using higher quality cameras and more markers to determine movements in different directions. The testing period will also be increased to at least two minutes to see if repeated stepping will dislodge the sensors further.

The chest band was only tested over tight fitting clothing. To see how it performs in different conditions it will be tested over different types of clothing such as a sweatshirt or a t-shirt. While testing the chest band it will be important to make sure that the clothing does not obstruct the camera's view of the sensor and markers and that the movement of the clothing is not causing it to appear that there is a change in distance when there is not.

After motion capture testing is performed, or simultaneously, the designs will be tested with an accelerometer within the design. This may be the Delsys Trigno™ sensor itself or a different microcontroller-accelerometer combination. This data should provide feedback on how the sensor moves around within the holder. The 3D printed models of the sensor can be hollowed out to fit the accelerometer. If there is more noise artifact than the motion capture predicts, the size of the portion that holds the sensor will need to be adjusted.

Going forward, test subjects will be asked to rate the ease of use and comfort of each design on two scales from one to five since this project depends not only on the security of the sensors but the comfort and ease of use as well. One will represent the design being very painful and very hard to put on and a five will be described as unable to feel the design and very easy to put on.

For the “Clip” design, further testing must be done to conclude whether the 18 gauge copper wire, 16 gauge steel wire, or some other wire type is the optimal material for ensuring both comfort and stability. Ideally, application of the Delsys Trigno™ sensors would provide conclusive data suggesting which material is superior. However, in the case where such sensors are unavailable, further motion capture testing with reduced error as well as comfort testing with more users will provide data capable of suggesting an ideal material.

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Appendix

Product Design Specifications

Function: The current methods used by Johnson Health Tech do not do a sufficient job in holding the center of mass and force sensors steady and in place. They use electromyography sensors that also function as accelerometers to collect data. The shoe holders are currently taped to the user with athletic tape that often slips and rolls up. The slippage causes less accurate data while the rolling can cause the user to trip. This project's goal is to create a safer and more stable sensor holder in order to collect more accurate data.

Client requirements (itemize what you have learned from the client about his / her needs):

- Two sets of sensor holders
- Each set contains two shoe holders and one chest strap
- The holders should hold the sensors vertically on the back of the shoe
- The chest holder should hold the sensor towards the bottom of the sternum
- The sensor holders should fit the Delsys Trigno EMG and accelerometer sensor
- The shoe holders should hold the sensors with minimal alteration to the gait of the runner
- The sensor holders should be reusable or inexpensive enough to discard them after each use.

Design requirements:

- Total cost should be less than $500

1. Physical and Operational Characteristics

a. *Performance requirements*: The device should be able to be used once a week and withstand being used by multiple runners or be built for a single use. It should be able to take the force of someone stepping. According to a Harvard study, the impact during running can be as much as three times the body weight which would translate on average to 2.28 kN for women and 2.64 kN for men [1] [2]. To allow most people to utilize the device, the sensor holder should be able to withstand 4 kN of force. The center of mass holder must be able to securely hold the sensor in place on the abdomen during running. There is no direct load on the device, but should be able to maintain position while undergoing vertical momentum. Both holders should be barely noticeable by the user as if they are running normally. They should be easily cleaned/sterilized, so they can be used by multiple users.

b. *Safety*: The shoe holders should not cause any slipping or tripping. If it wraps around the bottom of the shoe it should be able to grip the ground like a shoe, to avoid loss of traction and injury [3]. The device should not incorporate any hard materials that could rub against the user's skin. There are no real liabilities when it comes to the safety of the chest holder.

c. *Accuracy and Reliability*: The shoe holder should limit movement of the sensor to +/- 0.5 cm in any direction. The chest band should limit movement to +/- 2 cm in any direction. The device should also minimally change the runner's gait.

d. *Life in Service*: The devices should last at least a year, being used on average about once a week for several hours.

e. *Shelf Life*: It is not anticipated that there will be any particular storage conditions needed for this device.

f. *Operating Environment*: The devices will need to be able to be used in various environments both inside on a treadmill and outside on pavement during different weather/temperature conditions ranging from 0-32° Celsius during dry and rainy days. The shoe device will need to be compatible with up to 100 different users who have different shoe sizes (women's 5 through men's 13) and different running shoe brands/styles. Since the device will be attached to the user's shoe during physical activity, it will experience a variety of different loads (1-4 kN). The chest holder must be able to fit around the abdomen of a large variety of subjects in different amounts of shape.

g. *Ergonomics*: These devices must be as lightweight and minimally invasive as possible. Each component should not weigh more than 0.25 kg. The user should not experience much discomfort while wearing the device. This will be dependent on the material and the design. Additionally, the shoe device should not extend to the calf of the user.

h. *Size*: These devices should be adjustable to fit most users. One set of holders will be designed to fit women's shoes ranging from a women's size five to size eleven. This constitutes shoe lengths between 21.6 and 26.7 centimeters [4]. The other size will be for men's shoes ranging from a men's size eight to a size twelve. Thus, the sensor holder needs to be adjustable between 25.4 and 28.6 centimeters in length [4]. The part that secures the sensor should be able to fit the 26.85 mm x 37.00 mm x 14.75 mm sensor. The chest holder must have a circumference exceeding 100 cm, the average circumference of the abdomen of an American male [2]. To better fit a wide range of subjects, the design should be able to tightly fit an abdomen in the range 80 centimeters to 150 centimeters.

i. *Weight*: The goal is to make this product as light as possible so the user does not feel that they are running with weights on their feet. The average running shoe weighs 9 oz or 270 grams [5]. To keep interference at a minimum we want to keep each sensor under 45 grams. The weight of the chest sensor should be restricted to a similar weight as to not apply additional stress on the body as a subject runs.

j. *Materials*: Important material properties for this design are that it is lightweight, durable, and adjustable for different shoe sizes. Hard materials such as metals and plastics should be avoided as they could cause discomfort or injury to the user. Depending on the design, it may be preferable to use multiple materials. The chest strap should be washable or able to be wiped down with disinfectant like the shoe holders.

k. *Aesthetics*, *Appearance, and Finish*: The holders should be designed with the least amount of material that can reliably secure the 26.85 mm x 37.00 mm x 14.75 mm sensor to the heel of a shoe or to the center of mass. Excess material may cause the user to modify their natural gait. The color should be neutral so that it goes well with multiple different shoe types; although this is not an essential component of the design.

2. Production Characteristics

a. *Quantity*: Two sets of sensor holders. Each set includes a chest band and two shoe holders.

b. *Target Product Cost*: The total budget for this project is $500, but the product should be less than $50.

3. Miscellaneous

a. *Standards and Specifications*: The additive of the device to running shoes does not follow the standards for competitive athletic shoes as it gives an unfair advantage and information the shoe itself cannot provide [6]. Taking this into consideration, there are no specific standards that the design has to meet.

b. *Customer*: The sensor hold should be able to better stabilize the sensor than the current use of tape. It should be able to accurately measure the force and velocity of the lower limb and the center of mass. Although it is necessary for it to function properly during running trials, adaptability to other athletic endeavors is a welcomed bonus.

c. *Patient-related concerns*: The sensor holder should be able to be sterilized between use. They should be able to withstand being wiped down with a disinfecting wipe or spray.

d. *Competition*: There are similar designs for strapping different types of sensors to the user's shoe during different physical activities. One design that is similar is by PlayerMaker. Their product is a smart motion sensor with a strap system that is intended to be strapped to the user's cleat while playing soccer. It uses AI and machine learning algorithms to give insight on the player's performance and collects data such as stride length, acceleration/deceleration zones, cadence, and release velocity zones [7]. The strap goes around the heel and both above and below the cleat, and the sensor is held on the inside of the heel. US Patent (US7912672B2) attaches a sensor to the back of the heel by rubber bands on the heel cap [8]. The design has a smaller sensor that obtains data on vertical acceleration and an ankle cuff to which the sensor is attached.

Sources

[1] “Biomechanical Differences Between Different Foot Strikes,” Harvard University, Cambridge, MA, United States.

[2] C.D. Fryar, M.S.P.H., D. Kruszon-Moran, Sc.M., Q. Gu, M.D., and C.L. Odgen, Ph.D., “Mean Body Weight, Height, Waist Circumference, and Body Mass Index Among Adults: United States, 1999-2000 Through 2015-2016,” CDC, United States, Rep. 122, 2018.

[3] Frederick, E., 1984. Physiological and ergonomics factors in running shoe design. *Applied Ergonomics*, 15(4), pp.281-287.

[4] “Measure Your Shoe Size.” 6 pm. [Online], Available: https://www.6pm.com/measure-your-shoe-size. [Accessed: 6-Oct.-2020].

[5] “How Much Do Running Shoes Weigh?,” The Wired Runner, 13-Feb-2019. [Online]. Available: https://thewiredrunner.com/how-much-do-running-shoes-weigh/. [Accessed: 17-Sep-2020].

[6] *Technical Rules of World Athletics,* Standard 5.2.Note(i), 2020.

[7] Playermaker, “Play Smart. Connect Your Game. ,” *Playermaker*. [Online]. Available: https://playermaker.com/#:~:text=Playermaker%20is%20the%20game%20changer,on%20team%20and%20player%20performance. [Accessed: 17-Sep-2020].

[8] Method and Device for Evaluating Displacement Signals, by R. Feichtinger and J. Löschinger. (2011, Mar. 22). *Patent US 7912672B2.* Accessed on: Sept. 17, 202. [Online]. Available: Google Patents.

Computer Generated Images of Preliminary Designs and the Sensor

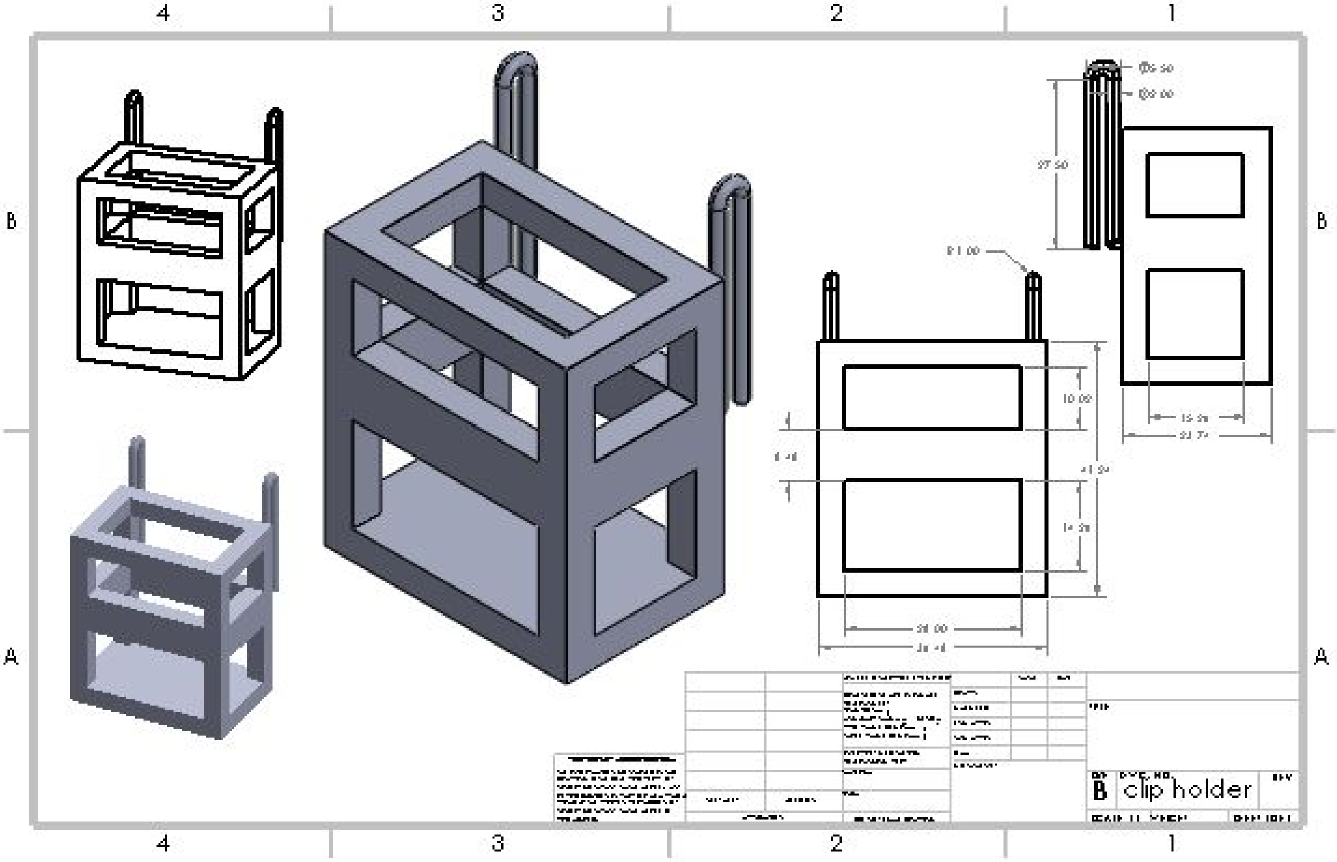


Figure A1: A 3D model drawing prototyping the “Clip” design.

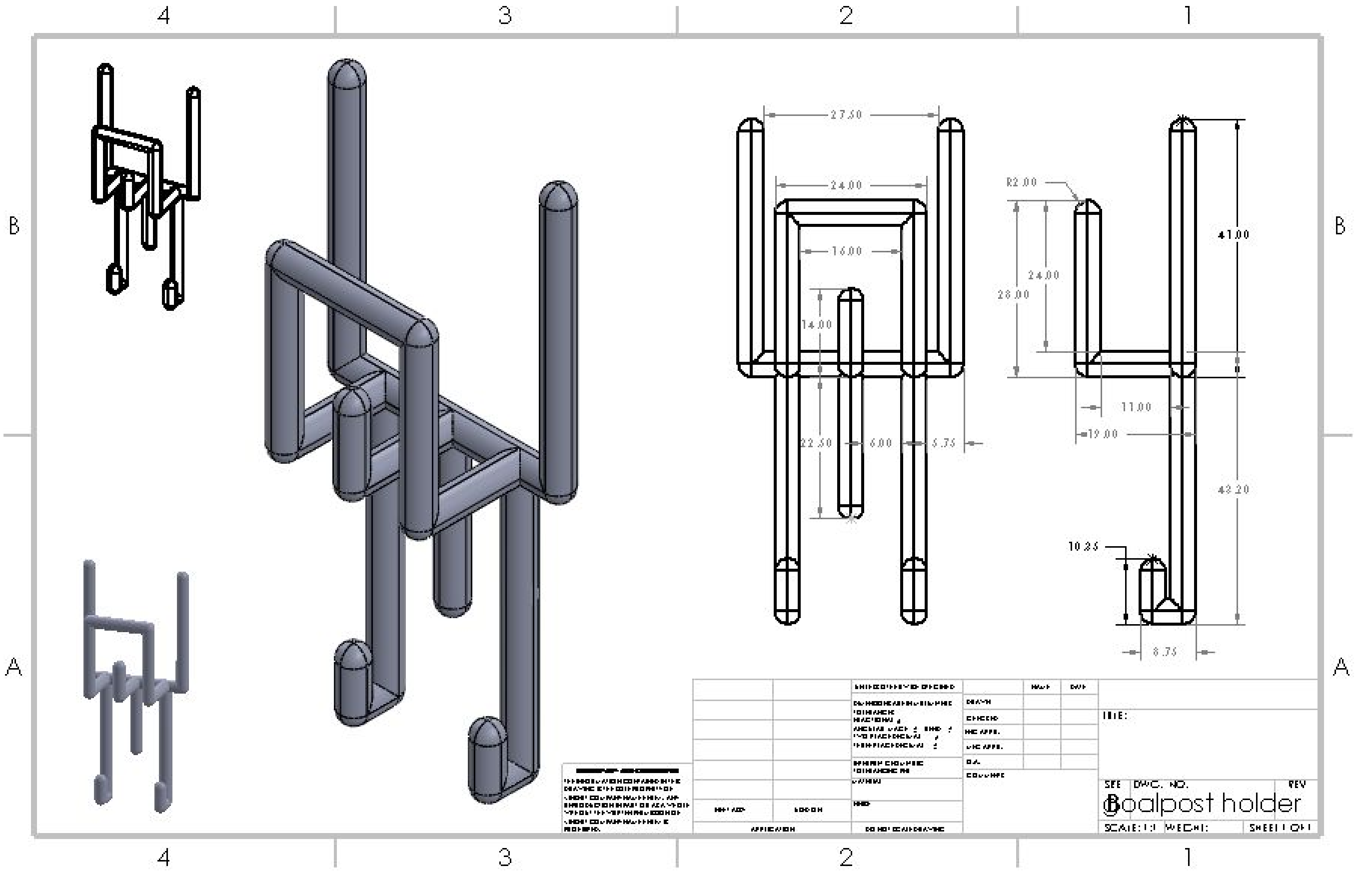


Figure A2: A 3D model drawing prototyping the portion of the “Goalpost” design that connects to the strap and holds the sensor.

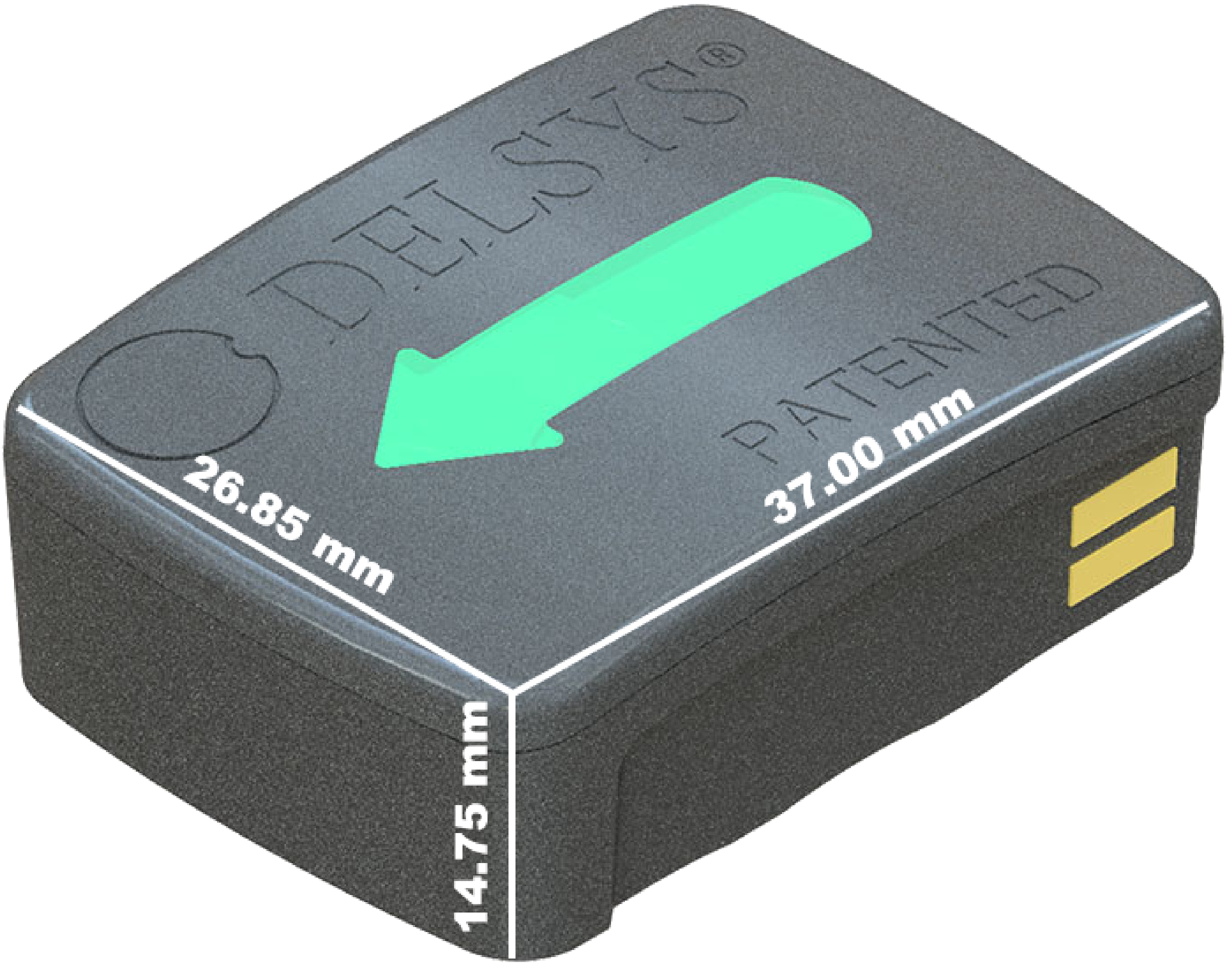


Figure A3: A computer generated image of the Delsys Trigno™ Avanti sensor from a 3D model used for 3D printing with included dimensions.

FBD Calculations

$W_{Sensor} = 14g$
$F_g = 9.81m/s^2 * 14g = 0.1372N$

The Clip

$-F_g + F_{Clip} - F_{Step} = 0$
$-F_g - F_{Step} = -F_{Clip}$
$F_{Clip} = 0.1372\ N + F_{Step}$

The Straps

$\Theta_{Lace} = 15^\circ$
$\Theta_{Strap} = 20^\circ$

X Direction

$F_{Shoe} - F_{Lace}\cos\Theta_{Lace} - F_{Band}\cos\Theta_{Strap} = 0$
$F_{Shoe} = F_{Lace}\cos\Theta_{Lace} + F_{Band}\cos\Theta_{Strap}$

Y Direction

$F_{Friction} - F_{Lace}\sin\Theta_{Lace} - F_{Band}\sin\Theta_{Strap} + F_g - F_{Step} = 0$
$F_{Friction} = F_{Lace}\sin\Theta_{Lace} + F_{Band}\sin\Theta_{Strap} + F_g - F_{Step}$

Greyed out forces are only applied when the user is running

MATLAB Code for Kinovea Data Analysis and Graphing

```
%% BME 400 Movement Analysis for Shoe Sensor
close all;
clear all;
file = uigetfile('.xlsx', 'Select file');
data = load(file);

% Movement Analysis
sensor_x = data(:, 1);
sensor_y = data(:, 2);
shoe_x = data(:, 3);
shoe_y = data(:, 4);
time = data(:, 5);

init_x = sensor_x(1)-shoe_x(1);
init_y = sensor_y(1)-shoe_y(1);
delta_x = (sensor_x-shoe_x);
delta_y = (sensor_y-shoe_y);
dist = sqrt((delta_x).^2+(delta_y).^2);
initDist = dist(1);
movement = dist-initDist;
avg = mean(movement);
stand_dev = std(movement);
%%
figure;
plot(movement);
ylabel('Change in Distance (cm)');
figure;
plot((delta_x-init_x));
ylabel('Change in Distance (cm)');
figure;
plot((delta_y-init_y));

%%
init1x_co = co_1_se_x(1)-co_1_sh_x(1);
init1y_co = co_1_se_y(1)-co_1_sh_y(1);
init2x_co = co_2_se_x(1)-co_2_sh_x(1);
init2y_co = co_2_se_y(1)-co_2_sh_y(1);
delta1x_co = co_1_se_x-co_1_sh_x;
```

```
delta1y_co = co_1_se_y-co_1_sh_y;
delta2x_co = co_2_se_x-co_2_sh_x;
delta2y_co = co_2_se_y-co_2_sh_y;
%%
dist_co1= sqrt((delta1x_co).^2+delta1y_co.^2);
dist_co2= sqrt((delta2x_co).^2+delta2y_co.^2);
init_dist1 = dist_co1(1);
init_dist2 = dist_co2(1);
movement_co1 = dist_co1-init_dist1;
movement_co2 = dist_co2-init_dist2;
init1_st = st_1_se_x(1)-st_1_sh_x(1);
init1x_st = st_1_se_x(1)-st_1_sh_x(1);
init1y_st = st_1_se_y(1)-st_1_sh_y(1);
init2x_st = st_2_se_x(1)-st_2_sh_x(1);
init2y_st = st_2_se_y(1)-st_2_sh_y(1);
delta1x_st = st_1_se_x-st_1_sh_x;
delta1x_co = co_1_se_x-co_1_sh_x;
delta1y_st = st_1_se_y-st_1_sh_y;
delta2x_st = st_2_se_x-st_2_sh_x;
delta2y_st = st_2_se_y-st_2_sh_y;
dist_co1= sqrt((delta1x_co).^2+delta1y_co.^2);
dist_st1= sqrt((delta1x_st).^2+delta1y_st.^2);
dist_st2= sqrt((delta2x_st).^2+delta2y_st.^2);
init_dist1 = dist_st1(1);
init_dist2 = dist_st2(1);
movement_st1 = dist_st1-init_dist1;
movement_st2 = dist_st2-init_dist2;
init1x_a = straps_1_sens_x(1)-straps_1_shoe_x(1);
init1y_a = straps_1_sens_y(1)-straps_1_shoe_y(1);
init3x_a = straps_3_se_x(1)-straps_3_sh_x(1);
init3y_a = straps_3_se_y(1)-straps_3_sh_y(1);
delta2x_co = co_2_se_x-co_2_sh_x;
delta1x_co = co_1_se_x-co_1_sh_x;
delta1x_a = straps_1_sens_x-straps_1_shoe_x;
delta1y_a = straps_1_sens_y-straps_1_shoe_y;

delta3x_a = straps_3_se_x-straps_3_sh_x;
delta3y_a = straps_3_se_y-straps_3_sh_y;
dist_a1= sqrt((delta1x_a).^2+delta1y_a.^2);
```

```
dist_a3= sqrt((delta3x_a).^2+delta3y_a.^2);
init_dist1 = dist_a1(1);
init_dist3 = dist_a3(1);
movement_a1 = dist_a1-init_dist1;
movement_a3 = dist_a3-init_dist3;
%%
figure
hold on
plot(movement_a1)
plot(movement_a3)
xlabel('Frames');
ylabel('Movement (cm)');
title('Overall Movement Of Straps')
hold off
figure
hold on
plot(movement_co1)
plot(movement_co2)
xlabel('Frames');
ylabel('Movement (cm)');
title('Overall Movement Of Copper')
hold off
figure
hold on
plot(movement_st1)
plot(movement_st2)
xlabel('Frames');
ylabel('Movement (cm)');
title('Overall Movement of Steel')
hold off
figure
hold on
plot(delta1x_a-init1x_a)
plot(delta3x_a-init3x_a)
xlabel('Frames');
ylabel('Movement (cm)');
title('Horizontal Movement of Straps')
hold off
figure
```

```
hold on
plot(delta1x_co-init1x_co)
plot(delta2x_co-init2x_co)
xlabel('Frames');
ylabel('Movement (cm)');
title('Horizontal Movement of Copper')
hold off
figure
hold on
plot(delta1x_st-init1x_st)
plot(delta2x_st-init2x_st)
xlabel('Frames');
ylabel('Movement (cm)');
title('Horizontal Movement of Steel')
hold off
figure
hold on
plot(delta1y_a-init1y_a)
plot(delta3y_a-init3y_a)
xlabel('Frames');
ylabel('Movement (cm)');
title('Vertical Movement of Straps')
hold off
figure
hold on
plot(delta1y_co-init1y_co)
plot(delta2y_co-init2y_co)
xlabel('Frames');
ylabel('Movement (cm)');
title('Vertical Movement of Copper')
hold off

figure
hold on
plot(delta1y_st-init1y_st)
plot(delta2y_st-init2y_st)
xlabel('Frames');
ylabel('Movement (cm)');
title('Vertical Movement of Steel')
```

```
ylabel('Change in Distance (cm)');
%%
avg_1a = mean(movement_a1(1:(length(movement_a1)-1)));
avg_3a = mean(movement_a3(1:(length(movement_a3)-1)));
avg_1co = mean(movement_co1(1:(length(movement_co1)-1)));
avg_2co = mean(movement_co2(1:(length(movement_co2)-1)));
avg_1st = mean(movement_st1(1:(length(movement_st1)-1)));
avg_2st = mean(movement_st2(1:(length(movement_st2)-1)));
st_1a = std(movement_a1(1:(length(movement_a1)-1)));
st_3a = std(movement_a3(1:(length(movement_a3)-1)));
st_1co = std(movement_co1(1:(length(movement_co1)-1)));
st_2co = std(movement_co2(1:(length(movement_co2)-1)));
st_1st = std(movement_st1(1:(length(movement_st1)-1)));
st_2st = std(movement_st2(1:(length(movement_st2)-1)));

avg_1ay = mean(delta1y_a(1:(length(delta1y_a)-1))-init1y_a);
avg_3ay = mean(delta3y_a(1:(length(delta3y_a)-1))-init3y_a);
avg_1coy = mean(delta1y_co(1:(length(delta1y_co)-1))-init1y_co);
avg_2coy = mean(delta2y_co(1:(length(delta2y_co)-1))-init2y_co);
avg_1sty = mean(delta1y_st(1:(length(delta1y_st)-1))-init1y_st);
avg_2sty = mean(delta2y_st(1:(length(delta2y_st)-1))-init2y_st);
st_1ay = std(delta1y_a(1:(length(delta1y_a)-1))-init1y_a);
st_3ay = std(delta3y_a(1:(length(delta3y_a)-1))-init3y_a);
st_1coy = std(delta1y_co(1:(length(delta1y_co)-1))-init1y_co);
st_2coy = std(delta2y_co(1:(length(delta2y_co)-1))-init2y_co);
st_1sty = std(delta1y_st(1:(length(delta1y_st)-1))-init1y_st);
st_2sty = std(delta2y_st(1:(length(delta2y_st)-1))-init2y_st);
%%0.9068
st_1ax = std(delta1x_a(1:(length(delta1x_a)-1))-init1x_a);
st_1cox = std(delta1x_co(1:(length(delta1x_co)-1))-init1x_co);
st_2cox = std(delta2x_co(1:(length(delta2x_co)-1))-init2x_co);
st_1stx = std(delta1x_st(1:(length(delta1x_st)-1))-init1x_st);
st_2stx = std(delta2x_st(1:(length(delta2x_st)-1))-init2x_st);
mean_1ax = mean(delta1x_a(1:(length(delta1x_a)-1))-init1x_a);
mean_3ax = mean(delta3x_a(1:(length(delta3x_a)-1))-init3x_a);
st_3ax = std(delta3x_a(1:(length(delta3x_a)-1))-init3x_a);
avg_3ax = mean(delta3x_a(1:(length(delta3x_a)-1))-init3x_a);
avg_1cox = mean(delta1x_co(1:(length(delta1x_co)-1))-init1x_co);
avg_2cox = mean(delta2x_co(1:(length(delta2x_co)-1))-init2x_co);
```

```
avg_1stx = mean(delta1x_st(1:(length(delta1x_st)-1))-init1x_st);
avg_2stx = mean(delta2x_st(1:(length(delta2x_st)-1))-init2x_st);
%%
total_mov =0;
for (i=1:359) %%Adjusted for frame length
   total_mov = total_mov+abs(movement_st2(i));
end
total_mov/359

%% Data Analysis for Chest Band
body1_x = VarName1;
body1_y = VarName2;
sens1_x = VarName3;
sens1_y = VarName4;
body2_x = VarName5;
body2_y = VarName6;
sens2_x = VarName7;
sens2_y = VarName8;

delta1_x = body1_x-sens1_x;
delta2_x = body2_x-sens2_x;
delta1_y = body1_y-sens1_y;
delta2_y = body2_y-sens2_y;
init1_x = delta1_x(1);
init2_x = delta2_x(1);
init1_y = delta1_y(1);
init2_y = delta2_y(1);

distance1 = sqrt(delta1_x.^2+delta1_y.^2);
distance2 = sqrt(delta2_x.^2+delta2_y.^2);
movement1 = distance1 - distance1(1);
movement2 = distance2 - distance2(1);
x_mov1 = delta1_x-init1_x;
x_mov2 = delta2_x-init2_x;
y_mov1 = delta1_y-init1_y;
y_mov2 = delta2_y-init2_y;
figure;
hold on;
plot(movement1);
```

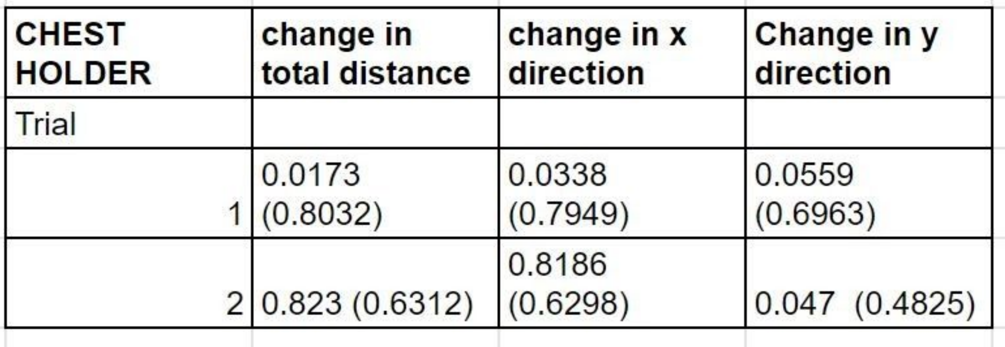
```
plot(movement2);
xlabel('Frames');
ylabel('Movement (cm)');
title('Overall Movement');
%%
mean(movement1)
std(movement1)
mean(movement2(1:207))
std(movement2(1:207))
```

Testing Procedure

1. Place one marker on the sensor and one on the shoe (for the chest band one on the sternum). Ensure that both will be visible throughout the entire duration of the testing period.
2. Measure the length of the shoe in cm.
3. Begin recording the user and have them run in place for 15 second.
4. Make sure that the markers stay within the frame of the camera and that the user does not move closer or further away from the camera to get the most accurate measurements.
5. Stop the recording and upload the video into Kinovea.
6. Draw a line from the heel of the shoe to the toe and add the length of the shoe as the reference. This gives the program information on how many pixels equate to real life measurements.
7. Add an origin to the image.
8. Right click on the markers and add a trace to each one.
9. Drag the trace to ensure that they are in the center of each marker.
10. Go through the video frame by frame to ensure that the traces stay centered on the marker.
11. Once the video is complete, the data can be analyzed in MATLAB.

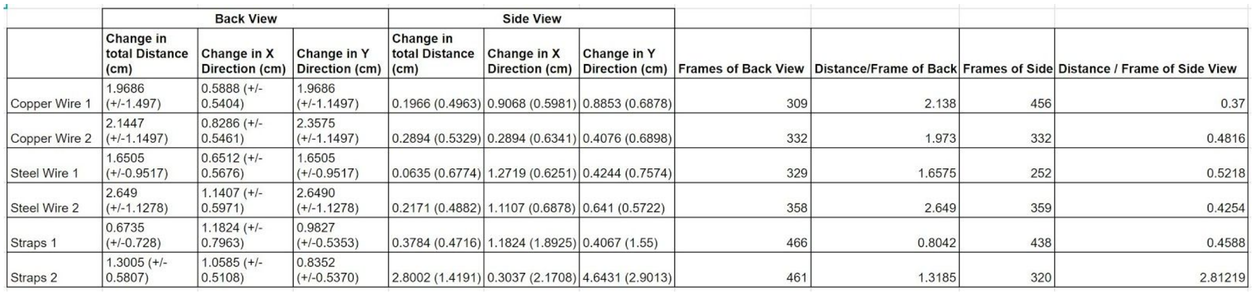
Raw Data

Table A1: The raw data after being ran through MATLAB for the chest holder design



CHEST HOLDER	change in total distance	change in x direction	Change in y direction
Trial			
1	0.0173 (0.8032)	0.0338 (0.7949)	0.0559 (0.6963)
2	0.823 (0.6312)	0.8186 (0.6298)	0.047 (0.4825)

Table A2: The raw data after being ran through MATLAB for the shoe sensor designs



	Back View			Side View						
	Change in total Distance (cm)	Change in X Direction (cm)	Change in Y Direction (cm)	Change in total Distance (cm)	Change in X Direction (cm)	Change in Y Direction (cm)	Frames of Back View	Distance/Frame of Back	Frames of Side	Distance / Frame of Side View
Copper Wire 1	1.9686 (+/-1.497)	0.5888 (+/-0.5404)	1.9686 (+/-1.1497)	0.1966 (0.4963)	0.9068 (0.5981)	0.8853 (0.6878)	309	2.138	456	0.37
Copper Wire 2	2.1447 (+/-1.1497)	0.8286 (+/-0.5461)	2.3575 (+/-1.1497)	0.2894 (0.5329)	0.2894 (0.6341)	0.4076 (0.6898)	332	1.973	332	0.4816
Steel Wire 1	1.6505 (+/-0.9517)	0.6512 (+/-0.5676)	1.6505 (+/-0.9517)	0.0635 (0.6774)	1.2719 (0.6251)	0.4244 (0.7574)	329	1.6575	252	0.5218
Steel Wire 2	2.649 (+/-1.1278)	1.1407 (+/-0.5971)	2.6490 (+/-1.1278)	0.2171 (0.4882)	1.1107 (0.6878)	0.641 (0.5722)	358	2.649	359	0.4254
Straps 1	0.6735 (+/-0.728)	1.1824 (+/-0.7963)	0.9827 (+/-0.5353)	0.3784 (0.4716)	1.1824 (1.8925)	0.4067 (1.55)	466	0.8042	438	0.4588
Straps 2	1.3005 (+/-0.5807)	1.0585 (+/-0.5108)	0.8352 (+/-0.5370)	2.8002 (1.4191)	0.3037 (2.1708)	4.6431 (2.9013)	461	1.3185	320	2.81219

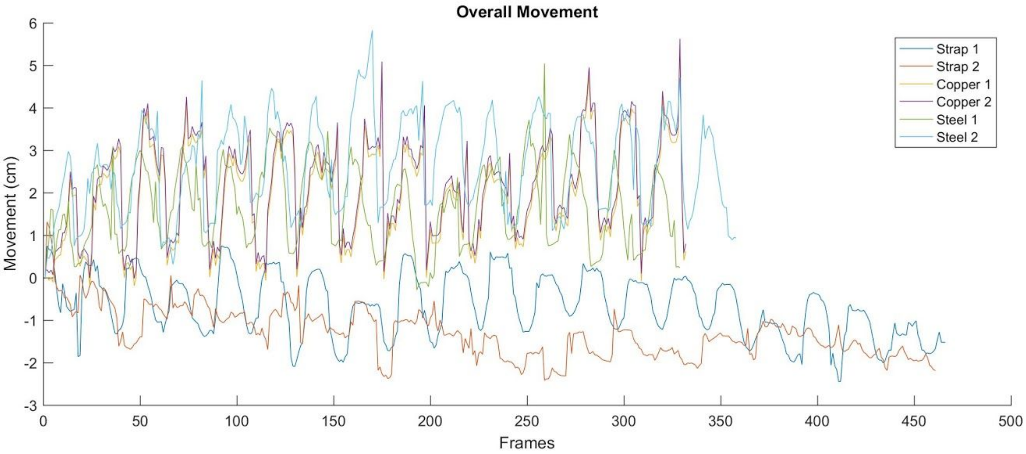


Figure A4: The total change of distance of the shoe sensor prototypes throughout the trial

MATLAB Code for Analysis of the Raw Testing Data

```
%% Phase 1- Straps Testing

a = [1.3, 0.5, 0.3, 0.0, 0.1, 0.0];

TF = isoutlier(a),

%% Back Perspective
b = [2.138, 1.973, 1.6575, 2.649, 0.8043, 1.3185];
s1 = std(b)/sqrt(6),
m1 = 1.0;

t_a = (2.138 - m1) / s1;
t_b = (1.973 - m1) / s1;
t_c = (1.6575 - m1) / s1;
t_d = (2.649 - m1) / s1;
t_e = (0.8043 - m1) / s1;
t_f = (1.3185 - m1) / s1;

p_a = 1- tcdf(t_a, 5),
p_b = 1- tcdf(t_b, 5),
p_c = 1- tcdf(t_c, 5),
p_d = 1- tcdf(t_d, 5),
p_e = tcdf(t_e, 5),
p_f = 1- tcdf(t_f, 5),

%% Side Perspective

sv = [0.37, .4816, 0.5218, 0.4254, 0.4588, 2.81219];
s2 = std(sv)/sqrt(6),
m2 = 0.2;

t_a2 = (0.37 - m2) / s2;
t_b2 = (.4816 - m2) / s2;
t_c2 = (0.5218 - m2) / s2;
t_d2 = (0.4254 - m2) / s2;
t_e2 = (0.4588 - m2) / s2;
t_f2 = (2.81219 - m2) / s2;
```

```
p_a2 = 1- tcdf(t_a2, 5),
p_b2 = 1- tcdf(t_b2, 5),
p_c2 = 1- tcdf(t_c2, 5),
p_d2 = 1- tcdf(t_d2, 5),
p_e2 = 1- tcdf(t_e2, 5),
p_f2 = 1- tcdf(t_f2, 5),
```

Materials and Expenses

Description	Item #	Supplier	Link	Quantity	Cost	Purchased?
1.5 in Elastic Strap (11 yards)	4337000305	eBoot	link	1	$10.99	Yes
1.5 in Double Side Release Buckle	NA		link	1	$6.98	Yes
Cable Clips, ONME 6 Pack Cable Holder	N/A	ONME	link	1	$4.99	Yes
Letsfit Resistance Latex Bands	N/A	Letsfit	link	1	$5.09	Yes
VELCRO Brand Mounting Squares	N/A	VELCRO	link	1	$2.89	No
16 Gauge Galvanized Steel wire	123130	Amazon	link	1	$5.99	Yes
Adafruit LSM303AGR Accelerometer Magnetometer - STEMMA QT Qwiic	4413	Adafruit	link	1	$8.95	Yes
Adafruit LSM6DS33 + LIS3MDL - 9 DoF IMU with Accel / Gyro / Mag - STEMMA QT Qwiic	4485	Adafruit	link	1	$9.95	Yes
Adafruit ItsyBitsy nRF52840 Express - Bluetooth LE	4481	Adafruit	link	1	$17.95	Yes
3D Printed sensor models		Makerspace		2	$1.52	Yes
				Total cost:	$73.78	
				Total cost with fees	$98.12	
				Budget Left:	$401.88	