PREVENTING WEIGHT LIFTING INJURIES BY BARBELL MODIFICATIONS

Biomedical Engineering Design

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Abstract

Weight training is the second most common form of regular activity done by Americans outside of walking, with about 8.9% of the population engaging in some form of lifting [1]. Of those ~29 million people, an average of ~970,000 total emergency department visits each year are due to a weight training injury [2]. With the benchpress being among the riskiest of lifting movements, there is much prerequisite for a device to decrease likelihood of injury. There exists many different types of devices to track a person's lift, be it something that affixes to the end of a barbell, or that is integrated in the equipment itself. There doesn't yet exist, however, one such device that can alarm the user *in real time* of a lifting imbalance. In order to eliminate this shortage, the team proposes a solution: Creating two barbell attachments consisting of a 3D printed attachment that houses an ultrasonic sensor that are positioned at either end of said barbell providing live updates of multiple lifting metrics (transverse angle of the barbell, lift velocity/force, etc.) to a separate screen attachment near the user's chest. The ultrasonic sensors were tested to ascertain whether or not they will accurately and precisely measure the motion of the barbell and hence effectively solve the problem. In this semester, the team was able to print a model for the prototype and set up a functional measuring and display system.

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Introduction

Motivation

Weightlifting is a growing form of exercise for individuals around the world, but with this comes an increase in individuals who have poor form or attempt to lift weights that are too heavy for them. This increase in inexperienced lifters and “ego” lifters has led to many hospital visits due to weightlifting injuries, nearly 1 million in the United States alone. A staple exercise in weightlifting is the barbell bench press and 20 to 40% of weightlifting injuries are due to it [3]. These bench pressing injuries can lead to temporary or permanent damage to the shoulder joint, which can have devastating effects on the day to day life of an individual.

According to the Mayo Clinic, weightlifting has many benefits for the body and mind no matter the age of the weightlifter [4]. This includes increasing bone density and strength, managing chronic conditions, and managing one’s weight. Weightlifting has the potential to improve an individual's way of life, so long as they are smart about what exercises they do and what weight they use.

A device that can decrease the amount of weightlifting injuries that occur during the barbell bench press would be integral in maintaining the health and wellbeing of individuals who do this exercise around the world. It could also encourage individuals to begin weightlifting if they have not yet and reap its benefits. The target demographic for the device is any individual who is seeking additional input on their form to prevent injury during lifting.

Existing Devices and Current Methods

An existing patent that is relevant in the level measurement of a barbell to decrease injuries is the Barbell level indicator [5]. The device contains a housing unit that fits to the barbell, an accelerometer to measure the angle and movement of the barbell, and an alarm system to indicate to the user when the barbell is slanted at a greater than desirable angle, it also has the capability to transmit the data to a mobile device. The barbell level indicator can be seen in figure 1.

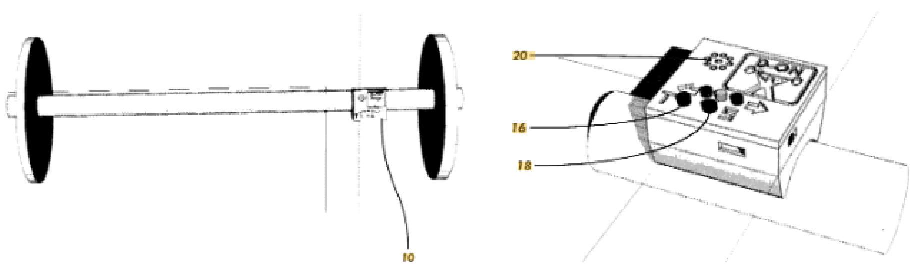


Figure 1: The barbell level indicator

This patent focuses heavily on the levelness of the barbell and alerts the user via a noise instead of a visual indicator. One drawback is that the device is not centered on the barbell, and is relatively large and clunky. This can lead to a degree of unevenness in the weight distribution, and may cause an unlevelness of the barbell. However, this design is universal for any lift that uses a barbell, it is not limited to only the bench press.

A second patent that is related to tracking the movement of the barbell is the Multi-functional weight rack and exercise monitoring system for tracking exercise movements [6]. This patent includes the systems and methods for tracking the barbell via cameras. The camera tracks the objects within the field of view and provides data to the user, this data can also be shared to other individuals.

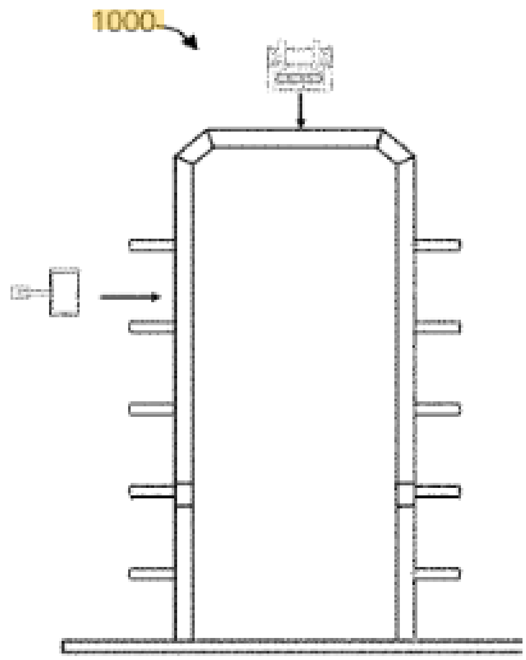


Figure 2: Multi-Functional weight rack and exercise monitoring system for tracking exercise movements

This device is capable of tracking the movement of the barbell for a various number of lifts, which makes it a universal design. However, this requires the purchase or fabrication of a complete weight rack, which is an unrealistic goal for the vast majority of lifters.

The Bar Sensei is a device that is currently on the market that provides instant feedback during barbell training and costs $400 [7]. As seen in figure 3, the Bar Sensei simply attaches to the barbell, and sends the data collected to a smartphone or tablet.

Figure 3: Bar Sensei

The Bar Sensei tracks the bar speed, power and force, and it can be used for any lift that uses a barbell. The device is also 1 ounce, which means that the location of where it is put will have negligible effect on the distribution of weight.

Problem Statement

The goal of this project is to reduce the number of weightlifting injuries starting with one of the most common and potentially hazardous lifts: the bench press. The cause of most weight training injuries is an imbalance in the lift, so the device will detect if the barbell is level and alert the user if it's not. Along with this feature, other data will be collected during the lift, including sets, repetitions (reps), speed, etc. Instead of simply logging the data, however, it will be displayed in real time to the user during their lifting motion. Hopefully the end result is a product that is both convenient and reliable, that protects its user from potential harm, and that is in the house of every weight-lifter in the nation.

Background

Physiology of the Lift

The barbell bench press is performed by descending a barbell down to one's chest then pushing it back up until the lifter's arms are fully extended whilst lying on their back (see figure 4). This compound movement targets the chest and shoulder muscles.

Figure 4: Barbell Bench Press

While the lift is simple, there are many variations to the lift that can target different parts of the used muscle groups differently; however some of these variations can lead to a higher chance of injury. According to the *Strength and Conditioning Journal*, if the lifter's hand placement is over 1.5 times their shoulder width, there is an increased risk of shoulder injury to the lifter due to the shoulder abduction being greater than 75 degrees [8]. The article stated that the shoulder is at its lowest level of risk of being injured when the shoulder abduction angle is less than 45 degrees (see figure 5); however, shoulder abduction angles less than 70 degrees is a healthy amount.

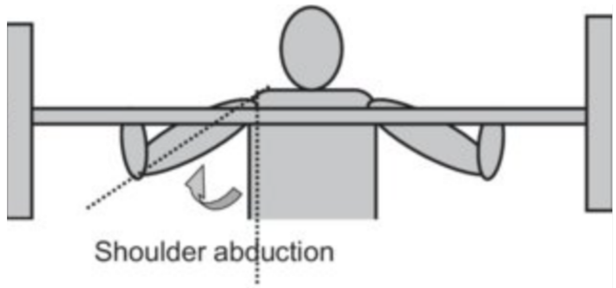


Figure 5: Shoulder abduction angle during the bench press

Injuries during the barbell bench press occur due to instability during the lift, this instability can be observed through asymmetries of the arms or body during the lift, unlevelness in the bar, or poor control of the speed of the bar. To diminish the risk of injuries, weightlifters should select a weight that minimizes these occurrences.

Design Specifications

The primary goal of the device is to track the movement of the barbell during a bench pressing movement and provide real time feedback to the lifter. Collaterally, this feedback could lower the risk of barbell bench press injuries from occurring to the lifter. Such movements of the barbell bench press that are being measured include the levelness of the bar along with the number of reps that have occurred. This data collected will then be displayed to the user during the lift so the lifter can focus on the exercise and what needs to be fixed to prevent injury. The device should be capable of working for 3-5 years before newer modificating devices surpass the existing one. The minimum amount of force and torque that the device should be capable of withstanding are 800 N and 17.39 Nm respectively. The modification must be able to be attached to an existing barbell, or work in tandem with current lifting equipment. The device must also be novel so that a patent can be made for it, and so that it can be marketable to a consumer base.

Preliminary Designs

Barbell Design 1: Full Barbell

The first preliminary design idea is to modify the barbell that will be used for the bench press exercise. This will require the fabrication of a complete barbell whose dimensions are that of standard olympic barbells [9], however the most middle portion of the barbell design contains a display screen and a lift tracking sensor as seen in figure 6. This design would require that the circuitry for the display screen and tracking sensor be inside of the barbell. The barbell will track which side of the barbell is higher and will relay that information to the user through the display screen in the middle.

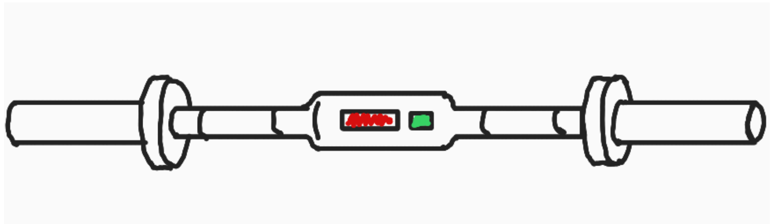


Figure 6: Drawing of Full Barbell Modification Design

During the lift, flexion can occur due to the weights on either end of the barbell. Because of this, the display would need to be constructed out of a flexible screen to prevent cracking during said flexion or due to contact with the lifter during the exercise. Also the circuitry of the bar will need to be securely constructed so no dislodgement or breaking of electrical components would occur during the lift. If either one of these failure points are reached, then the device is rendered useless.

Barbell Design 2: Barbell Attachment

The barbell attachment preliminary design will consist of one or more attachable sleeves or clips that are capable of being secured to a standard barbell, which has a diameter of 28.5 millimeters [10]. The attachable clips will have the capability to track the movement of the barbell and display the results.

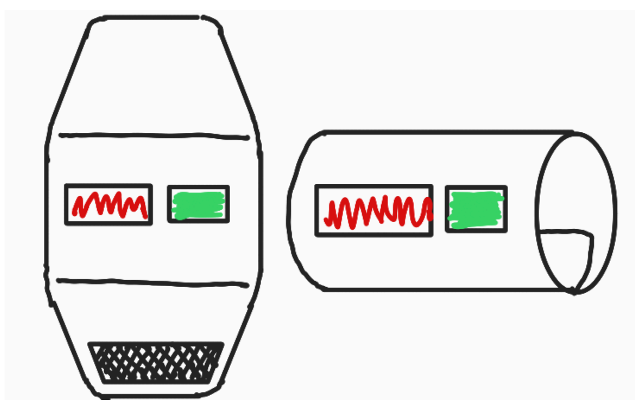


Figure 7: Drawing of potential barbell attachment designs.

The attachments must be placed evenly about the center so that the weight is symmetrically distributed across the barbell to minimize potential injury. Primarily information about the position of one sensor relative to the other will be displayed in the screens or lights attached to the clips.

Barbell Design 3: Full Suit and Augmented Reality

The third preliminary design idea to track the barbell lift and display the information to the lifter in real time consists of an augmented reality pair of glasses and motion tracking suit for the upper body, as seen in figure 8. In contrast to the other two preliminary designs, this will require the lifter to wear the tracking and display equipment instead of having it be/exist on the barbell itself.

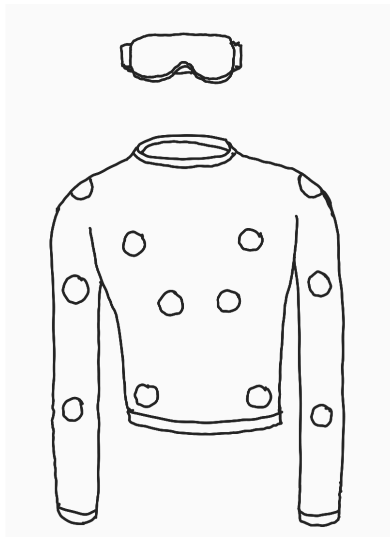


Figure 8: Drawing of Full Suit and AR design idea.

The motion tracking suit will track the lifter's key joints on the arm and upper torso that are integral to the lift; which include the wrists, elbows and shoulders - but other tracking locations can be added if desired. Tracking the lifter themself instead of the bar can provide more useful feedback on the form of the lifter on top of the amount of reps they have completed and the levelness of the bar.

The augmented reality glasses will be relaying information that is tracked from the motion tracking suit, and then this information will be displayed to the user. This means that the user does not need to focus on looking at the barbell during the lift and can observe the tracked information by simply keeping their eyes open.

Technology Design 1: Radar/Lidar/Ultrasonic

This technology relies upon waves to detect distances from a sensor. The measurements are completed by taking the time between the release of the wave to the return and dividing it by the speed of sound or light depending upon the sensor. Radar utilizes radio waves that bounce off objects then come back to the sensor to determine distances [11]. Lidar sensors utilize lasers that are emitted that determine the distance between the sensor and the object [12]. Ultrasonic sensors utilize very high pitched sound to bounce off objects and return in order to calculate the distance of the object [13].

This idea would require steady and consistent placement of the sensors in order to determine an accurate measurement of the barbell. This would also require multiple sensors in order to determine the angle of the bar. They would have to be placed symmetrically across the bar in order to maintain balance of the barbell for the user.

Technology Design 2: Accelerometer

An accelerometer works by reading a change in velocity and outputting it as a voltage. This is done by a piezoelectric material that causes a change in resistance causing a change in output voltage. This voltage can then be converted to an acceleration based on conversions given by the manufacturer. This could be placed anywhere on the barbell and read all of the accelerations and could take the integrals of the acceleration in order to calculate velocities and positions. This could easily calculate the angle by taking the change in accelerations at different points to calculate the change in distances and utilizing those to calculate the angle. This has been used quite frequently in similar patents and designs [14].

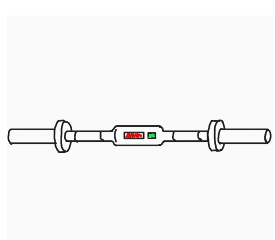
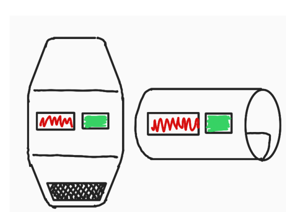
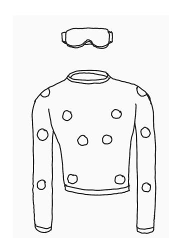
Technology Design 3: Inertial Mass Units

An inertial mass unit (IMU) is a combination of an accelerometer and gyroscope to measure velocities and accelerations to track a more clear three dimensional movement. This can be utilized to get an angle easily with the gyroscope and receive information about the accelerations with the accelerometer. This has also been used in many similar designs and patents. They typically require a bit of calibration to get to function smoothly. [15]

Preliminary Design:

Preliminary Design Matrix

Table 1: Preliminary design matrix of the viable barbell modification designs being evaluated against the following criteria: safety, ease of use, uniqueness, marketability, cost, and ease of fabrication

Design	Full barbell		**Barbell attachment**		Full suit + VR	
						
Safety (25)	4/5	20	5/5	25	5/5	25

Ease of Use (20)	4/5	16	5/5	20	2/5	8
Uniqueness (20)	3/5	12	2/5	8	5/5	20
Marketability (20)	3/5	12	4/5	16	5/5	20
Cost (10)	3/5	6	5/5	10	1/5	2
Ease of Fabrication (5)	2/5	2	4/5	4	1/5	1
Overall Score:	68		83		76	

Safety: The safety of the user is the number one priority of the device, this design criteria takes into account the ability of the device to properly track the bar and diminish weightlifting errors of the user. Such tracking measures include the balance of the bar and counting reps of the lift, these tracking measures allow for the weightlifter to focus on proper form and completing the lift.

Ease of Use: The device must be both intuitive to use and to visualize the data being tracked, if not it has potential to cause user error. User error could lead to potential weightlifting injuries, which is the opposite intention of the device, or it will nullify the functionality of the device.

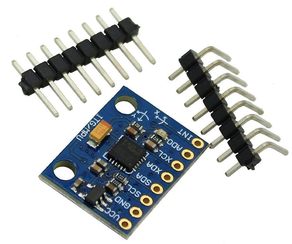
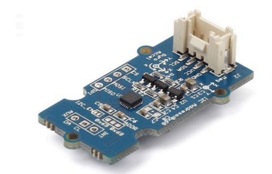
Uniqueness: The client is looking for the development of a device that has not been done before and is - in turn - patentable. The device must be novel in design and functional in order to be considered for a patent, so the singularity of the device will determine if it can be patented or not.

Marketability: The client is wanting this device to be able to go on the market and have interest in the device. In the past the client has actually taken a similar device (Dumbell color coded attachment) to a pitch competition that failed and did not have a single person show interest in the device. This time around our client understands the importance of marketability so that it can gain funding/support from investors.

Ease of Fabrication: This device we as a team want to be able to design ourselves. This is not to say that the device should be as simplistic as possible. More so that the device should not be more work than is needed to be done and our abilities to fabricate the device is not out of our skill sets. This is specifically for the device placement portion so being able to make something on a barbell as an attachment is much different than making a full suit full of sensors.

Cost: The value of the resources to fabricate the device is what this design criteria pertains to. Devices that require larger amounts of resources will be scored lower due to the need to keep the device within the budget.

Table 2: Preliminary design matrix of the viable barbell modification technologies being evaluated against the following criteria: accuracy, reliability, marketability, cost, ease of fabrication, and safety.

Technology	Radar/Lidar/ Ultrasonic		Accelerometer		IMU	
						
Accuracy (25)	5/5	25	4/5	20	3/5	15
Reliability (25)	3/5	15	4/5	20	4/5	20
Marketability (20)	5/5	20	2/5	8	3/5	12
Cost (15)	2/5	6	4/5	12	3/5	9
Ease of Fabrication (10)	2/5	4	4/5	8	3/5	6
Safety (5)	5/5	5	5/5	5	5/5	5
Overall Score:	75		72		67	

Accuracy: The accuracy of the technology is crucial to determine the effectiveness of the design. The accuracy is the ability of the technology to properly represent the actual data inputted by the user's movement of the barbell. This means when the bar is moving at 1.3 meters per second it should read 1.3 meters per second.

Reliability: The reliability of the technology is also crucial to the overall effectiveness of the design. Reliability is the technology's ability to consistently read the correct input from the user's movement of the barbell. This means that the technology should be able to work in as many situations as possible with as small user error as possible to decrease the chance of an incorrect reading.

Marketability: The design must be patentable and desirable by consumers. The design has to be both unique and seem appealing to potential users of the design. This means that it has to set itself apart from the competition.

Cost: The cost is always important to consider in a design. As this is a product made to be sold, it is very important to keep the costs at a minimum to compete with the competition.

Ease of Fabrication: This device we as a team want to be able to design ourselves. This is not to say that the device should be as simplistic as possible. More so that the device should not be more work than is needed to be done and our abilities to fabricate the device is not out of our skill sets. This ease of fabrication is specifically designed to the type of device chosen to track balance during the lift. The coding of the device should not be too complex for our team's abilities but is okay if it pushes us to learn new things.

Safety: This device should not be harmful to the user in either its electrical components or mechanical components. The device should not have a high likelihood of causing injury to the user. The device is not to be dangerous due to attachment to the barbell or addition to the barbell.

Fabrication/Development Process

Materials

Sensor Attachments

A total of two sensor attachments were made for use at either end of the barbell. Each one had a 3D printed housing made out of durable PLA filament that consists of a bearing with attached housing for electronics; a total of 5 individual bearing beads and 2 bearing-holders (to ensure each bearing bead is equally separated within the bearing) were also 3D printed for each of the attachments. Electronics for each include a Raspberry Pi Pico W, an ultrasonic sensor, a breadboard, a battery pack, 3 AA batteries, and 5 wires to connect everything. The power supply provides energy to the ultrasonic sensor and Pi Pico W, allowing for distance measurements and wireless transmission of data respectively.

Table 3: Materials for sensor attachments

Part	Description	Rationale for Use
Raspberry Pi Pico W	Microcontroller	Used to acquire and transmit data from ultrasonic sensor to screen attachment
Ultrasonic sensor	Distance measuring device	Emits ultrasonic waves and provides different voltage values to microcontroller based on the time it takes for them to come back to the

		sensor
Breadboard	N/A	Connects circuit components
Battery Pack	N/A	Houses 3 AA batteries to provide sufficient voltage and current to Pico W
3× AA Batteries	N/A	Power source for the circuit
5× Wires	N/A	Connects circuit components

Screen Attachment

Due to time constraints, a fully designed screen attachment was not created, and the team instead opted for a more bare-bones way to display data. A Raspberry Pi 4 Model B, along with a wired power supply, a breadboard, a 4-segment display, and 4 wires to connect everything were used for this model. The power supply provides energy for the Pi 4 to receive data from the two sensor attachments and convert the values into proper distance measurements, then it outputs 'HIGH', 'LOUU' (the letters 'UU' were used to represent a capital 'W'), or 'EUEN' (again a "V" was not present so a "U" was used instead) depending on the sensor output compared to an arbitrary second sensor value.

Table 4: Materials for screen attachment

Part	Description	Rationale for Use
Raspberry Pi 4 Model B	Microcontroller	Used to receive data from sensor attachments and calculate distances to display
Wired power supply	N/A	Power source for the circuit
Breadboard	N/A	Connects circuit components
4-Segment display	SparkFun 7 Segment 4 Digit Serial Display	Visually displays information regarding sensor position
4× Wires	N/A	Connects circuit components

Methods

The fabrication of the barbell sensor attachments occurred in the UW Makerspace utilizing the provided 3D Printers. Two separate prints occurred to print one entire sensor attachment, the more detailed parts were printed with the Bambu Lab 3D printer while the rest of the parts were printed in the Ultimaker. All parts were fabricated out of tough PLA black. Post printing, the team sanded the parts that were essential to the function of the bearing to ensure that the parts fit together properly.

The functional prototype required no 3D prints, but instead utilized the Raspberry Pi Pico W, Raspberry Pi 4 Model B, the ultrasonic sensor, and the serial display. The team used the materials listed in Table 3 and Table 4 (see above). The team was unable to complete the code that would enable wireless communication between the Raspberry Pi Pico W and Raspberry Pi 4, so the team instead wired all of the components together. The Fritzing Diagrams of the functional prototype can be seen below in figure 9.

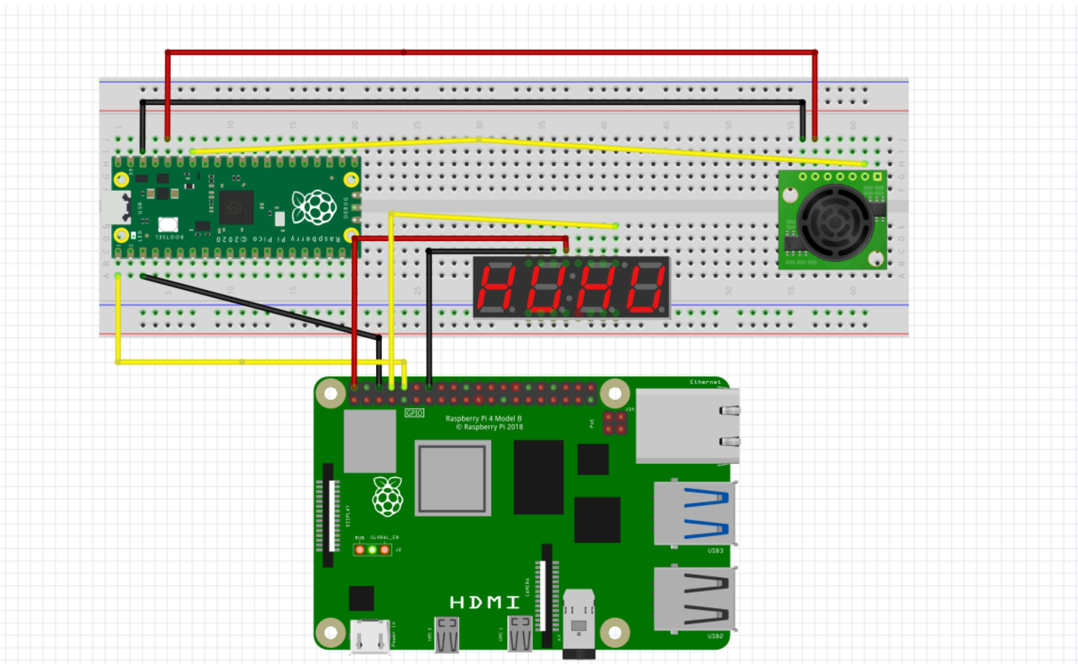


Figure 9: Fritzing diagram of the complete wired circuit of the sensor and display device

Final Prototype

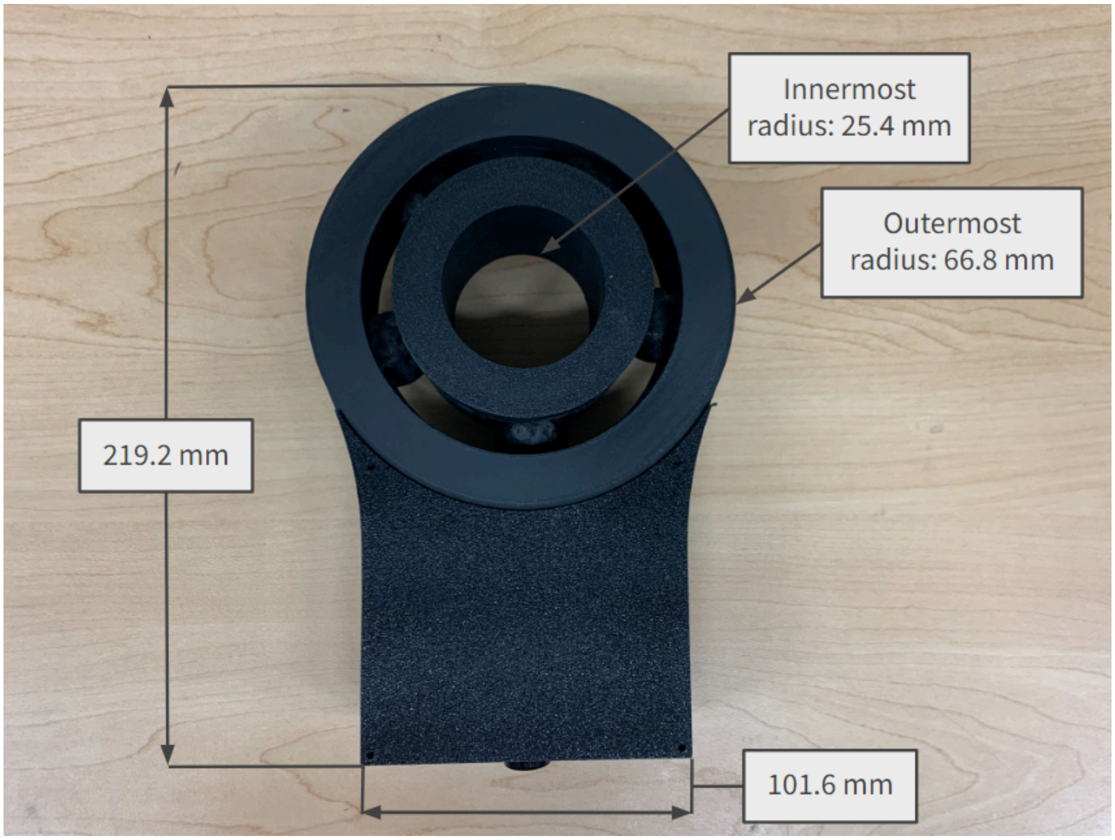


Figure 10: Top view of sensor attachment with important dimensions labeled.

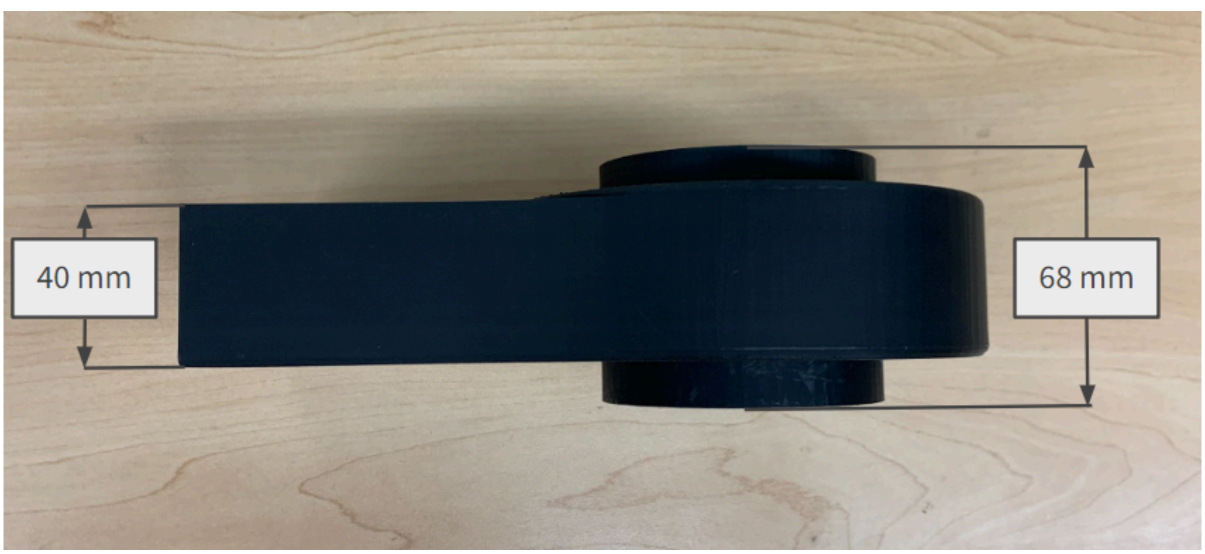


Figure 11: Profile view of sensor attachment with important dimensions labeled.

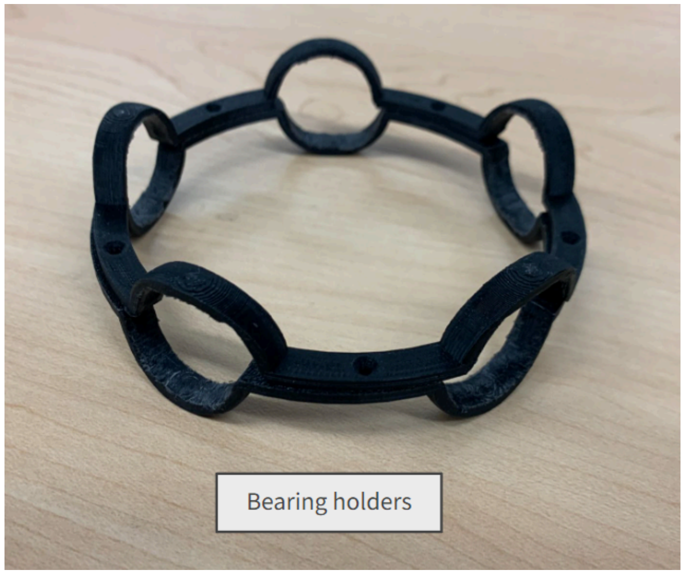


Figure 12: Bearing holders stacked on one another. Their purpose is to evenly distribute bearing balls within the bearing itself, allowing for a smoother turn. There are spots for 5 screws between bearing balls to hold the different pieces together between the inner and outer components of the bearing.

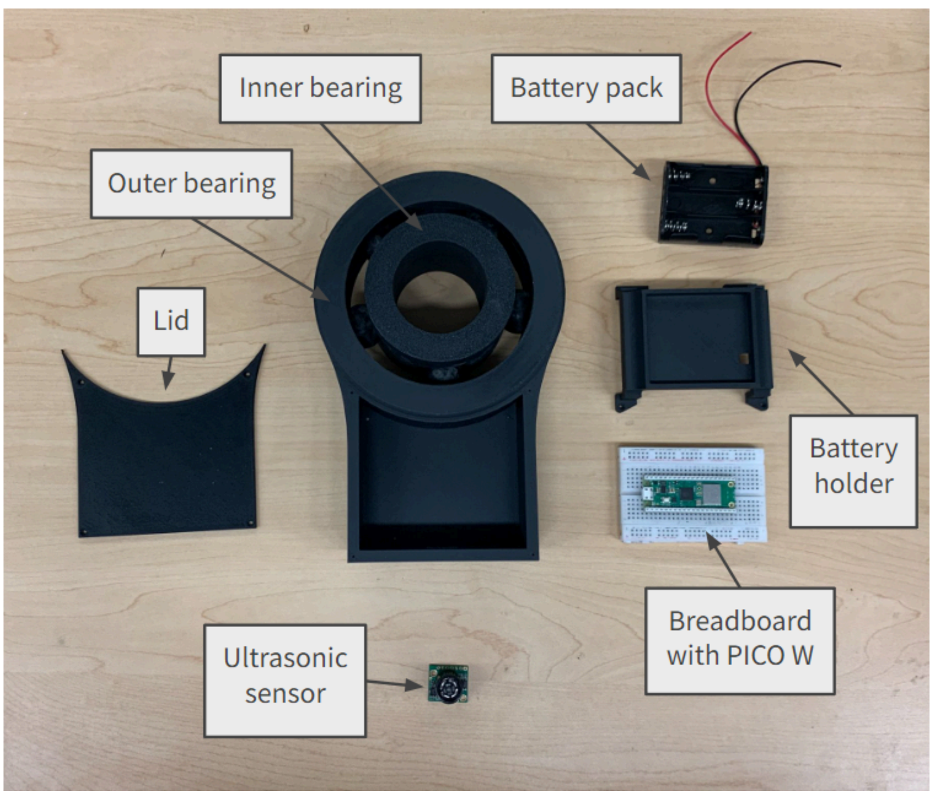


Figure 13: Disassembled components of sensor attachment include an inner bearing component, an outer bearing component, 5 bearing beads, a lid to house electronics, a battery pack, a 3D printed battery holder, a breadboard with connected Raspberry Pi Pico W, and an ultrasonic sensor.

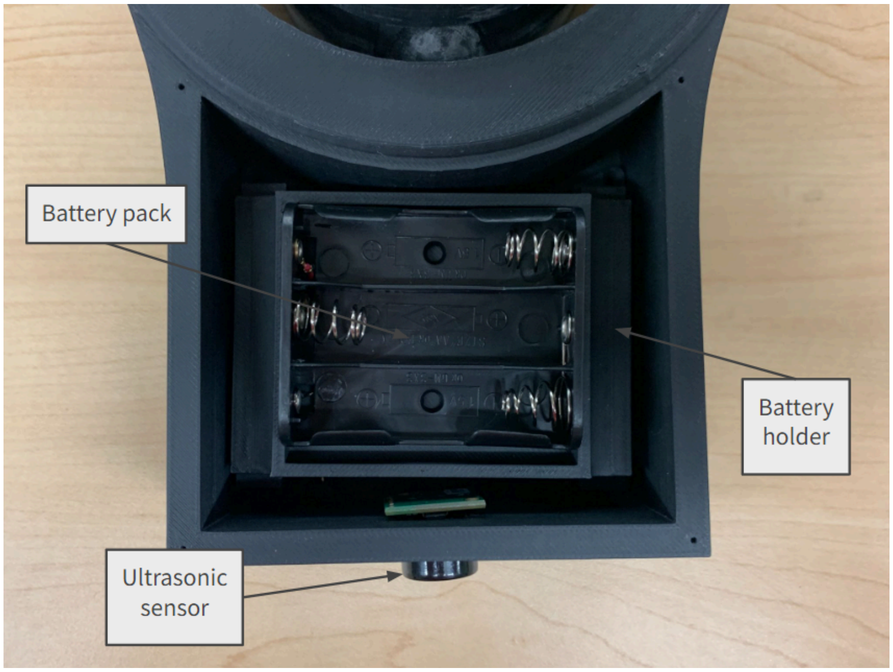


Figure 14: Blown up view of the electronics housing. Breadboard is not pictured because it is housed under the battery holder. There remains ample space for wires to connect everything up as shown in the Fritzing diagrams in the previous section.

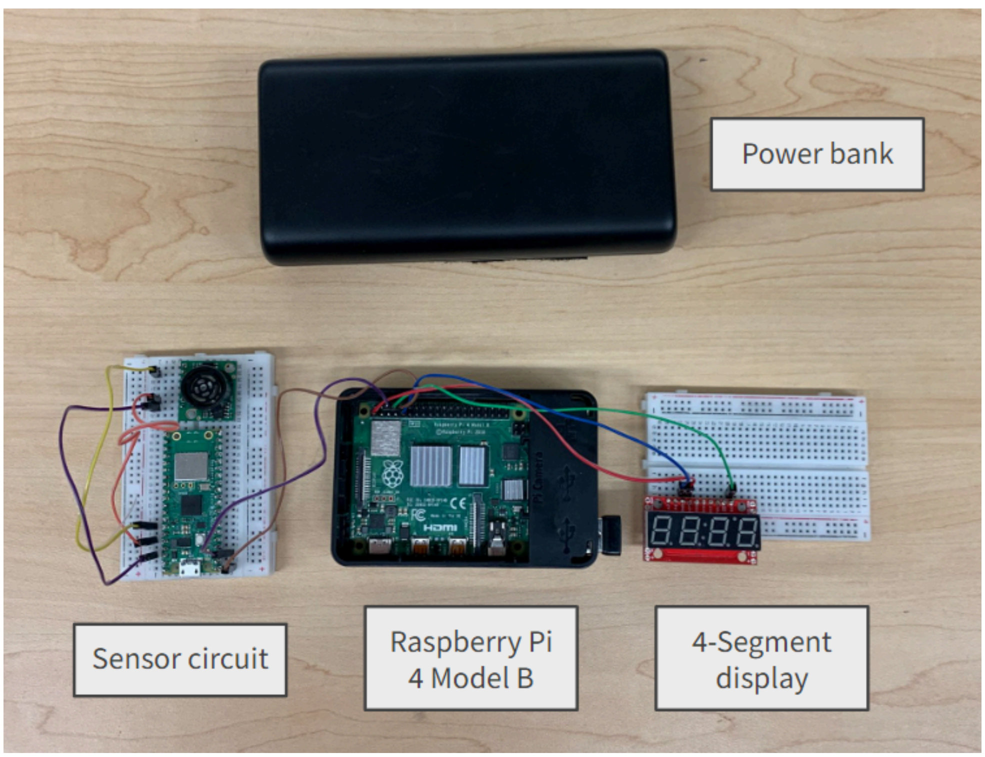


Figure 15: The functional prototype of the measuring and displaying features of the prototype. Parts include: the Raspberry Pi 4 Model B, Raspberry Pi Pico W, SparkFun 7 Segment Serial Display, and an ultrasonic sensor.

Testing and Results

Sensor Acuity Test

Because an ultrasonic sensor was ultimately chosen as the way the device obtains data to tell whether or not the barbell is even, it is important that the accuracy of the sensor be tested against real world distances to see if it has over 5% error measuring the distance between the device and the ground. In order to do this, both sensors (one for each end of the barbell) were tested at multiple different distances from a flat wall to see how close the sensor data was to the real distance, and to see whether or not there is a significant difference between sensor distance values themselves. For five trials, measurements were taken at 6 inch intervals starting at 12 inches and ending at 48 inches away from the wall. This gives a good amount of data for distances that are highly likely for the sensor to detect during actual weight lifting (between two and four feet off the ground).

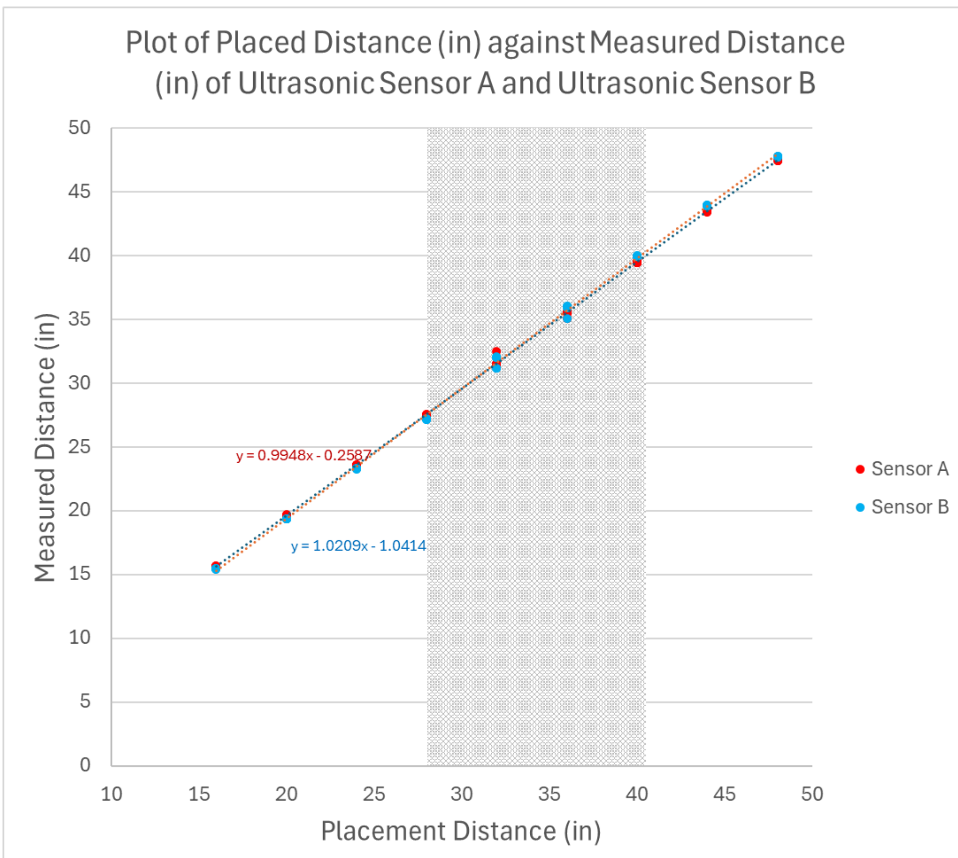


Figure 16: Plot of set distance (in) vs measured distance (in) of each sensor, with highlighted portion being the expected measured distance during a workout

Sensor Acuity Test Results

The sensor acuity test that was conducted yielded very accurate and precise results, which can be found in Appendix H. The graph in Figure 16 represents the plot of measured distances against the placement distance - in inches - for both sensor A (red) and sensor B (blue). Since it is a plot of expected against measured distances, the expected relationship of the plot would be a direct, linear relationship with a slope equal to 1. The slopes for sensor A and sensor B are 0.995 in/in and 1.0209 in/in respectively, this indicates that the ultrasonic sensors are very precise. To support how precise and accurate the sensors are, the team conducted a statistical analysis. In this analysis, it was found that the percent error of each ultrasonic sensor was 1.44% and 1.56%, with an average percent error of 1.5%. This percent error, the error from the measured value, is well below the acceptable error, 5%, that the team specified in the design requirements. The standard percent error, error between sensor values, was 0.98%, which is also below the acceptable error. The statistical analysis demonstrates that the ultrasonic sensors are both precise and accurate.

Sensor Beam Path Test

In order to understand more about how the sensor actually functions, the sensor beam path test was devised to chart out how the ultrasonic waves emitted by the sensor actually travel. This is important because, unlike with any other sensor outlined in the preliminary design matrix, the surroundings of the sensor could potentially impact or interfere with accurate distance readings, which are an important part of the design meant to keep the user safe. A flat object was placed in the periphery of the sensor path at varying distances, and the perpendicular distance from the middle axis of the sensor was measured (i.e. the radius of the beam path). For five trials, measurements were taken at 4 inch intervals starting at 6 inches and ending at 38 inches away from the sensor. Once again, these values were chosen because they reflect the actual distances that will be measured by the sensor in practice at the gym. To aid visualization, calculations were made to convert these radius measurements into angles from the sensor, the origin point of the ultrasonic waves.

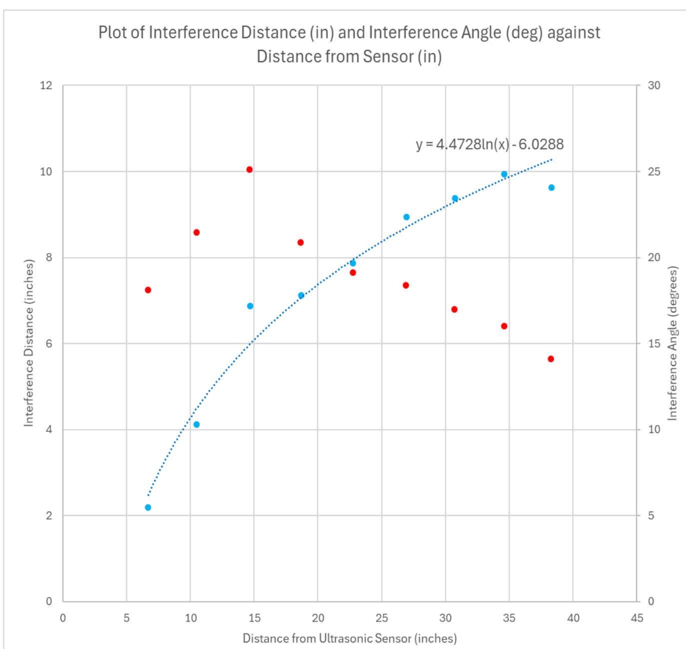


Figure 17: Plot of beam pattern width (blue) and angles (red) at varying distances from the sensor

Sensor Beam Path Test Results

The beam path test results, which can be found in full in Appendix H, were used to determine the area in which the ultrasonic sensors will observe a distance. The lateral distance in which the ultrasonic sensor picks up on the obstructing object increases in a logarithmic relationship, where the maximum radius begins to flatten out around 10 inches. The angle relative to the ultrasonic sensor to the obstructing object is observed to increase until roughly 15 inches away from the ultrasonic sensor, then it begins to decrease. This decreased angle value corresponds to the flattening out of the measured interfering distance.

Discussion

As observed in the testing and results, the ultrasonic acuity testing was conducted to ensure that the sensors were both precise and accurate, which they were. They were accurate to the actual value and to each other within roughly 1%, which is well below the acceptable 5% tolerance. They also had an accurate standard deviation of 0.12, which ensures the precision of both devices. It is important for the device to be both accurate and precise since the functionality and reliability of the device depend on these two factors. Without an accurate ultrasonic sensor, the values of each sensor are compared to one another to observe if the device is level and it may observe and display inaccurate information - leading to the user trying to correct an imbalance that does not exist, or to be unaware of an imbalance that does exist. This nullifies the use of the device. The precision of the ultrasonic sensor is also very important. If the ultrasonic sensor were to inconsistently measure the distance between the bar and the floor, then the same nullifying effects could occur that were stated before. In summary, since the ultrasonic sensors are accurate and precise, the device is capable of functioning in a manner that can help reduce injuries.

The other round of testing, the sensor beam path test, was conducted to ensure that error from external objects or individuals would be minimal to obsolete. Such examples of error could be individuals walking by, the barbell rack, or a personal belonging on the floor. Any individual walking by will be no closer than the end of the barbell, which is at least 1 foot from the sensor [9]. The barbell rack will be roughly 8 inches from the sensor, depending on the set up of each lifter. As discussed in the results, the sensor beam path follows a natural log relationship, with the maximum radius measured being nearly 10 inches. Since the average weightlifter will have the barbell no higher than 40 inches, the maximum area that will be within the beam path is 10 inches from the sensor. Since the maximum distance is 10 inches, there is no reason the device would pick up the motion of a nearby individual unless they walk into the bar. The rack; however, is within the area - which could lead to inaccurate values. The team did conduct all of these tests on a table where the ultrasonic sensor was no more than 6 inches above the table, and the ultrasonic sensor never misread the table instead of the obstructing object. This leads the team to believe that the stationary barbell rack would not be read by the ultrasonic sensor instead of the floor, but further testing would need to be conducted to ensure that this is true.

Since the ultrasonic sensors are within the acceptable tolerances for the accuracy and precision of the device, they are suitable for use. The code that will be used to compare the values will include a tolerance between sensor values since having the values read the exact same value throughout the lift would be very difficult, and that is under the assumption the lifter has perfectly equal arm lengths. This tolerance will be the 5% error, so long as the values are within 5% of each other, the device will display that the barbell is even. The team will also utilize a moving average to minimize the effect of outliers in measurement values, since the sensors are not perfect. The moving average will utilize the last 5 measurements and take the average, then compare these averages to each other.

Conclusion

To conclude, the design produced this semester completed the objective set out by the team at the start, of creating a proof of concept in four months time. The use of ultrasonic sensors to track and measure the leveling of the barbell during the lift is an application for this design project that would work. The team managed to fabricate a beginning level device that could hold the sensor, one on each side, while also holding a Raspberry Pi Pico W inside that can communicate with the center display console.

Although the team's results were satisfactory in providing a proof of concept, there are improvements that can be made to ensure the device is a fully functional and marketable product for the weightlifting industry. Such improvements include a functioning bearing design, wireless communication between the Raspberry Pi Pico W's and Raspberry Pi 4 Model B, and an improved central display.

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Appendix

Appendix A: Product Design Specification

Date: 2/8/2024

Team project: Preventing Weight Lifting Injuries by Barbell Modifications

Lab section: 305

Group members
Leader: Nolan BlomWillis
Communicator: Kaden Kafar
BSAC: Jacob Parsons
BWIG: James Waldenberger (jwaldenberge@wisc.edu)
BPAG: duties split between everyone

Client: Bob Gold
Advisor: Megan Settell

Function

Weight training is the second most common form of regular activity done by Americans outside of walking, with about 8.9% of the population engaging in some form of lifting [1]. Of those ~29 million people, an average of ~970,000 total emergency department visits each year are due to a weight training injury [2]. The goal of this project is to reduce this number starting with one of the most common & potentially hazardous lifts: The bench press. The cause of most weight training injuries is an imbalance in the lift, so our device will detect if the barbell is level and alert the user if it's not. Along with this feature, other data will be collected during the lift, including sets, reps, speed, etc. Instead of simply logging the data, however, it will be displayed in real time to the user during their lifting motion. Hopefully the end result is a product that is both convenient and reliable, that protects its user from potential harm, and that is in the house of every weight-lifter in the nation.

Client requirements

- Real-time feedback on reps during weight training
    - Display reps and sets
    - Inform user of uneven lifting
- Device must be something that hasn't been done before
    - New technology or ideas
    - No use of wristband devices for biometric monitoring
- Produce a measurable increase in the safety of weight training

- *Optional:* measurement of muscle force

Design requirements

1. **Physical and Operational Characteristics**

A. **Performance Requirements:**

The measuring device will be used often and must measure the balance of the lift and bar each time a lift is performed. There should be 95% accuracy for the balance measurement when lifts are performed and the usability should be easy to use, for the common adult.

B. **Safety:**

Since the product is a medical device, there are FDA regulations that are to be followed for the device. As a class II medical device, the product will need to follow general and premarket approval [3].

C. **Accuracy and Reliability:**

The device should be about 95% accurate in terms of showing the levelness of the bar, or rather if one side is higher than the other. Over time the wear of the calibration is due to grow, but during the time of the device's shelf life it should remain 100% accurate in measurements regarding balance.

D. **Life in Service:**

The device should last roughly a year before calibration is required. Annual calibration is the safest way to make sure the sensors remain up to date and accurate [4]. On top of this, the device should last around 3-5 years before updates are made or new versions would be better than a worn out device.

E. **Shelf Life***

The device should be stored at normal conditions of around 20-22 degrees celsius and humidity levels between 20% and 60%. It is an electronic device so it should not be placed on the floor for long term storage to avoid any water risk.

F. **Operating Environment**

The device will operate in weight room settings, which will fluctuate around 20 - 22 degrees celsius. The device may also be exposed to various liquids such as sweat, energy drinks, water, etc. - Therefore water resistance is a must for the device. It may also endure forces due to the bar being placed or rested on the user, these forces may be upwards of 1000 Newtons[5]. The device must be able to function under all of these conditions.

G. **Ergonomics**

The device must be able to withstand strong human grip strength (~800N) and torque (17.39Nm) [5]. Depending on the form factor, it should also be able to easily be attached/detached and adjusted with relative ease of the user.

H. Size

The device must be able to be integrated onto or into a standard barbell, which has a diameter of 28 mm and a holdable grip length of 1.37 m [6]. It is essential that the device is symmetrical along the sagittal plane within 5% error - plane perpendicular to the bar and parallel to the face of the ends of the bar, so that the device does not cause imbalance during the lift.

I. Weight

The mass of the device must not exceed 2 kilograms in order to be as minimally invasive to the lift as possible, and the mass must also be evenly distributed to not imbalance the bar during the lift, imbalance may lead to injuries and render the device useless.

J. Materials

The materials used for the device should be safe to come into contact with the body. Since the sensors will be wearable the patient should not have to worry about injuries to themselves or those around them. The material must also be non-corrosive or harmful to the barbell to allow for the longevity of the equipment.

Aesthetics, Appearance, and Finish

The product should have a good appearance that if it is brought to a public gym it would not make the user self-conscious. It should also be fine to the touch and be wearable and or usable comfortably while not inhibiting the movement of the lift.

Production Characteristics

a. **Quantity**

The goal of this project is to create an idea and a working proof of concept for the semester. The goal is to be able to get to a successful marketable product in the future. The final goal would be to sell as much of the product as possible.

b. **Target Product Cost**

The target product cost will be within the $100-$200 range which would place it below the average cost of the competition of around $300 [7]. This would ensure that there would be profitable margins for the product.

Miscellaneous

c. **Standards and Specifications**

The device will be considered a Class II medical device according to the FDA [8], and it will require FDA clearance. In order to market the device, a premarket notification 510(k) or De Novo will be required to be submitted.

d. **Customer**

The customer of the product needs a device that is able to both improve the safety of their lifts and improve the overall experience of their lifts. They would like it to be something that can be easily used and be visually appealing.

e. **Patient-related concerns**

The device must be designed as a modification or addition to the barbell to make the lifting process safer. The design of the device must also not impede on the ability of the user to lift the barbell in any manner, or else this may cause an increased amount of user error, which will lead to increased chance of injuries and adverse effects.

f. **Competition**

There are several related patents to this project that are necessary to avoid. The “Barbell level indicator” [9] is a patent that uses a housing shaped to fit adjacent to the barbell, with magnetic attachment, that utilizes an accelerometer, an alarm, and a microprocessor to analyze data from the accelerometer. This utilizes a phone app to output the workout data to the user. Another patent is the "Multi-functional weight rack and exercise monitoring system for tracking exercise movements” [xy]. It utilizes an array of cameras around an arch to detect the motion of the exercise equipment and matrices of distance values. This is also accompanied by a mobile app in order to receive information on the lift.

Appendix B: Raspberry Pi Pico W Code

```
import machine
import time

uart = machine.UART(0, baudrate = 9600, tx = machine.Pin(0), rx = machine.Pin(1))

def measure_pulse_duration(pin, timeout= 9000):
    start_time = 0
    end_time = 0

    while pin.value() == 0:
        pass
```

```
    start_time = time.ticks_us()

    while pin.value() == 1:
        if time.ticks_diff(time.ticks_us(), start_time) > timeout:
            return 0

    end_time = time.ticks_us()

    pulse_duration = time.ticks_diff(end_time, start_time)

    return pulse_duration

while True:
    pin = machine.Pin(28, machine.Pin.IN)
    pulse_duration = measure_pulse_duration(pin)
    distance = pulse_duration/147
    print("Pulse duration: ", pulse_duration, "us")
    print("Distance: ", distance, "in")

    uart.write("{},{}\n".format(pulse_duration, distance))

    time.sleep(1)
```

Appendix C: Raspberry Pi 4 Model B Code

```
import serial
import time

# define serial port and baud rate
serial_port = '/dev/ttyS0' # change this to your serial port
baud_rate = 9600


ser = serial.Serial('/dev/serial0', baudrate = 9600)


# define the characters to display (L, O, W)
CHAR_MAP = {
        'L' : b'L',
        'O' : b'O',
        'R' : b'R',
        'B' : b'B',
        'A' : b'A',
        'U' : b'U',
```

```
            'H' : b'H',
            'I' : b'I',
            'G' : b'G',
            'E' : b'E',
            'N' : b'N',
}

# function t osend data to the display
def send_data(data):
            with serial.Serial(serial_port, baud_rate) as ser:
            ser.write(data)

# function to display a string on the 7-segment display
def display_string(string):
            data = b''
            for char in string:
            if char in CHAR_MAP:
            data += CHAR_MAP[char]
            else:
            print("Invalid character:", char)
            return
            send_data(data)

# display "LLO" all at once
while True:
            data = ser.readline().decode().strip()
            if data:
            pulse_duration, distance = map(float, data.split(','))

            print("Pulse duration: ", pulse_duration, "us")
            print("Distance: ", distance, "in")

            if 0.0 == distance:
            display_string(“NULL”)
            elif 11.16 > distance:
            display_string("LOUU")
            elif 12.84 < distance:
            display_string("HIGH")
            else:
            display_string("EUEN")

            time.sleep(1)
```

Appendix D: Expense Report

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor or Cat#	Date	QTY	Cost Each	Total	Link
Ultrasonic Sensors										
CUI Ultrasonic	Ultrasonic Sensor	CUI	N/A	CUI Devices	N/A	3/14	2	$6.70	$22.93	url
Max Ultrasonic	Ultrasonic Sensor	Max Sonar	N/A	MaxBotix	N/A	3/14	2	$29.95	$68.95	url
Other										
Power Supply	Battery used to supply power to screen attachment	QTshine	N/A	Amazon	N/A	4/14	1	$29.95	$29.95	url
Screen	Display attached to center of barbell	SparkFun	N/A	Dr. Nimunkar	N/A	4/14	1	$0	$0	url
Velcro	Used to attach housing blocks to barbell	Foxgor	N/A	Amazon	N/A	4/14	1	$9.99	$9.99	url
Wire Components	Extra electrical components to attach everything	N/A	N/A	Makerspace	N/A	4/14	1	$0	$0	N/A
Housing Block	3D Printed Housing chamber	N/A	N/A	Makerspace	N/A	4/19	1	$18.28	$18.28	N/A
Raspberry Pi Pico W	Used to gather data from ultrasonic sensors and wirelessly transmit it to the main terminal	Generic	B0B72GV3K3	Amazon	N/A	4/14	3	$27.99	$27.99	url
Battery Housing	Holds 3 AA batteries to power the Pico W microcontrollers	LampVPath	B07T7MTRZX	Amazon	N/A	4/14	3	$6.99	$6.99	url
AA Batteries	AA Batteries to power Pico Ws	Duracell	B002UXRXEG	Amazon	N/A	4/14	10	$14.32	$14.32	url
								TOTAL:	$199.40	

Appendix E: CAD Model

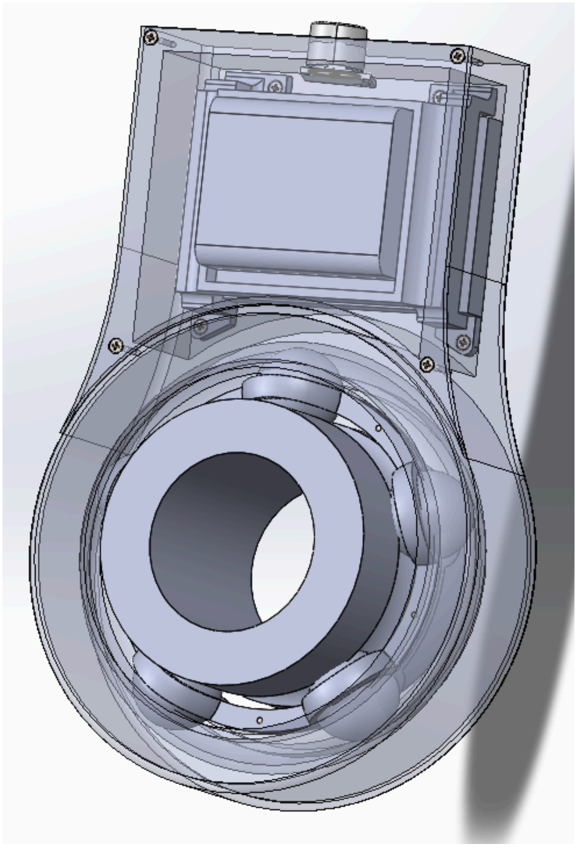

Figure 18: Image of CAD model for the sensor attachment

Appendix F: Fabrication Protocol

Ultrasonic Sensor Holder

1. Print the bearing holder model from SOLIDWORKS on a 3D printer of your choice using tough PLA (the team used the Ultimaker and Bambu 3D printers)

2. Remove supports from prints and sand down rough edges

3. Insert 5 balls into the ball bearing groove and lock them in with the inside ring, this is the ring that will be in contact with the barbell

4. Secure the balls in place using the bearing holders and M2 screws

5. Insert the battery pack with batteries into the housing chamber, and cover with printed battery holder

6. Connect power supply wires to the breadboard of the Raspberry Pi Pico W (Vcc and GND), and insert the ultrasonic sensor into the hole.

7. Wire the ultrasonic sensor to the Pico W

8. Screw in the battery holder and cover using M2 screws

Functioning Prototype

1. Gather 2 breadboards, the Raspberry Pi Pico W, the Raspberry Pi 4 Model B, the ultrasonic sensor, power supply, serial display, and jumper cables

2. Wire the ultrasonic sensor to the Pico using the pulse wave (PW) pin, Vcc pin, and GND pin on the ultrasonic sensor to the 3.3V pin, GND pin, and a GPIO pin of your choice on the Pico W - make sure to define this GPIO pin in the code

3. Wire the Pico W to the Pi 4 using the Pico W's GND and TX pins, wire these pins to the Pi 4's GND and RX pins respectively

4. Wire the Serial Display to the Pi 4 using the Vcc, GND, and RX pins of the serial monitor and connect these to the 3.3V, GND, and TX pins of the Pi 4

5. Supply the Pico W and Pi 4 with power from the power supply

Appendix G: Testing Protocol

Acuity Test

1. Measure out and mark every 4 inches from 16 inches to 48 inches away from a wall or large obstructing object

2. Connect one of the ultrasonic sensors to the computer and run the code to allow for the sensor to measure distances (can find code under project files)

3. Position ultrasonic sensor at 16 inches and record the value there

4. Move the ultrasonic sensor to 20 inches and record said value, repeat this process all the way up to 48 inches

5. Repeat steps 3 and 4 for 5 trials

6. Repeat steps 2-5 for the other ultrasonic sensor

Beam Path Test

1. Position ultrasonic sensor at least 48 inches away from a wall or obstructing object, make sure the ultrasonic sensor is at least 8 inches from the table or floor

2. At roughly 6 inches from the ultrasonic sensor, slowly move a large obstructing object (like a folder) from far away closer to the ultrasonic sensor until the value recorded changes - mark this position of the obstructing object

3. Repeat this process at 4 inch increments until the last measurement is roughly 38 inches away

4. Measure and record the perpendicular distance (in inches), that was marked in step 2

5. Calculate the angle of the beam path at this position, cot(perpendicular distance / distance from sensor)

Appendix H: Raw Testing Data

Sensor Acuity Test

<u>Sensor A</u>

Target Distance (in)	Trial 1 (in)	Trial 2 (in)	Trial 3 (in)	Trial 4 (in)	Trial 5 (in)	Average (in)	Standard Deviation	% Error
16	15.61905	15.63625	15.70068	15.59184	15.70068	15.6497	0.49158	2.189375
20	19.67347	19.55782	19.70068	19.68707	19.6667	19.65715	0.05704	1.71426
24	23.55012	23.61905	23.63265	23.59184	23.4966	23.57805	0.055377	1.758117
28	27.5102	27.58503	27.59864	27.52381	27.54422	27.55238	0.038301	1.598643
32	32.55102	31.502	31.55102	31.53061	31.57143	31.74122	0.453421	0.8087
36	35.102	35.51701	35.53281	35.61905	35.57143	35.46846	0.208609	1.4765
40	39.55102	39.57823	39.48299	39.4463	39.4966	39.51103	0.053151	1.222433
44	43.46939	43.4966	43.5034	43.52831	43.45522	43.49058	0.028825	1.57764
48	47.43538	47.44218	47.49939	47.55782	47.6393	47.51481	0.085396	1.010804

<u>Sensor B</u>

Target Distance (in)	Trial 1 (in)	Trial 2 (in)	Trial 3 (in)	Trial 4 (in)	Trial 5 (in)	Average (in)	Standard Deviation	% Error
16	15.45578	15.45578	15.46939	15.42857	15.46939	15.45578	0.016665	3.401363
20	19.38775	19.36735	19.38775	19.34694	19.41497	19.38095	0.025453	3.09524
24	23.31973	23.36054	23.36735	23.32653	23.27891	23.33061	0.035544	2.789117
28	27.17687	27.23129	27.22449	27.19048	27.20408	27.20544	0.022765	2.837707

32	31.17687	32.06123	31.16327	32.01361	32.12925	31.70885	0.49357	0.900856
36	36.04082	35.10204	35.9932	35.93197	36.08163	35.82993	0.410707	0.472411
40	39.95238	40.02041	39.98639	40.0	39.95918	39.98367	0.028296	0.04082
44	43.95238	43.95238	43.93877	43.92517	43.95238	43.94422	0.012169	0.126782
48	47.82993	47.72789	47.81633	47.81633	47.82993	47.80408	0.043132	0.408163

Average Standard Error Between Sensor Values: 0.602642%
Average Percent Error for both Sensor Values: 1.501003%
Average Standard Deviation for Both Sensors: 0.117643

Sensor Beam Path Test

Distance to Sensor (in)	Obstruction Distance (in)	Angle (deg)
6.6875	2.1875	18.113
10.5	4.125	21.448
14.6875	6.875	25.084
18.6875	7.125	20.87
22.75	7.875	19.093
26.9375	8.9375	18.355
30.75	9.375	16.955
34.625	9.9375	16.014
38.3125	9.626	14.104