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 an array of ultrasonic sensors 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 device will be tested to ascertain whether or not it accurately and effectively solves the problem at hand, and based on its performance therein, will potentially need to be taken through the design process again.

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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.

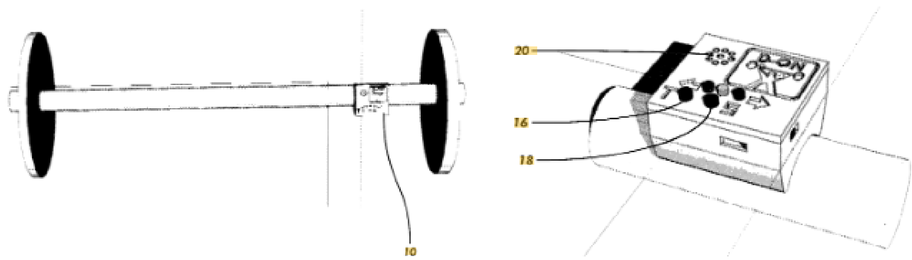


Figure 1: The barbell level indicator

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.

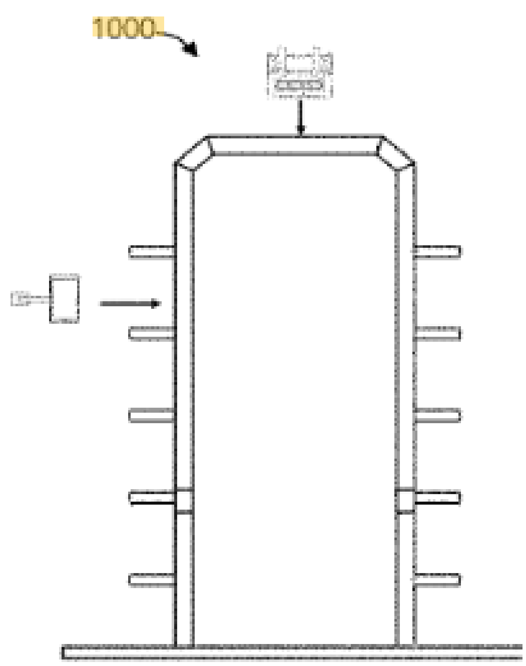


Figure 2: Multi-Functional weight rack and exercise monitoring system for tracking exercise movements

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.

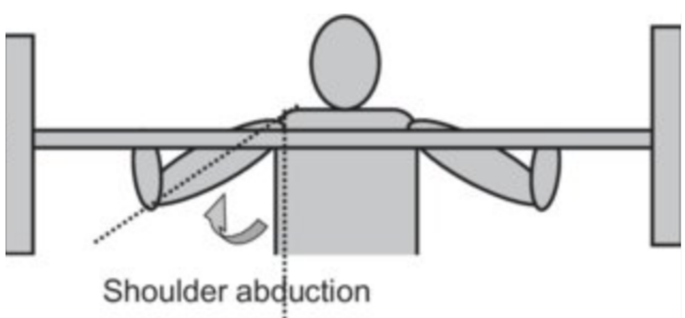


Figure 5: Shoulder abduction angle during the bench press

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.

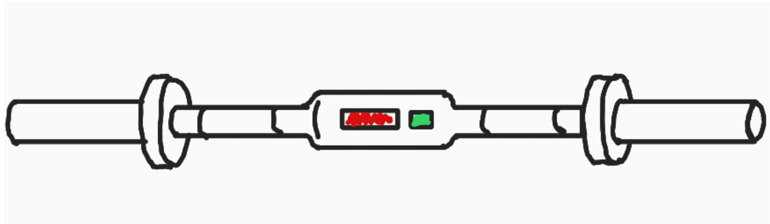


Figure 6: Drawing of Full Barbell Modification Design

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.

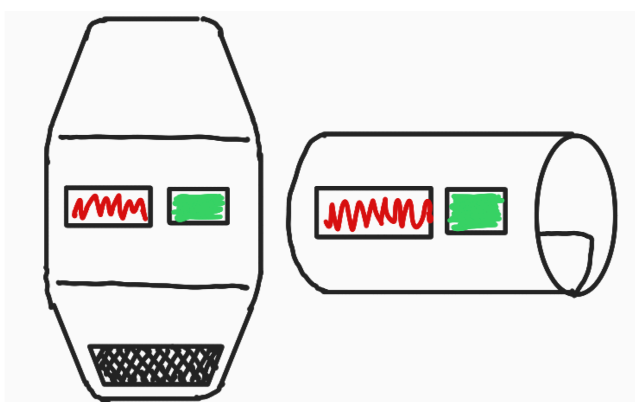


Figure 7: Drawing of potential barbell attachment designs.

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].

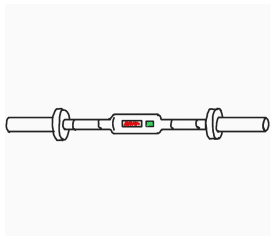
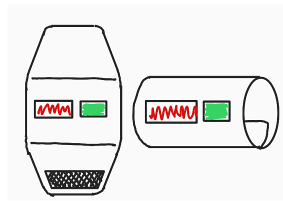
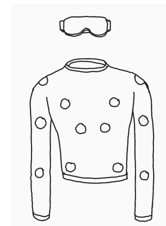
Technology Design 3: Inertial Mass Units

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]

Design Evaluations

Barbell Design Matrix

Table 1: Design Matrix for Barbell Design

Design	Full barbell		Barbell attachment		Full suit + AR	
						
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	

Barbell Design Criteria

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.

Barbell Design Matrix Evaluations

Full Barbell

The full barbell preliminary design scored a 68/100, resulting in the lowest scoring design out of the 3. While the device scored highly in the safety and ease of use categories (4/5) due to the familiarity of the design with lifters who have used a barbell before, it scored low in the remaining categories, specifically its cost and ease of fabrication. The manufacturing of this device is not something that the team is capable of conducting with the resources provided at the University of Wisconsin - Madison, and it would be very costly and difficult to fabricate it elsewhere.

Barbell Attachment

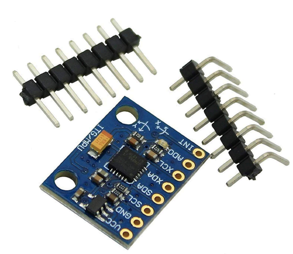
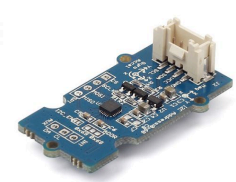
The barbell attachment idea scored the highest out of the 3 preliminary designs with a score of 83/100. This idea scored highly in all categories besides uniqueness. The wide range of opportunities that this idea provides is due to its versatility. The device simply attaches to any barbell and tracks its movement, and displays the results. This means it is very easy to use and provides no potential sources of harm since it does not impede the lift at all. It is also the most affordable and marketable out of all the preliminary designs.

Full Suit and Augmented Reality

The final preliminary design, the tracking suit with augmented reality, scored a 76/100. This design scored highly in uniqueness and marketability due to how different it is compared to the existing products currently available. This device also tracked the movement of the lifter, instead of the barbell, which has the ability to provide more useful information on the form during the lift. However, this idea requires the most amount of prior knowledge on how to use the device, and will be the most costly due to the need to use virtual reality.

Technology Design Matrix

Table 2: Design Matrix for Technology Method

Technology	Radar/Lidar/ Ultrasonic	Accelerometer	Inertial Measurement Unit (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	

Technology Design Matrix Criteria

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.

Radar/Lidar/Ultrasonic

The winner of the three technologies was the ultrasonic sensor with a score of 75/100. Because the ultrasonic sensor give a direct measurement of the distance between the barbell and the ground, it scored the highest in accuracy because the relevant data would require minimal adjusting/rounding. However, there is some concern with the reliability of the sensor because of the potential for the axial angle of the barbell (i.e. how the user's wrist is turned, affecting the direction of the ultrasonic sensor itself) causing larger-than-expected readings for the distance measurement. That being said, because of it's uniqueness is this application the ultrasonic sensor scored perfectly in the marketability category, which is largely responsible for its success with this specific design matrix, even with relatively low scores in the cost and ease-of-fabrication categories.

Accelerometers

Accelerometers were a close second to ultrasonic with a score of 72/100. As explained above, the accelerometer, and inertial measurement unit, for that matter, scored lower than the ultrasonic sensor because of the required algorithms needed to get the information required of the device. These two, however, scored higher in reliability because there is no concern about the wrist-angle of the user. The accelerometer specifically found success with the cost and ease-of-fabrication categories because of its relative simplicity to the other two technologies. The main reason the accelerometer doesn't beat out the ultrasonic sensor is because of its lackluster score in the marketability category. The reason for this detrimental score is because accelerometers are the industry standard for this type of equipment, and have quite literally already been used in a design by the client that did not gain any traction in the market.

Inertial Measurement Units

Lastly, the inertial measurement unit (IMU) came in last place for the technologies with a score of 67/100. This technology had similar shortcomings as the accelerometer as outlined in the previous section, mostly because the two have similar components. The IMU was largely outclassed by the accelerometer when it comes to ease of fabrication and cost categories because of its slightly more complex makeup, but it doesn't actually give too much relevant data to make up for it. The least weighted category of safety in the design matrix was that way because there is no major risks of electrocution or harm to the user from any of the three technologies.

Proposed Final Design

Figure 9: Drawing of proposed final design,

The proposed final design is a combination of the barbell attachment and ultrasonic sensor designs. It will have a center display and pad that contains a display with a way to indicate good form during the bench press. This will require a battery, microcontroller, wireless receiver, and solid connections that will not disconnect or short when repeatedly pressed with heavy weight of the barbell and the weights it holds. This display will have to be either small or flexible or both of the two in order to prevent discomfort with the display hitting the bencher's chest when benching. It will also have to be able to withstand the force on it when under compression from the user's chest.

There will also be two arrays of ultrasonic transceivers that will attach to the ends of the barbell. This will allow for the ultrasonic transceivers to be unimpeded and allow for balance for the user when benching. This array of ultrasonic transceivers will include between four and six transceivers in order to cover the full 360 degrees of the barbell within the range of the sensors. The transceivers will be used as it is a combination of an emitter and receiver in one small unit to decrease the volume of the overall unit. This will require a battery and a wireless transmitter to send the data collected to the center microcontroller for processing. This array will be able to calculate distance, velocity, acceleration, force, and angle of the bar. From this data it would be possible to eventually give more advanced recommendations to the user such as for them to increase weight, decrease weight, fix form, and or give recommendations for sets and reps with a given weight.

In the future it may be smart to upgrade to radar sensors instead of the ultrasonic sensors as they are much more reliable. However, due to the drastically more expensive cost of the radar sensors, it makes more sense to start with the cheaper alternatives in order to get the proof of concept working before upgrading the sensors to more reliable tracking.

Fabrication and Development

Materials

The team will need to order more radar systems for fabrication. This will most likely be in the form of ultrasonic sensors due to the inexpensiveness relative to radar. A gyroscope will also need to be obtained so that the radar systems can be properly oriented to the surrounding space.

Fabrication Process

The team plans to create a system of radars that can be attached to the barbell and track balance of the barbell to see if one side is ahead (closer to the ground) than the other side. This will start with adapting the code the team has made for one single ultrasonic sensor to track displacement to multiple ultrasonic sensors. There will also need to be fabrication for the gyroscope attachment for proper orientation for the ultrasonic sensor systems. There will need to be code fabricated to relate the gyroscope and ultrasonic sensors. Lastly, there will need to be a sleeve attachment that the ultrasonic sensors are attached to for a good fit to the barbell.

Testing

To ascertain whether or not the design is working as intended, relevant testing of the attachments is required. There are four important tests that must be carried out before the design can be seen as complete:

The first test concerns the transverse angle of the barbell. The angle value given by the sensors will be compared with a manually measured angle for the same position and compared against each other for a range of angles of the barbell. Percent error calculations will be compared against our design requirements to determine whether or not our design is effective in this regard.

The second test makes certain that our proposed final design can overcome the shortcomings of using the ultrasonic sensor to acquire data. Position values given by the sensors will be compared against one another at a range of known wrist angles. Percent error calculations will be compared against our design requirements to determine whether or not our design is effective in this regard.

The third test concerns the durability of the design. The prototype will have to undergo multiple strain tests, including: Being dropped at various heights, being dropped while attached to the barbell at various heights/weights. The screen will also be tested to ensure that it can withstand the impact on the chest of the user while bench pressing.

The fourth and final test verifies that each attachment can work in tandem with one another effectively and efficiently. This will be a qualitative assessment of the entire device during a lift to see whether or not it is effective in its purpose, easy to understand, and ergonomic to use/equip.

Results

The current prototype utilizes just a single ultrasonic sensor to calculate the distance to the ground of the barbell. It was able to track distance, velocity, acceleration, and force. It could also be assumed that it would be able to easily track the angle of the barbell given a second sensor utilizing the distance between and trigonometry. See the arduino code in the Appendix to see calculations. However, it is not the most reliable and is a bit slow at the moment due to the cheap sensor and limited range of movement of the current prototype.

Because the prototype is not finished, there has been no further testing of it at this time. It is expected that the barbell attachments will perform up to par with the design requirements (below 5% error) when upgraded to improved sensors. Furthermore, the components should work well in tandem with minimal latency and the axial rotation of the barbell shouldn't affect the distance measurement output when the full design is completed.

Discussion

Ethical Considerations

The main ethical consideration of this project is ease of use for the user. This design should be easily used by anyone who is able to complete a bench press. It should make the lift easier for them and not more difficult. This means it should be quickly set up and not impair the use at all. It should be able to improve the experience of both someone new to the gym and an olympic lifter.

A secondary ethical consideration that the team wants to take in is regarding the body type of the user. The main concern and difference between body types that needs to be considered would be the length of arms on an individual as this would impact the range at which the barbell is moving. If someone were to have longer arms there needs to be a high-end for the scale that our sensor system can pick up. Same will go for someone with shorter arms as that will be the lower end of the scale if distances that our sensor system can pick up.

Sources of Error

Potential sources of error are that during usage on a barbell, the ultrasonic sensor may temporarily pick up on an individual walking by, or a water bottle on the floor. This can momentarily relay information about the levelness or speed of the barbell that is inaccurate. This error needs to be minimized so the user of the device does not have to compensate for false information. Also the user could be distracted by the levelness markers acting up during the lift as well.

Conclusion

Barbell bench press injuries are one of the leading causes for weightlifting injuries for lifters at all levels. The team's client Mr. Robert Gold and the team believe that it is important to fabricate a device that will provide feedback on the user's lift to help prevent weightlifting injuries. The team will design a device that uses radar to measure the movement of the barbell and provide real time feedback to the lifter during the lift. Information such as the levelness of the bar and the number of reps the lifter has performed will be displayed during the lift for them.

The next steps for the team heading forward is to order better ultrasonic sensors or radar to continue to prototype and begin testing. The team must construct a proof of concept for a device that is attachable to a barbell that will track the motion of it while displaying real time feedback to the user.

References

[1] “Sports and exercise among Americans : The Economics Daily: U.S. Bureau of Labor Statistics.” Accessed: Feb. 08, 2024. [Online]. Available: https://www.bls.gov/opub/ted/2016/sports-and-exercise-among-americans.htm

[2] K. Golshani, M. E. Cinque, P. O’Halloran, K. Softness, L. Keeling, and J. R. Macdonell, “Upper extremity weightlifting injuries: Diagnosis and management,” J Orthop, vol. 15, no. 1, pp. 24–27, Mar. 2018, doi: 10.1016/j.jor.2017.11.005.

[3] V. Bengtsson, L. Berglund, and U. Aasa, “Narrative review of injuries in powerlifting with special reference to their association to the squat, bench press and deadlift,” *BMJ Open Sport & Exercise Medicine*, vol. 4, no. 1, p. e000382, Jul. 2018, doi: https://doi.org/10.1136/bmjsem-2018-000382.

[4] “Strength training: Get stronger, leaner, healthier,” Mayo Clinic, https://www.mayoclinic.org/healthy-lifestyle/fitness/in-depth/strength-training/art-20046670 (accessed Mar. 6, 2024).

[5] M. M. Ruiz, “Barbell Level Indicator,” Apr. 18, 2017

[6] J. Rothman and N. Rodman, “Multi-functional weight rack and exercise monitoring system for tracking exercise movements ,” Aug. 11, 2020

[7] Bar sensei, http://files.assess2perform.com/barsensei.html (accessed Feb. 28, 2024).

[8] C. M. Green and P. Comfort, “The Affect of Grip Width on Bench Press Performance and Risk of Injury,” *Strength and Conditioning Journal*, vol. 29, no. 5, pp. 10–14, Oct. 2007.

[9] W.Henniger,“Barbell,”D843,524.Mar.19,2019.Available: https://patents.google.com/patent/USRE49513E1/en?q=(barbell)&oq=barbell

[10] “The rogue bar 2.0,” Rogue Fitness, https://www.roguefitness.com/the-rogue-bar-2-0-blbr (accessed Feb. 1, 2024).

[11] Admin, “How do radar sensors work?,” ICON Process Controls, https://iconprocon.com/blog-post/how-do-radar-tank-level-sensors-work/#:~:text=1%3A%20Puls

e%20radar%20sensors%20emit,waves%2C%20rather%20than%20a%20pulse. (accessed Mar. 6, 2024).

[12] "What is LIDAR? Learn How Lidar Works," Velodyne Lidar, https://velodynelidar.com/what-is-lidar/#:~:text=A%20typical%20lidar%20sensor%20emits%20pulsed%20light%20waves%20from%20a,calculate%20the%20distance%20it%20traveled. (accessed Mar. 6, 2024).

[13] "What is ultrasonic sensor: Working Principle & Applications," Robocraze, https://robocraze.com/blogs/post/what-is-ultrasonic-sensor#:~:text=An%20ultrasonic%20sensor%20is%20a,the%20sound%20waves%20to%20return. (accessed Mar. 6, 2024).

[14] O. Engineering, "How to measure acceleration?," https://www.omega.com/en-us/, https://www.omega.com/en-us/resources/accelerometers#:~:text=An%20accelerometer%20is%20a%20device,the%20force%20exerted%20upon%20it. (accessed Mar. 6, 2024).

[15] Z. Strout, "How does an IMU work?," SageMotion, https://www.sagemotion.com/blog/how-does-an-imu-work (accessed Mar. 6, 2024).

Appendix

A. Product Design Specifications

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.

References

[1] “Sports and exercise among Americans : The Economics Daily: U.S. Bureau of Labor Statistics.” Accessed: Feb. 08, 2024. [Online]. Available: https://www.bls.gov/opub/ted/2016/sports-and-exercise-among-americans.htm

[2] K. Golshani, M. E. Cinque, P. O’Halloran, K. Softness, L. Keeling, and J. R. Macdonell, “Upper extremity weightlifting injuries: Diagnosis and management,” J Orthop, vol. 15, no. 1, pp. 24–27, Mar. 2018, doi: 10.1016/j.jor.2017.11.005.

[3] P Thompson, T Balgemann, M Tyler. *Introduction to PDS, FDA, and Standards & Codes.* pp 23-31.

[4] “What kills Sensor Accuracy & when to calibrate: APG sensors,” APG, Inc., https://www.apgsensors.com/about-us/blog/what-kills-sensor-accuracy-when-to-calibrate/#:~:text=The%20simple%20answer,is%20once%20per%20year. (accessed Feb. 7, 2024).

[5] “HUMAN PERFORMANCE CAPABILITIES.” Accessed: Feb. 08, 2024. [Online]. Available: https://msis.jsc.nasa.gov/sections/section04.htm

[6] W. Henniger, “Barbell,” D843,524. Mar. 19, 2019. Available: https://patents.google.com /patent/USRE49513E1/en?q=(barbell)&oq=barbell

[7] J. Rothman and N. Rodman, “Multi-functional weight rack and exercise monitoring system for tracking exercise movements ,” Aug. 11, 2020

[8] “What is a class 2 medical device in the US?,” Greenlight Guru, https://www.greenlight.guru/blog/class-2-medical-device#:~:text=A%20class%20II%20medical %20device,%2C%20and%20post%2Dmarket%20surveillance. (accessed Feb. 8, 2024).

[9] M. M. Ruiz, “Barbell Level Indicator,” Apr. 18, 2017

B. Arduino Code

```
int trigPin = 11;     // Trigger
int echoPin = 12;     // Echo
int timeDelay = 50; // Time delay between each measurement
double m, inches;
float mass;


void setup() {
  //Serial Port begin
  Serial.begin (9600);
  //Define inputs and outputs
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin, INPUT);
  Serial.print("Enter Mass of lift in lbs: ");
  while (Serial.available() == 0){
  }
  mass = Serial.parseFloat() / 2.205;
}


void loop() {
  // Start tracking time for velocity and acceleration measurements.
  long double t1 = micros();
  // Trigger the sensor to take a measurement.
  triggerSensor();
  // Set echoPin as an input
  pinMode(echoPin, INPUT);

  // Convert the time into a distance
   double meters1 = readDistanceMeters(echoPin);      // Divide by 29.1 or
multiply by 0.0343
    double inches1 = readDistanceInches(echoPin);     // Divide by 74 or
multiply by 0.0135
   // Delay the measurement by a set timeDelay to allow for distance and
time to be traveled.
  delay(50);
  // Trigger the sensor to run again.
  triggerSensor();
  //Set echoPin as an input.
```

```
  pinMode(echoPin, INPUT);

  // Convert the time into a distance again.
  double meters2 = readDistanceMeters(echoPin);
  double inches2 = readDistanceInches(echoPin);
  // Take a second time to calculate the velocity
  long double t2 = micros();
   // Find the time by finding the change in time and dividing by 1000 to
get to seconds.
  double time = (t2 -t1) /1000000.0;
  //Find the change in distnces for meters and inches.
  double meters = meters2-meters1;
  inches = inches2 - inches1;
  //Find the first velocities in both meters and inches.
  double vel_meters1 = meters / time;
  double vel_inch1 = inches / time;

  // Start a third time counter.
  long double t3 = micros();
  // Trigger the sensor to run for the third time
  triggerSensor();

  // Set echoPin as an input.
  pinMode(echoPin, INPUT);

  // Convert the time into a distance in meters and inches.
  double meters3 = readDistanceMeters(echoPin);
  double inches3 = readDistanceInches(echoPin);
   // Delay the time between the initial and secondary pulse to allow time
to travel.
  delay(50);
  // Trigger the sensor a fourth time.
  triggerSensor();

  // Set the echoPin as an input.
  pinMode(echoPin, INPUT);

  // Convert the time into a distance in meters and inches
  double meters4 = readDistanceMeters(echoPin);
  double inches4 = readDistanceInches(echoPin);
```

```
  // Take a fourth time for acceleration measurements.
  long double t4 = micros();
  // Find the change in time and divide by 1000 to get to seconds.
  double times = (t4 -t3) /1000000.0;

  // Find the change in distance in meters and inches.
  double meterss = meters4-meters3;
  double inchess = inches4 - inches3;
  // Find the second velocity in meters and inches.
  double vel_meters2 = meterss / times;
  double vel_inch2 = inchess / times;
  // Find the time from the start of the measurements to the end.
  double time2 = (t4 - t1) / 1000000.0;
   // Calculate the acceleration fromt he change in velocity over the
change in time.
  double accelerationInches = (vel_inch2 -vel_inch1) / (time2);
  double accelerationMeters = (vel_meters2 - vel_meters1) / time2;
  // Calculate the force of the user
  double force = accelerationMeters * mass;
  Serial.print("Distance(m)(): ");
  Serial.print(meters4);
  Serial.println();
  Serial.print("Velocity(m/s): ");
  Serial.print(vel_meters2);
  Serial.println();
  Serial.print("Acceleration(m/s^2): ");
  Serial.print(accelerationMeters);
  Serial.println();
  Serial.print("Force(N): ");
  Serial.print(force);
  Serial.println();

  delay(10);
}
void triggerSensor() {
  digitalWrite(trigPin, LOW);
  delayMicroseconds(5);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);
```

```
}
double readDistanceInches(int echoPin) {
  return pulseIn(echoPin, HIGH) / 74.0 / 2.0;
}
double readDistanceMeters(int echoPin) {
  return pulseIn(echoPin, HIGH) / 2910.0 / 2.0;
}
```