Design of an Improved Football Shoulder Brace

A Major Qualifying Project Report
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Abstract

Shoulder injuries make up 12-14% of total football injuries, yet many players decline wearing braces. Shoulder braces available for football players attempt to reduce injuries and enable faster return to play after shoulder injury, but are limited by critical factors. Our team modelled and manufactured a shoulder brace that limits vulnerable ranges of motion by 10-25 degrees, provides 32N of compression to increase dislocation force, absorbs impact force to the deltoid, and is constructed from a perforated neoprene material to maximize breathability. Custom force sensors detected impact, were inaccurate on curved, soft surfaces, but measured at low forces. Impact forces felt by the dummy were measured with custom written Arduino code and an accelerometer with a sampling rate of 1.3 kHz.

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1. Introduction

Football is one of the most popular sports played in America, with over 1 million high school athletes participating, 130 college FBS Division 1 teams, and 32 NFL teams (Shankar, 2007). Participating in football puts an athlete at an elevated risk of injury. With an estimated 99.1% injury chance after playing 4-years of football, there is an apparent need for injury prevention devices and protection for joints (Canal et al, 1981). One study found 12-14% of injuries sustained by high school and collegiate football players are of the shoulder joint and ligaments of the glenohumeral joint. With little evolution of equipment through the recent decades other than that of the helmet, shoulder joint injuries continue to plague football athletes, taking them out of games and leaving them with chronic joint instability. Currently, there are shoulder braces on the market that attempt to limit shoulder mobility and reinforce the joint, but do little to accommodate player comfort, realistic game use, and wear and tear of the brace.

The goal of this project was to design, prototype, and test a better shoulder brace for offensive linemen. By creating a better shoulder brace, football players may be more receptive to wearing one, and therefore have a reduced chance of injury to the shoulder and return to play faster after an injury thereby increasing on-field play time. With an improved shoulder brace, more football players with a history of shoulder instability will opt to wear it, as well as those that want a decreased chance of shoulder injury in the first place. Also, an athlete wearing a sufficient brace would reduce their downtime off the field, due to shoulder injury, by weeks. About 64% of NCAA athletes who have injured their shoulder will experience chronic shoulder instability, that of which can be greatly reduced if wearing a suitable brace (Dickens et al, 2014).

2. Literature Review

2.1 Injury Prevalence in American Football

The game of American football is violent and aggressive in nature, often leading to players getting injured. Per the National Football League, primetime games played on Saturday, Sunday and Monday averaged an injury rate of 6.7 injuries per game from 2014-2017, while Thursday night games averaged 5.7 injuries per game as shown in Figure 1 (Stluka, n.d).

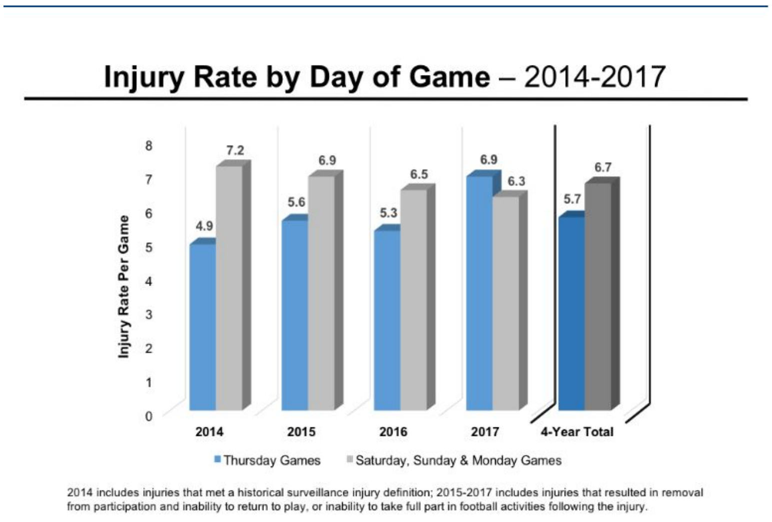


Fig. 1: *NFL injury rate by day of game 2014-2017 (Stluka, n.d)*

As Shankar et al states, “Football is also a leading cause of sports-related injuries, with an injury rate almost twice that of basketball…”(Shankar, 2007). Sustaining an injury while playing football is not only limited to players in the NFL. With over 1 million high school football players suiting up each year, studies suggest there are between 300,000 and 1.2 million high school athletes injured annually during the high school football season (Shankar, 2007 ; Feeley, 2008).

Serious injuries that come to mind are those affecting the lower extremities; knees, ankles, and feet. Joints are particularly vulnerable given their limited range of motion and plethora of interconnecting muscles, tendons, ligaments, and bones. Some of the most common injuries that often get overlooked are those affecting the shoulder and its stability. Shoulder injuries are the fourth most common musculoskeletal injury, falling behind injuries to the hand, knee, and ankle (Kaplan, 2005). This was exemplified during the 2004 NFL Combine, where 336 of the nation's top collegiate football players were evaluated by various NFL medical staff. These evaluations would confirm the prevalence of shoulder injury and shoulder instability affecting some of the nation's top athletes. Of the 336 prospects, 50% had a history of shoulder injuries. 226 shoulder injuries were reported, equating to 1.3 incidences of shoulder injuries per player injured. Surgically, 56 players (34%) had a total of 73 surgeries. Of these shoulder injuries, 41% were acromioclavicular separation (the joint connecting the clavicle to the scapula), 20% anterior instability (labral tears near the front of the shoulder), 12% rotator cuff injury, 4% clavicle fracture, and 4% posterior instability (labral tears near the back of the shoulder). The injuries that were surgically repaired the most were labral instability, AC joint separations and rotator cuff damage (Kaplan, 2005). Although this study only looked at collegiate athletes, shoulder injury and instability is one of the leading injuries reported at the high school level as well. Of 1,877 injuries reported from high school football players near Birmingham, Alabama, 13.3% consisted of shoulder injuries; the second highest injury reported beside the knee (Culpepper, 1983). The amount of injuries that can occur to the upper extremities should not be overlooked, as they take up a huge percentage of total injuries and may occur in a variety of ways.

2.2 Shoulder Anatomy

A closer look at the anatomical structure of the shoulder joint itself reveals just how intricate and delicate the joint is. It is made up of three bones: the scapula, clavicle, and humerus. The two joints that link these bones together are the acromioclavicular joint (AC Joint) connecting the clavicle and scapula, and the glenohumeral joint connecting the scapula and humerus. The glenohumeral joint, or shoulder ball-and-socket is allowed to have a wide range of motion due to its generally shallow socket (Sheehan et al, 2013). This wide range of motion can often put our shallow glenohumeral joint, and the numerous ligaments and muscles that secure the joint, at risk. Key components that affect shoulder stability, pain, and comfort include the labrum, rotator cuff, and AC joint ligaments. Nearly 50% of all dislocations reported are of the shoulder (Sheehan et al, 2013), and a large number of these dislocations can be attributed to contact sport athletes. These dislocations most often severely impact labrum and rotator cuff health, and in many cases lead to tears in both.

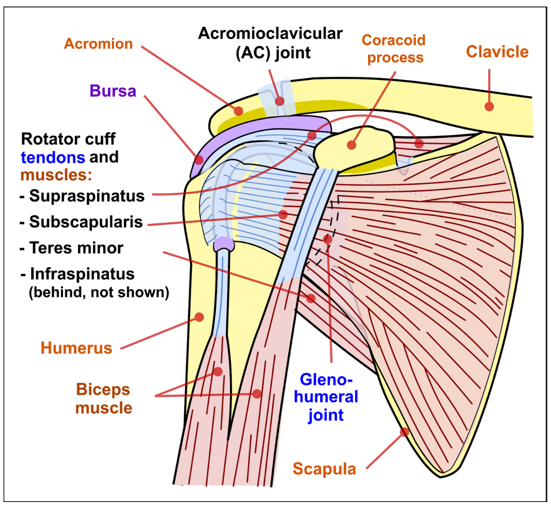


Fig. 2: *Front view of the shoulder*

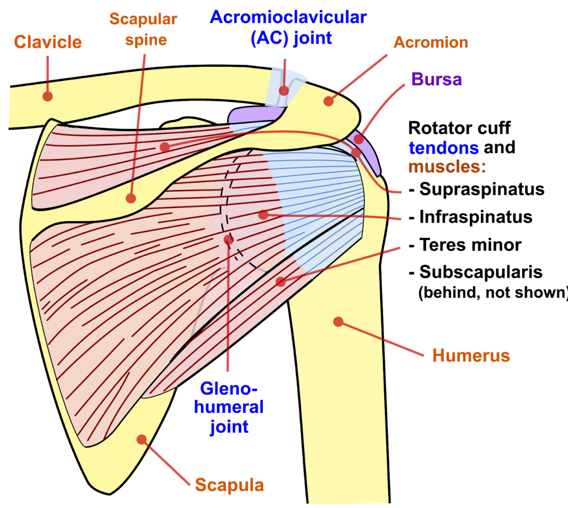


Fig. 3: *Back view of the shoulder*

2.2.1 Labrum Anatomy

The labrum is a cup-shaped rim of fibrous cartilage tissue that lines and reinforces the ball-and-socket, and surrounding tendons and muscles of the glenohumeral joint (Sheehan, 2013). The labrum is composed of a superficial mesh, a dense circumferential braided core, and a loosely packed peri-core zone of fibrous cartilage (Hill et al, 2008). The labrum anchors to the glenoid bone through anchoring fibers present at the osseous interface between bone and labrum cartilage (Hill et al, 2008). It contributes to shoulder stability and, when torn, can lead to partial or complete shoulder dislocations and chronic instability if not treated operatively (Fealy, 2010). Tears to the labrum occur during traumatic dislocations, where the labrum cartilage is torn or frayed, and the bony layer connecting the labrum to glenoid bone is fractured (Sheehan et al, 2013). Further, once a labrum is torn, its ability to do its job in keeping the head of the humerus in the socket of the shoulder is greatly diminished (Fealy, 2010). There are two types of labrum tears common to athletes. A SLAP tear is when the labrum is torn where the bicep connects to the shoulder. Bankart tears are characterized as tears to the labrum in the anterior and posterior positions. Both tears are inherently disastrous for shoulder stability and longevity. (Fealy, 2010). After a traumatic injury (tear) to the labrum it is hard for the body to deliver nutrients and regrowth factors to it, as the labrum does not receive extensive blood flow post-injury (Sheehan et al, 2013).

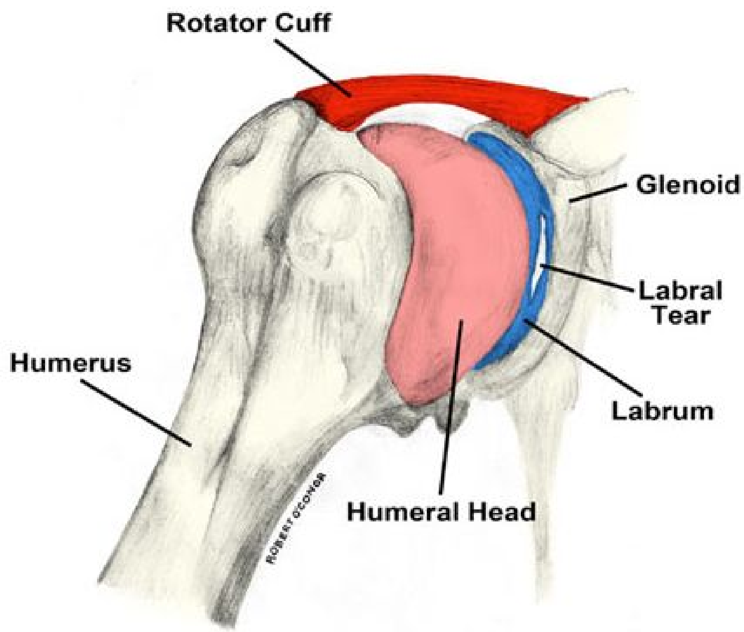


Fig. 4: *Glenohumeral joint and subsequent labrum positions* (Fealy, 2010)

2.2.2 Rotator Cuff Anatomy

Comprising four different muscles, the rotator cuff (RC) contributes to the integrity, mobility, and security of the glenohumeral joint (Bellendir, n.d.: Inverarity, 2019; Felson, 2019). The rotator cuff holds the head of the humerus in the shoulder socket, and helps raise and rotate the arm. The four muscles that make up the rotator cuff are the supraspinatus, subscapularis, infraspinatus, and teres minor (Inverarity, 2019). The supraspinatus holds the humerus in place, keeps the upper arm stable, and helps lift the arm. The subscapularis holds the upper arm to the shoulder blade and helps with vertical and rotational arm movement. The infraspinatus contributes the most to the rotation and extension of the shoulder, while the teres minor is the smallest and assists in the rotation of the arm away from the body (Inverarity, 2019 & Felson, 2019). Much like the labrum, after injuring the RC muscles, it is difficult to return to 100% because of poor blood flow to the shoulder joint. RC tears and instability occur after periods of chronic impingements or extreme stresses and jolting experienced in contact sports like football (Bellendir, n.d.).

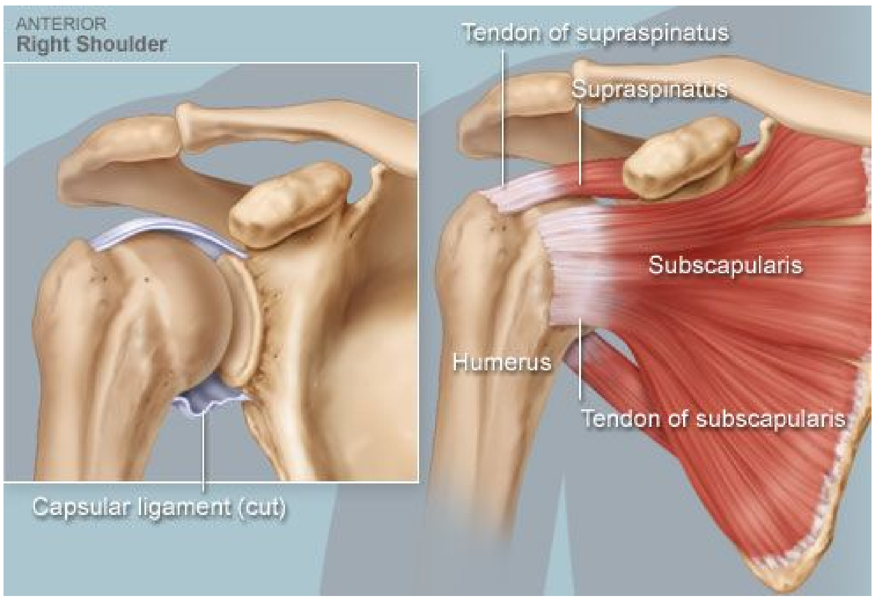


Fig. 5: *Anatomy of the rotator cuff* (Fealy, 2010)

2.2.3 AC Joint Anatomy

Connecting the clavicle and scapula, the acromioclavicular joint (AC joint) allows additional range of motion to the scapula, assists in arm movements such as shoulder abduction and flexion, and enables the transmission of forces from the upper arm to the rest of the skeleton. The AC joint is stabilized by three main ligaments. The acromioclavicular ligament has superior, inferior, anterior, and posterior components, and mainly serves to provide horizontal stability (Wong, 2018). The coracoclavicular ligament is sited on the posteromedial and anterolateral region of the undersurface of the distal clavicle and provides vertical stability. The coracoacromial ligament is a strong triangular band that connects the coracoid process to the acromion and also provides vertical stability (Wong, 2018).

2.3 Shoulder Vulnerability

Shoulder instability is most common in the anterior and posterior positions of the glenohumeral head within the shoulder socket. Injury to the anterior and posterior locations of the joint happen due to dislocations and subluxations of the joint itself. As stated by Sheehan et al, “Acute traumatic glenohumeral dislocation is one of the most commonly encountered shoulder injuries...Approximately 85-95% of initial shoulder dislocations are anterior and most commonly seen in patients 10-20 years old after a traumatic injury” (2013). Kaplan’s 2004 NFL combine study found 76% of surgical procedures previously performed on collegiate football players were to correct anterior instability (Kaplan, 2005). Where anterior tears occur when the humeral head in the shoulder socket gets pulled abruptly forward in the joint, posterior tears and instability often occur from falls or absorbing force in front of the body thereby jolting the humeral head back. Figures 6 and 7 exhibit posterior translation of the humeral head when abrupt forces are absorbed by the arm and shoulder in front of the body. Anterior injuries of the shoulder occur in vulnerable positions of abduction and external rotation that position the joint in the anterior direction. Abduction is the act of raising the arm up from the side of the body, and external rotation pushes the arm back and positions the glenohumeral head forward. (Andrews, Wilk, & Reinold, 2008). The more that a shoulder is abducted, the fewer soft tissue stabilizers are functionally contributing to anterior stability (Weise et al, 2004), and the easier it becomes to dislocate the shoulder anteriorly from sudden forces that translate the humeral

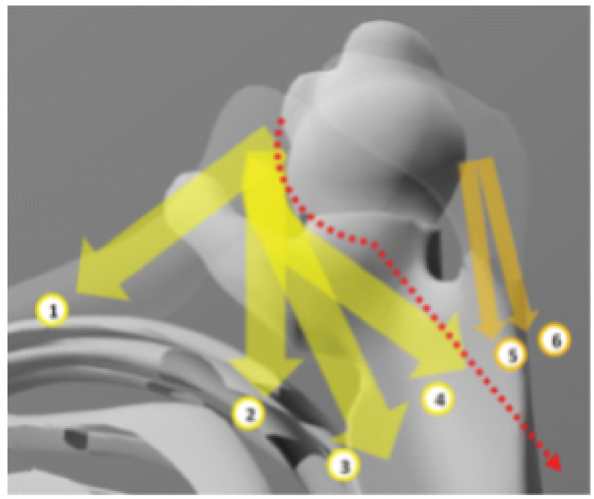


Fig. 6: *Posterior translation vectors of the humeral head (Sheehan et al, 2013)*

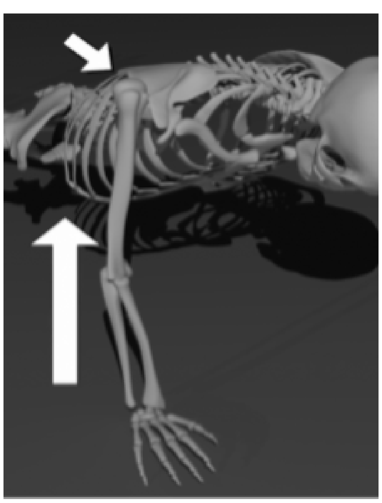


Fig. 7: *Visual representation of falling on an outstretched hand (Sheehan et al, 2013)*

head to the front (anterior) of the socket. The joint is in its most vulnerable position for anterior translation when the arm is abducted 90 degrees from the side of the body because stability relies solely on the inferior glenohumeral joint at this position (Weise et al, 2004). One study conducted on cadaver upper extremities found that when constant forces are applied to the shoulder attempting to dislocate it, reaction forces within the joint reach a maximum at 90 degrees abduction and decrease considerably when the arm is lowered, showing just how vulnerable the shoulder is in this position (Apreleva, 2000). Shoulder dislocations and subluxations anteriorly and posteriorly can break, tear, stretch, and disrupt glenohumeral ligaments, cartilage and bones leading to further instability and injury. Weise further states, "The most common injury mechanism of acute anterior glenohumeral dislocations is excessive indirect force involving abduction, horizontal abduction, and external rotation, as often occurs during arm tackling in football."(2004). The arm and shoulder positioning are often compromised during contact with another player or the playing surface. 67.7% of all injuries occur during contact with another player, and 14.9 % occur during contact with the playing surface (Shankar, 2007).

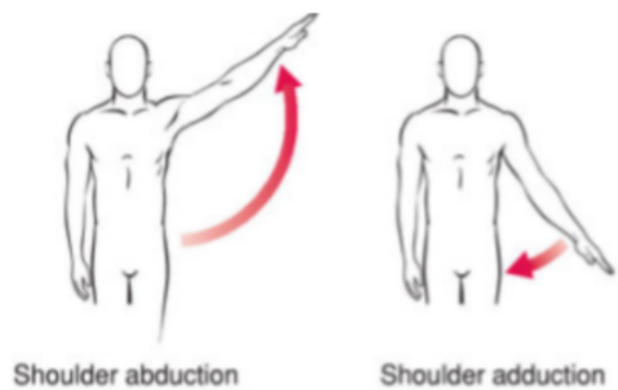


Fig. 8: *Demonstration of abduction and adduction shoulder movement (Chloe, 2016)*

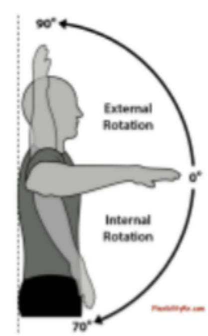


Fig. 9: Demonstration of internal and external shoulder rotation (Cula, n.d.)

Much like labrum injuries, rotator cuff injuries that occur in football are usually caused by awkwardly falling on an outstretched arm, or large amounts of forces applied through the motion of pulling the arm or pushing it back toward the body (Miniato, 2019). With this in mind, the use of a shoulder brace through resisting vulnerable shoulder positioning and limiting humeral translation from abrupt forces is a common way of combating instability, rotator cuff injuries, and labrum injuries while playing American football (Baker et al, 2016).

Impact to the side, front, and rear deltoid can lead to displacement of the AC joint and lead to shoulder separations. AC joint injuries and shoulder separations are common to football players due to hits and tackles players receive to the side of their body, and at times need to be surgically repaired after injury (Kaplan, 2005). By padding the areas around the deltoid and upper arm that receive impact from helmets and other players, shoulder separations can be prevented (Cedars Sinai, 2019). Injuries to the AC joint and shoulder separations cause the shoulder blade and collarbone to drift away from the body causing pain and discomfort (Cedars Sinai, 2019).

A study on 45 healthy cadaver shoulders from ages 17 to 35, found that the force needed to dislocate the glenohumeral joint in the anterior position ranged from 588N to 1100N (Symeonides, 1972). A mouthpiece that recorded data on the G-force linemen experience averaged about 10 units of G-force felt in each hit about 62 times a game per player. This amount of force on a person could amount to a car crash impacting a wall at 30 mph (Farrell, 2017). A similar study on the displacement force of reverse shoulder arthroplasty implants found that the Delta SC implant (top performer) dislocated at approximately 525 N. The test was performed with 155 N compressive force on the shoulder; the typical value of unrestricted shoulder force produced by intact muscles and ligaments (Gutiérrez, Keller, Levy, & William E. Lee, 2008). At the low end of a healthy shoulder, 525 N of force is enough to cause dislocation. A study done by Virginia Tech-Wake Forest's Center for Injury Biomechanics, found that football players can generate 568 N to 806 N of force on impact. This was found by measuring the forces generated to the front of a football helmet using varying realistic velocities of moving football players (Rowson, McNeely, & Duma, 2007). Force is dictated by the rate of change of momentum ($F=dp/dt$), which explains how a football player receives so much impact force per game (Halliday, Resnick, & Walker, 2013). For instance Saquon Barkley, running back for the New York Giants ran a 4.40 second 40-yard dash at the NFL Football Combine at 234lbs (NFL, 2020). Using these numbers and assuming Saquon Barkley covers approximately 10 yards in 1.1 seconds, the force needed to completely stop forward movement of Barkley running at a full sprint head on equates to 8,823.5N. This number was calculated from the set of equations below (Halliday, Resnick, & Walker, 2013). The resulting high forces are results of the duration of impact of football hits being around 0.1 seconds (Schwarz, 2009). This abrupt change of momentum and the consequently high forces can greatly exceed the forces needed to dislocate and damage the shoulder. As Halliday, Resnick, & Walker showed,

$$F = \frac{impulse}{\Delta t}$$

$$\Delta P = m(\Delta v)$$

$$\Delta P = impulse$$

$$impulse = F\Delta t = m\Delta v$$

$$F = \frac{m\Delta v}{\Delta t}$$

$$m = 234lbs = 106.141 \text{ kg}$$

$$\frac{40yrds}{40s} \times \frac{1m}{1.09361yrds} = 8.313m/s = \Delta v$$

$$\Delta t = 0.1s$$

$$F = \frac{106.141kg(8.313m/s)}{0.1s} = 8,823.5N$$

$$impulse = 8,823.5N(0.1s) = 882.35kg \cdot m/s$$

The stability of a shoulder is determined primarily by the compressive forces generated by the muscles (Gutiérrez, Keller, Levy, & William E. Lee, 2008). With a fully torn rotator cuff and labrum (0 N of compressive force), the shoulder dislocates with applied forces of 138 N to 201 N (Clouthier et al, 2011). A realistic shoulder implant shows that 66 N, 110 N, 155 N (normal muscular force), and 200 N of compressive force resulted in approximate displacement forces of 250 N, 400 N, 525 N, and 625 N respectively (Gutiérrez, Keller, Levy, & William E. Lee, 2008). Therefore, with an additional 45 N of compressive force on the glenohumeral joint, the lesser chance that the shoulder has of dislocating.

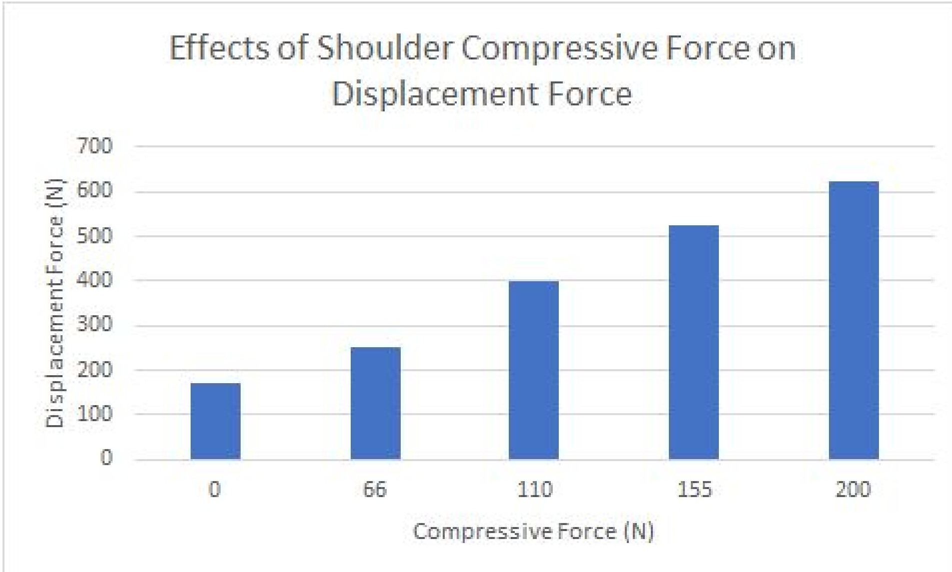
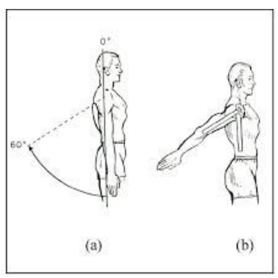
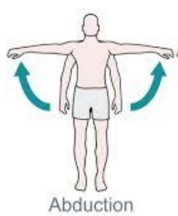
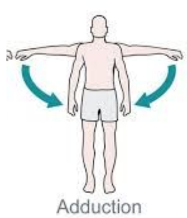
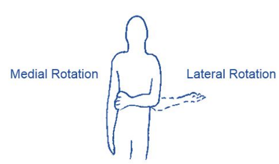


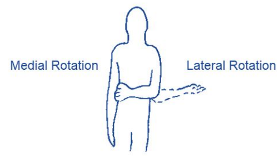
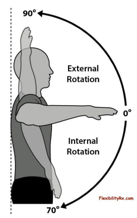
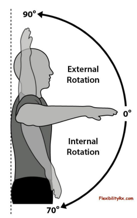
Fig. 10*: Effects of shoulder compressive force on displacement force*

2.4 Range of Motion

There are ten types of measurable motion of the shoulder. Table 1 shows the maximum ranges of motion achievable by the average healthy shoulder. The values found in Table 1 were stated by the Washington State Department of Health & Social Services.

Table 1: Shoulder Ranges Of Motion

Design Requirement	**Diagram (When Applicable)**	**Healthy Shoulder ROM (Washington State DoH & DoSS)**
Flexion		180 Degrees
Extension		Shoulder rotates 45-60 degrees
Abduction		Shoulder rotates 150 degrees
Adduction		Shoulder rotates 30-50 degrees
Medial Rotation		Shoulder rotates 70-90 degrees

Lateral Rotation		Shoulder rotates 90 degrees
External Rotation		Shoulder rotates 90 degrees
Internal Rotation		Shoulder rotates 60-70 degrees

2.5 The Use of Braces

With shoulder injuries being so prevalent in football, the use of shoulder braces can keep players on the field by preventing injury or improving the stability of a previously injured shoulder. A study of 45 football players that all play offensive linemen at the collegiate level (90 shoulders) between 2007-2015 shows a shoulder brace's effectiveness in injury prevention (Baker, Tjong, Dunne, & Lindley, 2016). During this sample time, 145 total seasons of football were played amongst the 45 players and data was taken on the number of shoulder injuries that occurred and whether or not a shoulder brace was worn. Of those 145 seasons, a total of 87 were completed by players not wearing a brace and the remaining 58 seasons by players wearing a brace. From this study, only 9 athletes lost time in practices and games while wearing a brace, due to injury and rehab, compared to 37 that lost time while not wearing one (Baker, Tjong & Dunne, 2016). The 45 players totalled 1000 snaps of football. When not wearing a brace, 1.90

per 1000 snaps resulted in a shoulder injury, while only 0.71 per 1000 snaps resulted in injury with a brace (Baker, Tjong & Dunne, 2016). This statistic proves that a shoulder brace would be useful in preventing injuries on the football field.

In addition to preventing injury, a shoulder brace can improve stability after an injury has occurred. Individuals with a history of shoulder instability aren't as aware of joint positioning and may be more susceptible to vulnerable positions. A study comparing shoulder braces and joint-repositioning of forty subjects found that active joint-reposition sense in subjects with unstable shoulders was improved by wearing a shoulder brace. The forty subjects consisted of 22 men and 18 women. Of the forty, twenty were Division 1 athletes with a history of shoulder instability. When wearing the shoulder brace, the group of subjects with "unstable shoulders" showed improvement in actively repositioning their shoulder joints when externally rotating 10 degrees from full external rotation. This means that when extending their arm out 80 degrees from their body, the subjects that were wearing a brace had better positioned shoulder joints. Additionally, the subjects with "unstable shoulders" exhibited a limitation to the maximal external rotation when wearing the shoulder brace (Chu, 2002). This limitation can help prevent the shoulder from rotating past the point of injury. This makes a case for why an athlete with previous shoulder instability should consider wearing a brace as it not only prevents vulnerable shoulder positions but raises levels of joint awareness for the athlete.

2.6 Current Braces

Many developments in shoulder brace technology have been made since the 1980's. With no industry standard for testing, new designs are frequent with a few leading the pack in popularity. As determined by a survey to the WPI football team, the most commonly used braces are the Sully Sports Brace, Donjoy Shoulder Stabilizer, and EVS Sports SB03. Each design has its own benefits and drawbacks. The developments in shoulder brace technology, difference in designs, and their pros and cons are described in Table 2 below. The data on each shoulder brace was obtained from the manufacturer and opinions gathered from the WPI Football Team survey.

Table 2: Current Shoulder Braces

Current Shoulder Braces	Pros	Cons	Material And Weight	# of Straps	Price
 Sully Shoulder Brace	Custom Strapping One piece design	Velcro fastening wears away Low breathability	"Perforated, breathable, rubber-like neoprene" (Donjoy website) 1.5-2lbs	1-4	$140
 Donjoy Shoulder Stabilizer	Adjustable Strapping User controlled ROM Provide abduction, and external rotation control Support for AC separations	Bulky strapping mechanism Straps interfere with jersey	Latex-free black polyester Lycra material 1.6lbs	6	$156-210
EVS Sports SB03 	Under or over the shirt wear Lightweight and breathable Straps allow for user controlled ROM	Possible allergic reaction to neoprene Need more than one person to put on Comfort (opinionated by wearers)	Vented neoprene 14-15 Ounces	6	$45-50

 Denison & Duke Wyre Harness	Max Shoulder Abduction below 90 degrees.(Weise et al, 2004)	Lacing system stretches and loosens over time of use Need multiple people to put on Canvas does little in terms of ventilation	Canvas Leather Laces	0 straps, 5 laces	N/A

Most linemen agree that braces are an uncomfortable part of playing the game. Ross Pierschbacher said during an interview done on various college football linemen, "They are itchy. They are awkward. They are cumbersome and largely unattractive and, when used over a long period of time, can develop what has been generously described as a ' disgusting crust'" (Borden, 2017). Where Pierschbacher was describing knee braces, this is still a problem with most braces, unless they are designed around comfort and effectiveness.

2.6.1 Fitting with Equipment

The two pieces of football equipment that are in contact with a shoulder brace are the jersey and shoulder pads. A football jersey is made to fit tight to the torso with very short sleeves that rest over the shoulder pads. Thus, football jerseys are susceptible to interference with shoulder brace straps. Shoulder pads are worn under the jersey and consist of a cushioned interior and hard shell exterior to absorb impact to the shoulders and upper torso. Shoulder pads come in a range of universal sizes and are often provided when playing for a football team. Shoulder pads are checked by equipment staff to confirm that they fit the width of a persons' shoulders. A product specialist for Sports Unlimited stated "it's incredibly important to find the right gear for your size...Improperly fitting football equipment, no matter how high-end and advanced, isn't worth the box they put it in" (Porter, 2015). Additionally, every pair of shoulder pads has some combination of buckles, elastic straps, and/or laces to secure and adjust them.

When fitted correctly, shoulder pads will be secured to the torso or any layer of clothing, braces, or pads underneath them. The correct order for wearing each piece of equipment begins with securing the brace to the upper body and arms, followed by the shoulder pads and jersey.

2.7 Electronic Measuring Techniques

In past studies involving wearable sensors measuring impact, electronic measuring techniques such as piezoresistive materials and accelerometers have been put to use to solve force detection problems. These allow for real time data collection of high speed and high force impacts that are otherwise unattainable with analog measuring techniques. Accelerometers provide accurate, and non intrusive measuring, but do not show localized force, only the total force applied. Piezoresistive materials can detect where forces are applied, but are much more unreliable.

2.7.1 Force Sensing with Piezoresistive Materials

A WPI project group went about solving their force sensing problem in a project titled the Smart Ballistic Vest with the piezoresistive material Velostat. Impact inflicted onto the chest was detected using Velostat, a material that changes resistance when pressure is applied, then using a simple circuit this drop in voltage was detected by a microcontroller, which then sent an alert to a dispatcher via RF transmission (Fairman & Santimore, 2011). This impact sensor was built by layering copper sheets, Velostat and a nonconductive top layer, as depicted in Figure 11.

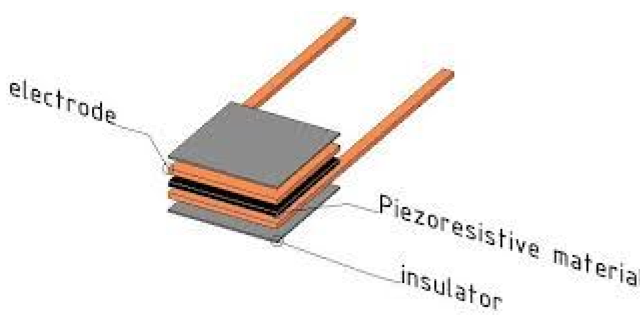


Fig. 11: *Piezoresistive force sensor* (Valle-Lopera, D. A., et al, 2017)

One advantage that this type of force sensing has is that these force sensors are flexible and, as the Smart Ballistic Vest showed, can be fitted underneath existing fabric. This material is inexpensive, at $5 per 11”x11” sheet, however the level of accuracy at which it can measure force remains to be seen as their application for this project was detecting if impact had occurred, not measuring the amount of force.

2.7.2 Force Sensing with Accelerometers

In a head trauma study done by the National Football League, accelerometers were placed within the helmet to measure changes in acceleration (Farrell, 2017). Accelerometers sensed changes in acceleration using capacitors separated by a spring. These changed in electrical output depending on the acceleration forces applied as the plates of the capacitor either separated or closed together due to their inertia and ability to move with the spring. Capacitance is dependent on the distance between the plates, as shown by the equation for capacitance $C = \frac{\varepsilon * A}{d}$ where ε is the permittivity of the dielectric of the capacitor, A is the area of the plates and d is the distance between the plates (Farrell, 2017). Accelerometers also sometimes use piezoelectric materials that output charge when experiencing acceleration forces that impact the material. The output from the accelerometer is usually in meters per second squared or in G-forces (Farrell, 2017). By using this acceleration value and the mass of the athlete, the force applied to the athlete can be determined using $F = m * a$. Many accelerometers are fairly affordable, around $5-$15, with the price increasing depending on the range of acceleration that is being monitored and the sampling rate that is needed. In previous impact measuring applications, it has been found that a sampling rate greater than 1kHz is required for sensors measuring impact force (Merchant et al, 2019). This requirement is difficult to come by for easily implementable products. However Adafruit produces an accelerometer that can measure up to 16g at a sampling rate of up to 1300 Hz that costs $18 per sensor. This sensor comes in a breakout board format, which allows easy access to the pins of the sensor for ease of use, as well as only taking up a 25mm by 19mm footprint.

2.7.3 Microcontrollers

In order to operate the aforementioned sensors they need to be connected to a microcontroller to power them and read the outputs of each sensor. Often these microcontrollers are attached to development boards that make utilizing the pins of the microcontroller easier and provide a platform to add additional components. Popular choices of development boards come from Arduino, Adafruit and Texas Instruments as well as many others. The boards range in price depending on their capabilities and what on-board features they carry such as Bluetooth or on-board sensors. One significant difference between the microcontrollers, which do the actual computing on the board, is how they are programmed. The Arduino controllers use the Arduino IDE and are programmed with the programming language C++ and have a large user base for community support. This community support is very important in the selection of a development board because most companies make a board that can fit in with whatever the project requires, but actually operating the board tends to require forum support and additional documentation. Other microcontrollers do not have this support which means that operating the board can be difficult. There are many aftermarket options compatible with Arduino that are only about $12, including many ESP 32 chipset development boards that have a large community-following for signal processing and Internet of Things projects.

3. Design

There was very little objective evidence to make conclusions on current shoulder braces and why or why not players like them. Thus, our team implemented a completely optional and confidential survey that was emailed to the WPI Football Team. A total of 51 responses were gathered. Some of the questions in the survey included asking respondents what position they play, if they have ever injured their shoulder(s) playing football before, and what they like/dislike about wearing a brace. When asked why the players do not wear shoulder braces their responses included, “Most (shoulder braces) are uncomfortable and restrict a lot of mobility”, “Annoying to put on, can get in the way”, and “Too bulky and uncomfortable.” Statistics from the survey show a staggering 88.6% of respondents with a previous shoulder injury do not wear shoulder braces. It was also found that 46.7% of players would consider wearing a shoulder brace for injury prevention, 71.4% of respondent Offensive Linemen (OL) and Defensive Linemen (DL) have injured their shoulder playing football before, while only one OL/DL player said that they wear a shoulder brace. Some notable responses from the OL/DL were that the braces made them too hot, were uncomfortable, and actually strained the shoulder instead of securing it. These responses were consistent with responses from other position groups, pointing toward shoulder braces being uncomfortable, bulky, and either too restrictive or not restrictive enough. The responses gathered from this survey are significant because they helped our team’s preliminary and final designs. A copy of the survey can be found in Appendix 1.

We used extensive background research, first-hand knowledge of the offensive line position, personal experience of playing football with shoulder braces, and the responses from the survey completed by the WPI Football Team to identify each design element of the shoulder brace and their weighted importance. The results are shown in Table 3 and were used when determining the priorities for our initial and final designs.

Table 3: Initial Design Criteria

Criteria	Importance (1-10)	Description
Protective	10	• Provides 45 N of compression to the shoulder to increase dislocation force from 525 N to 625 N. • Reduces impact force by a substantial amount on the side of the deltoid.
Mobility	10	• Reduce ranges of motion that have high probability to cause shoulder dislocations
Comfort	8	• Maximum thickness of 0.118in (3mm) (comparable to current braces) • High strength low abrasive stitching • No noticeable skin reactions or irritations through all of testing • Does not have material in unnecessary locations. • Perforated material for breathability
Weight	8	• Under 3 lbs to be comparable or lighter to the weight of other shoulder braces on the market.
Ease of Use	7	• Takes less than 30 seconds to put on. • Has the ability to be put on without additional help.
Cost	6	• Affordable to consumers with a price of around $100. Refer to Table 2 for comparable brace prices.
Manufacturability	6.5	• Able to manufacture under $75, so price stays within cost range above. • Manufacture in a range of sizes, that can be determined by basic upper body measurements. • Relatively simple design for ease of manufacturing to keep costs low and limit the turnaround time.
Longevity	5	• The brace has enough abrasion resistance to last through all of the testing period. • Able to last through 4 years of High School or Collegiate football. • Stitching holds and materials doesn't lose elasticity for 4 whole seasons.

3.1 Compressive and Reaction Forces of the Shoulder Joint

Before our preliminary design process could begin, it was vital to identify the different kinds of forces involved in shoulder dislocations and subluxations. Looking at Figure 12, we see that the impact force in a football collision was measured as high as 806 N (Rowson, McNeely, & Duma, 2007). With a dislocation force for a healthy shoulder of 525 N, it is clear that football collisions put the shoulder at risk of injury. With an additional 45 N of compressive force in both the x and y directions, the AC Joint and glenohumeral joint were supported, which improved the force needed to dislocate the shoulder to 625 N (Gutiérrez, Keller, Levy, & William E. Lee, 2008). By incorporating impact absorbing padding to the side delt of the already compressed shoulder, the dislocation force further increases. The calculations in Section 3.1.1 show that an impact absorption of 22.46 % with 45 N of compression on the shoulder will increase the dislocation force to 806 N.

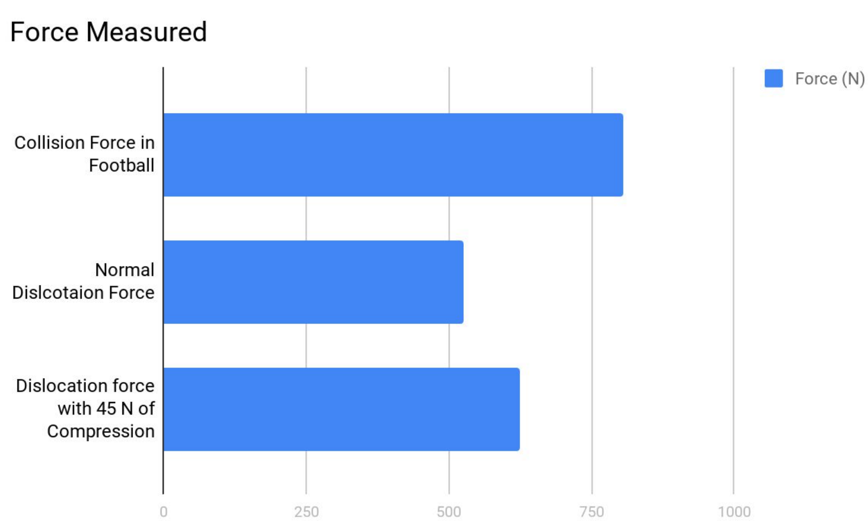


Fig. 12: *Dislocation forces compared to football forces* (Gutiérrez, Keller, Levy, & William E. Lee, 2008)

Compressive Force Diagrams:

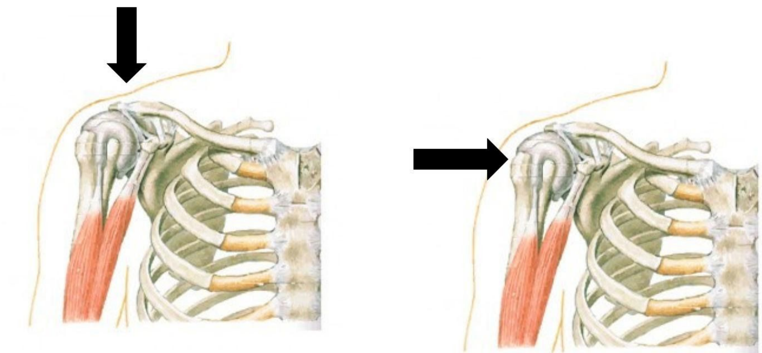


Fig. 13: *Direction of 45 N compressive force on the top of AC joint and side of glenohumeral joint*

3.1.1 Impact Resistance Calculation

Calculating the required reduction in impact force to prevent dislocation of a shoulder under 45 N of compression.

$\mathbf{F_f}$ = 806 N (Max force measured in a football collision)
$\mathbf{F_{dn}}$ = 525 N (Low force needed to dislocate a healthy shoulder)
$\mathbf{F_{dc}}$ = 625 N (Force needed to dislocate a healthy shoulder with additional 45 N compression)
$\mathbf{P_{dcf}}$= ? (Percentage that force needed to dislocate shoulder with 45 N compression is of max football impact force)
$\mathbf{P_I}$ = ? (Percentage of impact that must be absorbed)

$$\frac{F_{dc}}{F_f} = \frac{P_{dcf}}{100}$$

$$P_{dcf} = \frac{(F_{dc} * 100)}{F_f} = \frac{625N * 100}{806N} = 77.54\%$$

$$P_I = 100\% - 77.54\% = 22.46\%$$

3.2 Preliminary Design

The design constraints of Table 4 were chosen using knowledge of existing shoulder braces, the ROM limitations of the shoulder, dislocation forces of the shoulder, and responses from the WPI Football Team survey. Target ranges of motions were determined with the input from the WPI athletic training staff and Associate Head Athletic Trainer Shannah Dalton, who stated that 10-20 degrees of reduction from healthy ranges of motion would greatly reduce the risk of shoulder injury. Each of these constraints were used in the brainstorming of our initial and final designs.

Table 4: Preliminary Design Constraints

Design Constraint	**Target**
Flexion	130-150 Degrees
Extension	45 Degrees
Vertical Abduction	90 Degrees
Vertical Adduction	0 Degrees
Horizontal Abduction	110 Degrees
Horizontal Adduction	65 Degrees
Medial Rotation	70 Degrees
Lateral Rotation	60 Degrees
External Rotation	70-80 Degrees
Internal Rotation	60-70 Degrees
Compressive Force	45 Newtons on AC and Glenohumeral joints
Impact Force Absorption	22.46% Impact Force Reduction on Side of Deltoid
Permeability	Perforated/minimal material
Abrasion	Little to no wear through all testing
Time to Put On	As fast as comfortably possible
Weight	< 3lbs

Our team brainstormed to determine design components that would meet the target constraints outlined in Table 4. An example of the initial brainstorming our team conducted can be found in Appendix 2. Ideas gathered from this brainstorming session included adding a side delt protection plate and protecting both shoulders with our brace, among various other considerations. Various ideas for side delt protection were considered including using small beads sewn in a pocket to the shoulder area, using foam padding, and also using hard plastic plating. It was agreed that the small beads could act as abrasives during washing of the brace, ultimately decreasing the longevity of the brace. Also, the hard plastic plating would not maximize the maneuverability of the shoulder and instead hinder its movement, whereas soft foam not only promotes mobility but could also provide adequate protection. Also incorporating both shoulders into the brace came from the idea to correct and protect both shoulders. This came about from our group's collective experience playing football and wearing shoulder braces, as well as lack of dual shoulder braces available to athletes. Where adding dual shoulder support does increase weight, it also stops the athlete from developing muscular imbalances and accomodation injuries.

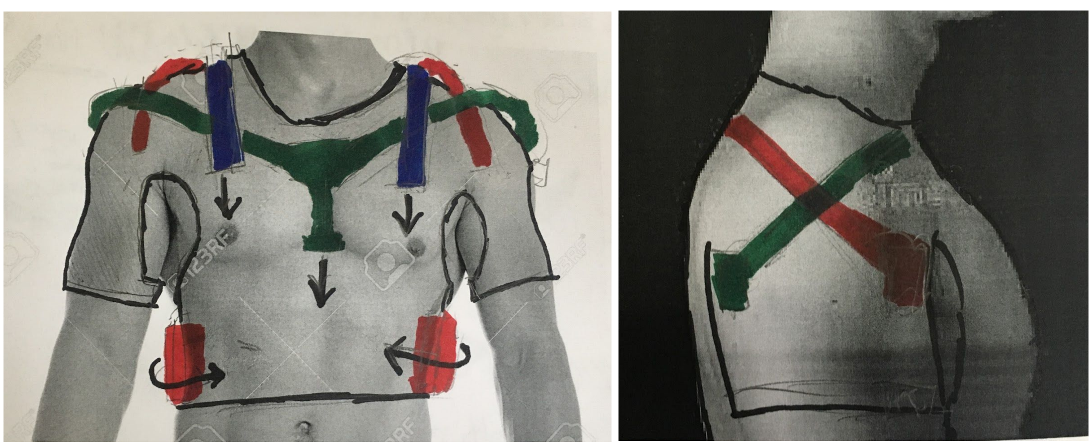


Fig. 14: *Initial shoulder brace design with strap locations and directions*

Figure 14 shows the initial designs for the underlayer and strapping mechanisms of our shoulder brace. The design was targeted to reinforce both shoulders, as injury often occurs to both shoulders especially after previously injuring one. The brace would be put on similar to a bullet proof vest, with it being placed over the head and straps pulling from the back to the front of the rib cage to fasten the brace around the torso, allowing for easy use and improved support. In addition, the vest would stop above the belly button and have cutouts underneath the arms to improve comfort and reduce weight. The sleeves were designed to go halfway down the bicep to be comfortable while enhancing compression and support when compared to other shoulder braces. The straps were located to provide compression to the AC and Glenohumeral joints, while limiting vulnerable ranges of motion and staying consistent with our ease of use criteria. Each of the straps would be accessible from the front, so the user could adjust them on their own. The black arrows show the direction that the straps would be pulled and Table 5 explains the purpose for each strap.

Table 5: Initial Design Strap Functionality

Strap Color	**Location/Usability**	**Function**
Red	• Permanently attached to the front of the shoulder, pulling back across the glenohumeral joint. • Strap crosses the back and secures to the opposite side front of the rib cage.	• Improves anterior stability and provides limitation to anterior mobility. • Compression of the glenohumeral joint. • Acts as a strapping mechanism for the brace around the torso.
Green	• Permanently attached to the back of the shoulder, pulling over to the front of the glenohumeral joint. • Combines with the same strap from the opposite shoulder at the middle of the chest and pulls straight down to secure.	• Improves posterior stability and provides limitation to posterior mobility. • Compression of the glenohumeral joint.
Blue	• Permanently attached to the back of the AC joint, on the shoulder blade. • Pulls over the AC joint and secures to the pectoral area.	• Compression of the AC joint

3.3 Final Design

Using Table 6 below, our team mapped out the design objectives of our final shoulder brace as functional requirements. Table 6 collectively takes what was researched and brainstormed, and relates it to functions the shoulder brace should accomplish. Thereby, each functional requirement can be accomplished by incorporating the adjacent design parameter in Table 6.

Table 6: *Functional Requirements of the Shoulder Brace*

Functional Requirements	**Design Parameters**
● Eliminate Shoulder Dislocations ○ Support Labrum and RC Muscles ■ Limit shoulder mobility in x, y, and z directions ○ Compress Glenohumeral Joint	● Wearable mechanism ○ Elastic straps around the shoulder joint ■ Straps limiting shoulder movement in x, y, and z directions ○ 45N of compressive force
● Prevent AC Joint Injury ○ Apply downward pressure on AC Joint	● AC joint straps ○ Compress AC joint in -y direction
● Prevent Shoulder Separation during Impact ○ Spread energy and force from point load ○ Stop ball-socket displacement in the x, y, and z directions	● Reduced impact forces on upper arm ○ Interconnected pad shape ○ Padding at point of deltoid impact, on the side, top, front, and rear of the deltoid
● Provide Comfort to the Athlete ○ Control air permeability ○ Does not cause irritation ○ Allows for needed positional shoulder mobility	● Comfortable brace material ○ Minimal or perforated material ○ Non-irritating material ○ Pliable material, material capable of stretching
● Ability to Last for Four Seasons of Use ○ Resist wear ○ Resist size shrinkage or stretching ○ Resist fatigue failure and tearing ○ Maintain high yield strength	● Durable material ○ High strength stitching ○ Abrasion- resistant material ○ Material with low thermal expansion coefficient ○ Material with high tensile/compressive strength

Our team's most important functional requirements were to compress the shoulder joint, construct the brace to be more comfortable than current shoulder braces, limit ranges of motion, and absorb impact forces to the deltoid. One consideration made by our team was that the shoulder brace must be as lightweight and compact as possible to fit comfortably underneath shoulder pads. Once design criteria, design constraints, strap functionality, and design parameters had been determined; final design of the brace, material selection, and prototype construction were completed.

3.3.1 Design Modeling

Solidworks, a computer-aided drafting program, was used to virtually model the brace. Virtual modeling was used to make the final design, but this step did not include physical construction of the prototype. The brace was modeled in flat pieces, much like it would look pre-sewn and pre-manufactured. In order to find the dimensions of each piece, we took measurements of an XL sweatshirt and tightened the tolerances to account for a tight fit of a brace. After finding these values, we broke the brace model up into eight total parts to be sewn together. These were: The back of the vest, front of the vest, two arm sleeves, two AC joint straps, and two tri-straps. The strap layout of our final design matches the preliminary design straps described in Table 6. Sharp edges in the design were filleted in solidworks to remove any high stress concentrations. We then added an extra ⅝" of material along edges that were to be sewn to account for seams.

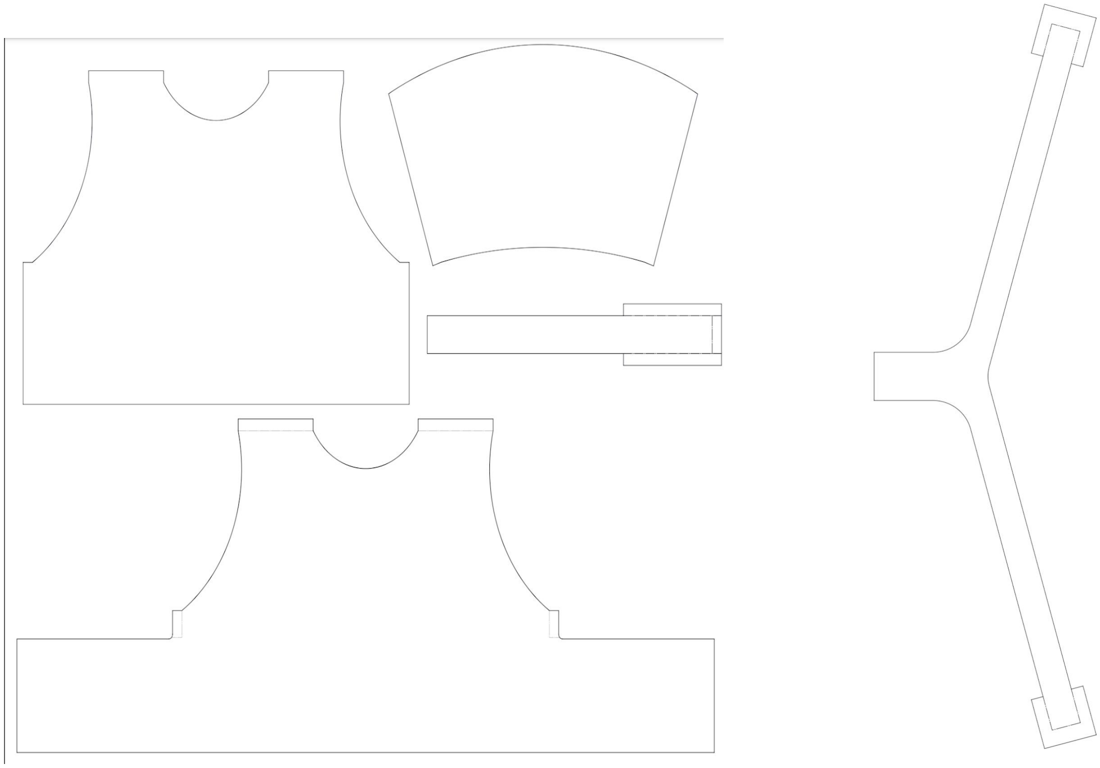


Fig. 15: *Brace pattern*

3.3.2 Shoulder Brace Material selection

After creating the final design, we put each of the pieces into a simulation study in Solidworks to compare different material strengths, and analyze failure locations. By modeling the brace with flat pieces in SolidWorks, we calculated how forces affect each portion of the brace. For instance, we anchored one end of the strap and applied a longitudinal force, similar to what would occur when pulling and fastening the straps down to secure the brace. The most valuable analysis conducted in Solidworks was maximal stress simulations. Maximal stresses were found after applying forces to the brace pieces and comparing the maximal stresses to the yield stresses of the different materials.

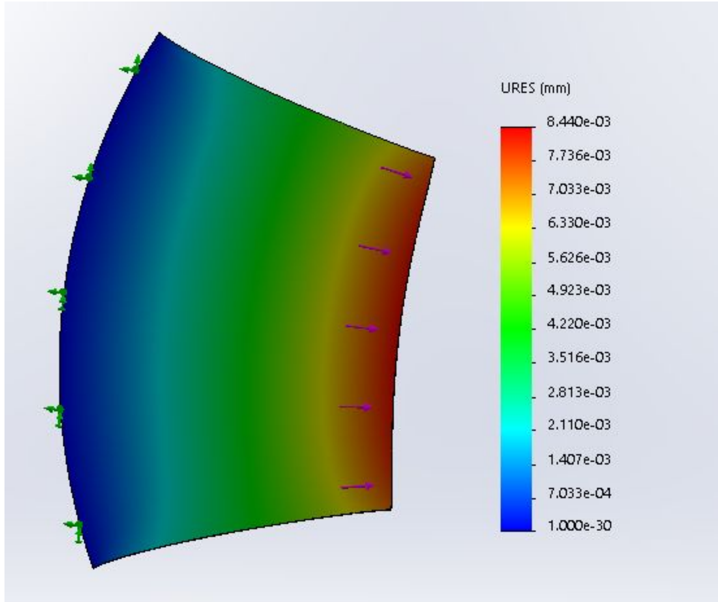


Fig.16: *Example of tests run in solidworks*

Table 7 lists the different materials that our team simulated in Solidworks as well as material properties of those materials. The materials in this table were gathered from material used in current braces listed in Table 2, research using CES Edupack software, and ASTM D737 permeability tests of experimental material (SHEICO Group, 2020). Table 7, was used by our team to compare and narrow material selection of the final design and prototype.

Table 7: Shoulder Brace Material Properties

Material	Young's Modulus (psi)	Yield Strength (ksi)	Tensile Strength (ksi)	Thermal Conductivity (BTU/hr.ft.°F)	H20 Absorption (%)	Air Permeability (FT^2/day.atm)	Water Durability/ Abrasion Resistance
Neoprene	239-305	1.74-3.48	1.74-3.48	0.0867-0.116	0.6-0.8	2.33e-7-7.27e-7	Excellent/ NA
Canvas	6.38-18.6	65.3-88.8	72.5-119	0.144-0.202	2.4-3.4	NA	Excellent/ NA
Polyester	0.435-0.885	83.1-106	83.1-106	0.0809-0.0867	NA	NA	Excellent/ Good
Nylon	0.58-0.725	83.1-106	83.1-106	0.0809-0.0867	NA	NA	Excellent/ NA
*Ventiprene	NA	NA	NA	NA	NA	2,880**	NA
*Spacer Fabric	NA	NA	NA	NA	NA	139,248**	NA

*denotes experimental material not currently used in shoulder braces

**numbers found using ASTM D737 air permeability test standard procedure

Using the properties from Table 7, our team decided to move forward with a perforated neoprene as the material that our prototype brace and straps would be made of. There were no mechanical property values for perforated neoprene, therefore we made the assumption that the values closely resemble that of neoprene with increased breathability, and slight reductions in tensile strength and tear resistance. We chose perforated neoprene because of a very high Young's Modulus, a more favorable breathability, and the fact that current braces on the market use neoprene as the base and strap material. To improve the tensile strength and tear resistance of the perforated neoprene we decided to layer it between two sheets of nylon fabric. The woven fibers of the nylon layers have an ultimate tensile strength of 82.7 MPa, which improves the overall tear resistance and tensile strength properties of the composite material. However, for our final design we chose Ventiprene with a thickness of 0.118in (3mm), as both the brace and strap material due to its breathability while maintaining similar mechanical properties to neoprene (SHEICO Group, 2020).

Once perforated neoprene was chosen, simulations were conducted with neoprene to identify if the material could withstand forces applied to it while being worn. Because no mechanical property values were available for perforated neoprene, our team decided to simulate with neoprene as it would have the highest property resemblance to perforated neoprene when compared to other materials. As shown in Table 8, the arm sleeves, dual shoulder strap (tri-strap), and AC joint strap were simulated in Solidworks with 10-50N of applied tensile forces stretching the straps and stretching the arm sleeve. Tensile force magnitudes of 10-50N were used to mirror the 45N of compression that we wanted to apply to the shoulder, that would occur from applying tension to the straps. The AC joint-strap and tri-strap would be particularly vulnerable to stresses along the length of the straps because they would be the main securing mechanisms for the AC and shoulder joints that the athlete would pull tight. Maximum stresses were gathered from the simulation and cross-checked against the yield strength of neoprene to confirm that the material was in fact durable enough to be used. As shown in Table 8, all of the maximum stresses fell well below the yield strength of neoprene, thereby validating neoprene as a suitable brace material.

Table 8: Solidworks Simulation Results of Neoprene

Arm Sleeve				
Force (N)	Max Von Mises Stress (N/m^2)	Max Strain	Max Displacement (mm)	Yield Strength (N/m^2)
10	8959.0	.0047	.9314	2.206E+07
30	26880.0	.0141	2.7940	2.206E+07
50	44790.0	.0235	4.6570	2.206E+07
Dual Shoulder Strap				
10	4.10E+05	0.1961	122.7	2.21E+07
20	8.20E+05	0.3278	242.2	2.21E+07
30	1.23E+06	0.4921	368.1	2.21E+07
40	1.64E+06	0.6557	490.8	2.21E+07
50	2.05E+06	0.819	613.4	2.21E+07
AC Joint Strap				
10	5.30E+04	3.00E-02	14.5	2.21E+07
20	1.24E+05	0.05992	29	2.21E+07
30	1.86E+05	0.08988	43.49	2.21E+07
40	2.48E+05	0.1198	57.99	2.21E+07
50	3.10E+05	0.1498	72.49	2.21E+07

3.3.4 Side Delt Padding Final Design

As discussed, to eliminate shoulder separations and absorb impact, padding was incorporated onto the arm sleeve of the brace around the side deltoid area. However, after our initial design, we realized that the deltoid padding would need to contour around the very mobile shoulder. This meant looking at various different padding designs, and disregarding any designs that would not fit a shoulder. For comfort and functionality, the padding needed to be flexible because the shoulder is a very mobile joint. To meet these requirements we decided on hexagonal padding, which is a common design for current thigh pads in football. The pattern allowed for flexibility and contortion around the player's arm frame. Football collisions occur on a relatively large surface area, so the gaps between the padding would not be vulnerable to direct impact. To determine the gap size between each pad in our design, we deconstructed a thigh pad and measured the distance between the hexagons using a caliper. The gap distance for hexagonal thigh pads and our final side delt padding design was approximately 0.1in.

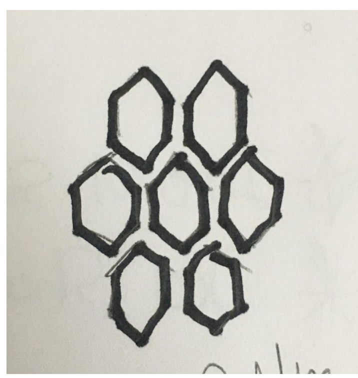


Fig. 17: *Hexagonal deltoid padding design*

The first step to design the individual hexagons of the padding was to create the shape of the shoulder. The profile of the shoulder that we used was created by making a paper mache cast of the shoulder of one of the team members with the build of an average-sized football player. After the paper mache dried, it was removed from the shoulder with the shoulder profile intact. Once hardened, hexagonal shaped paper was cut and glued to the shoulder profile covering the side, front, and rear delt areas. The flatter portions of the shoulder were covered with larger hexagonal shapes as less mobility is needed in those regions. Smaller hexagons were used for areas of the shoulder that move and flex more, allowing for greater mobility. Also, organically shaped pads were included in transition areas between hexagons of different sizes to better contour around the deltoid area and encompass more of the deltoid in padding without compromising mobility. Hexagons used included side lengths of 0.5in, 0.4in, and 0.3in. These lengths were based on the padding used in Nike football girdles. The hexagons with 0.5in sides were placed in areas of the upper arm where it was predominantly flat. Hexagons of 0.4in and 0.3in side length were used in areas of the deltoid and upper arm that were more curved and rounded.

Fig. 18: *Shoulder casting process*

3.3.4.1 Side Delt Material Selection

In order to determine the material that would best absorb impact for the side delt padding of our shoulder brace, we compared the properties of different foam materials. The values in Table 9 were determined through CES Edupack and SolidWorks simulation. In SolidWorks, we created a hexagonal pad out of each material and applied 50 N of force to the top of the pad while having the entire backside of the pad fixed, similar to padding being fixed on the side of a brace. The simulation gave us the Maximum Von Mises stresses, displacement, and strain values that are displayed in Table 9. We chose EVA foam and rigid polyurethane foam to test with physical experimentation. We chose EVA because it has a very high toughness, meaning it could withstand high stresses that would result from hard hits in football, thereby ensuring the pad's longevity. In addition, EVA was the least rigid of the foams because it had the greatest compressive displacement, and EVA's stress stayed well below its yield strength. Furthermore, EVA foam is currently used for padding in football helmets, thigh pads, hip pads and knee pads (Protective Apparel, 2019). Rigid PU foam was chosen because it, conversely, had a high compressive displacement which would allow us to compare the physical results of hard vs. soft foam. Additionally, PU's stress stayed below its yield strength. In addition, we chose Sorbothane Rubber to move forward into physical testing. Sorbothane Rubber is a polyether-based, polyurethane material that exhibits visco-elastic and high damping properties (Sorbothane, 2020). Sorbothane was not tested in SolidWorks due to the inability to acquire mechanical properties such as yield strength and Young's Modulus. Additionally, it had proven applicability and use on NASA's Space Station, precision laboratory equipment, and performance shoe insoles (Sorbothane, 2020). Data for the fracture strength for three different hardnesses of Sorbothane were gathered. This included a tensile strength at break of 1.79E+05 N/m^2 for 30 durometer Sorbothane, 7.38E+05 N/m^2 for 50 durometer Sorbothane, and 1.32E+06 N/m^2 for 70 durometer Sorbothane (Sorbothane, 2020). Even though this data is for fracture strength, all of the Max Von Mises stresses found while simulating the other materials fall below these values, thereby giving our team confidence that Sorbothane could perform comparably in physical testing.

Table 9: Side Deltoid Pad Material Analysis

Material	Yield Strength (N/m^2)	Max Von Mises (N/m^2)	Max Displacement (mm)	Max Strain	Fracture Toughness (ksi/$in^{0.5}$)	Toughness (G) (ft.lbf/in^2)
Neoprene	2.21E+07	3.02E+04	3.65E-02	0.0112	0.155	7.565
EVA	9.76E+06	2.94E+04	9.23	2.876	1.035	78.25
HDPE	2.82E+07	2.53E+04	6.42E-05	2.05E-05	1.47	1.387
LDPE	1.18E+07	3.37E+04	4.09E-04	1.29E-04	0.03415	0.246
Flexible PU Foam	4.80E+04	2.87E+04	6.57E-06	2.05E-06	0.01665	0.1635
Rigid PU Foam	8.78E+05	2.90E+04	1.27E-03	3.98E-04	N/A	N/A

Once EVA, PU foam, and Sorbothane had been chosen, our team conducted reactionary force tests using an Instron 9400 Series Drop Tower. The Instron machine drops a known weight from a predetermined height and measures the velocity of the dropper with a motion sensor and reactionary impact force in lbf with a force plate. With the help of lab advisor Russel Lang, we dropped 15.28 lbs from rest from a height of 10 cm above the surface of our materials. The Sorbothane Rubber samples came in different hardnesses or shore values, where a high shore value equalled a higher hardness. We conducted tests on Sorbothane with shore hardness values of 30, 40, 50, 60, and 70. For each sample, we ran three tests and calculated the average reactionary force and standard deviation (Figure 19). As shown in Figure 19, we found that EVA Foam had the lowest reactionary force with an average of 324.274 lbf +/- 4.79. This average was 4.9 times lower than the PU Foam. In addition, our initial tests resulted in high reactionary forces for the Sorbothane samples. However, the sorbothane samples had thicknesses of nearly half that of the PU and EVA samples, which would have resulted in a higher reactionary force. To correct for this, we stacked the 30 and 40 shore Sorbothane samples to match the thickness of the EVA sample. The first test with the stacked Sorbothane sample produced a high reactionary force of 1,012.66 lbf. With tight standard deviations on the previous tests we concluded that no further testing needed to be done and the EVA Foam had the best force absorption capabilities.

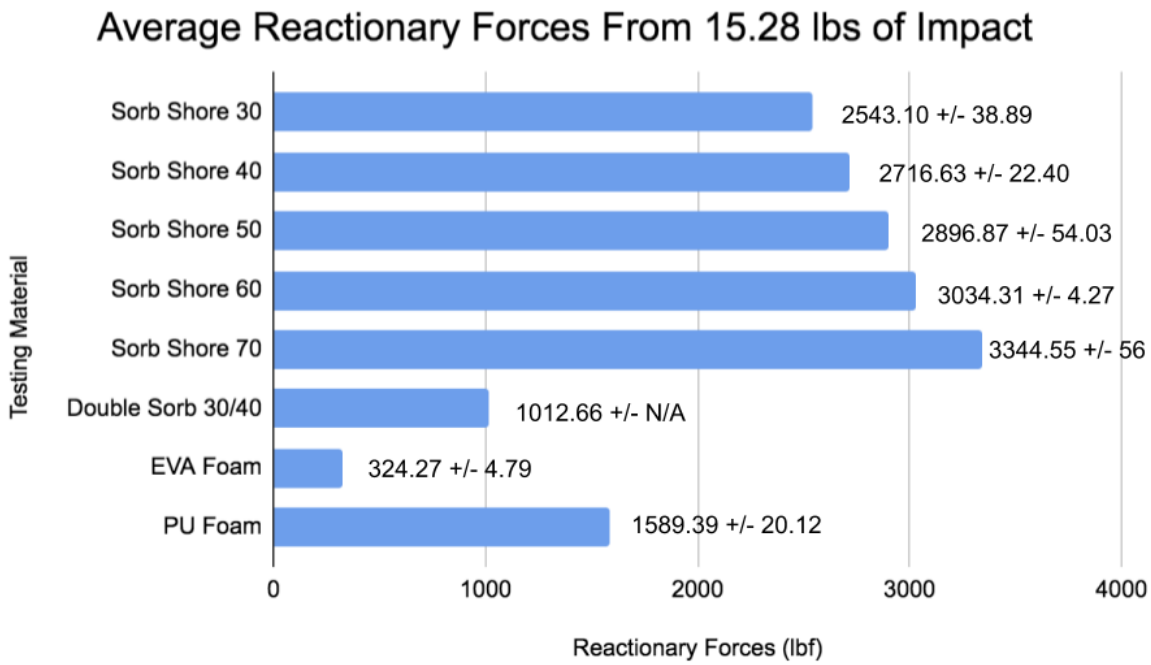


Fig. 19: *Results from tests conducted with Instron 9400 Series Drop Tower*

*Due to very small standard deviations when compared to their average, error bars did not show well on the graph, therefore standard deviations were labelled.

Fig. 20: *Instron 9400 Series Drop Tower setup*

Fig. 21: *Instron 9400 Series Drop Tower setup close view*

The most effective adhesive for this hexagonal deltoid padding design would be LORD 7650 adhesive. LORD 7650 adheres to foams such as open cell polyethylene, urethane foam, plastic, as well as fabric (Parker Hannifin Corp, 2018). LORD 7650 initially adheres two surfaces together while breaking down bonds found on their surfaces. As it cures, cross-linking occurs between the two surfaces binding them together (Parker Hannifin Corp, 2018). We used Loctite Flexible Adhesive in place of LORD adhesive due to difficulties acquiring the LORD adhesive. The Loctite adhesive appeared to be a suitable substitute because it is flexible, and can be used with fabrics and foams.

3.4 Prototype

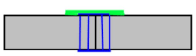
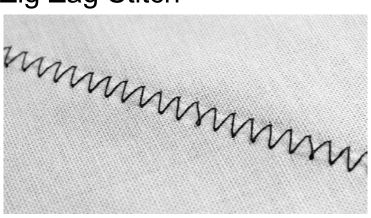
Once our team's design had been finalized with materials selected and tested, a shoulder brace prototype was constructed with perforated neoprene. This prototype was constructed out of perforated neoprene for a number of reasons, including a combination of its high yield strength, its strong breathability, and having a closer resemblance to Ventiprene than normal neoprene. Our final prototype design consisted of 0.118in (3mm) thick perforated neoprene layered between two sheets of nylon fabric.

3.4.1 Brace Tailoring

After receiving the neoprene material, we printed the sewing patterns that were created with SolidWorks onto a 3.5'x 6' paper. Next, we cut out the paper designs and secured them to the neoprene fabric. Once all of the pieces of the brace were cut out, they were taken to Designs by Joseph to be sewn together. Dotted lines in the patterns outlined 5/8" of extra fabric that would account for seams and highlight the parts of the design that would be sewn. Due to Joseph's input on the complexity of the design and the possibility of reducing compression, the prototype did not include underarm cut outs.The neoprene was then cut in the appropriate form to be sewn.

One challenge facing the construction of the prototype was stitching the pieces of the shoulder brace together. The different stitching options considered are presented in Table 10. Attempts to use a standard sewing machine proved unsuccessful regardless of stitch type, due to friction between the neoprene and sewing machine surface. Due to the complexity of the stitching, a local tailor, Designs by Joseph, helped stitch together the brace using a flatlock stitch which is often used for sporting equipment. With the seams now professionally sewn, our team was confident in the strength and longevity of the stitching.

Table 10: Stitching Types

Type of Stitch	Pros	Cons
Straight Stitch 	• Simple to follow • Strong and reliable	• May have extra material • Could be uncomfortable if done wrong
FlatLock Stitch  	• Strong and durable • Comfortable overall fit	• Difficult stitch to do • Need specific sewing machine
Zig Zag Stitch 	• Easy to do in person • Comfort	• Used for thin clothing usually • Not the strongest stitch

Once the brace had been sewed together, it was tried on by our group member that it was dimensioned for. While wearing the brace, adjustments were marked with white sharpie that included tightening around the abdomen and shortening the sleeves to allow for better mobility and comfort. These adjustments were then communicated to Joseph for his help in fine tuning the brace. Adjustments to the length of the brace were not needed, since it stopped right above the belly button. After the brace was tailored, the AC joint straps and tri-straps could be marked and sewn in place. To do this, the brace was once again worn by the group member, and each strap was held in the place that the team determined most suitable for correct compression application.

Once held in place, outlines of the straps were made in the positions to where they would be sewn on. Outlines were also made for where velcro would be sewn to the brace to fasten the brace and straps. Each outline was marked either velcro or sew to identify whether to sew in velcro or sew the strap to the brace. We decided to make one of the tri-straps completely detachable by having velcro at both ends to make the compression of the shoulders more adjustable and improve personal customization. The brace was then returned to Joseph, and all straps and velcro patches were secured.

Fig. 22: *Marked velcro and sewing outlines*

3.4.2 Padding Prototype

To create the side delt padding we first outlined the hex pattern from the paper mache shoulder model. We did this by covering the shoulder model with clear cling wrap and tracing the hex design with a permanent marker. Next, we removed the cling wrap and laid it on top of the 1’ x 1’ EVA Foam square. Then, we used a carbon knife to cut the design out of the EVA Foam. Initially, we attempted to adhere the EVA cutouts directly onto the neoprene shoulder brace using Loctite Flexible Adhesive. This led to sloppy results because the design was difficult to piece together and the adhesive was not tacky enough.

Fig. 23: *Cut-Out for hex pad*

Since our initial trial failed, we decided to adhere a jersey material to both sides of the EVA Foam design, thus creating a secure pocket containing the padding that could be sewn onto the brace. First, we pieced together the individual foam cutouts onto a layer of clear tape to hold the pieces in place. Then, we spread the Loctite adhesive onto the exposed side of the padding and laid a sheet of the jersey material on top of it. After letting the adhesive dry for 24 hours, we pulled the tape off and repeated the adhesive process with the opposite side of the padding and another sheet of jersey material. Once the adhesive was completely dry, the side delt pad pocket was outlined on one of the shoulders with a white marker, indicating where the padding was to be sewn on. Finally, the brace was returned to Joseph with all adjustments communicated, and completed.

Fig. 24: *Side delt pad construction*

Fig. 25: *Finished brace fit onto dummy*

3.5 Grid Sensor Design

A sensor made from Velostat material was designed and built to measure the force absorbed by the deltoid padding. The initial step for building the piezoresistive force sensor was to test resistive properties of the material on its own. This was accomplished by placing the nodes of a digital multimeter one inch apart and measuring the resistance between those points, and repeating this process across the length of the material. This resistance varied across the material, suggesting inconsistencies within the material. Latency was also tested, to measure how responsive the material was and how long the signal was retained. This was done with a rough prototype, seen in Figure 27, connected to a voltage divider as described, with oscilloscope leads on the column and row of the sensor being tested. The time between force being applied and the signal dropping back to normal was approximately 12 ms, and about 6 ms before the signal had dropped significantly from the peak. This means the measurement period for the sensor needed be less than 6 ms from the first sensor to the last sensor.

The sensor itself was based on the construction of older keyboards for computers, as this addressed the need to see where the force was applied. The initial design was a laminating sheet as the insulation material with Velostat circles at the intersections of a grid of copper tape. The rows were connected to a resistor, then to ground, to form a voltage divider. Then, the "output lead" of the sensor carried the voltage across the Velostat. Each column was connected to a digital input pin on an ESP 32 development board and each row was connected to an analog input pin. This construction is sketched out in Figure 26.

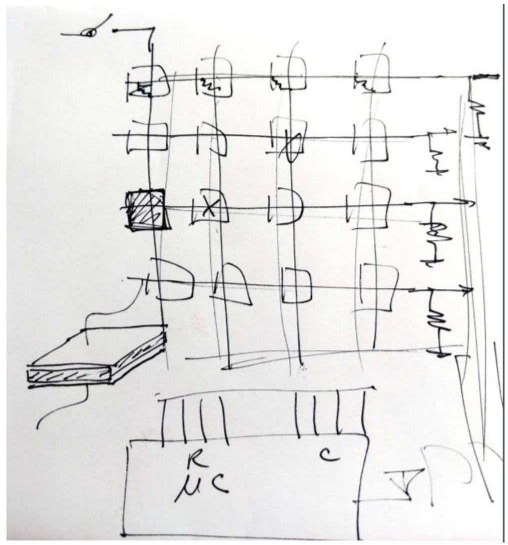


Fig. 26: *Grid Sensor construction sketch*

On the software end, the board activated one digital input pin, then each row read the voltage values measured across the sensors. This pin was then turned off, and the next digital pin was turned on, the processor read all the analog input pins, and so on for the rest of the sixteen sensors. This allowed for near-instantaneous measurement of the force applied to the sensor, limited only by the speed of the analog to digital conversion done by the microcontroller, which was within the timeframe that the material held the signal. The complete source code for the Grid Sensor processing is given in Appendix 3.

The first prototype was built as a two by two grid to test for initial manufacturing practice and the latency test, and can be seen as Figure 27. The prototype was tested for resistive consistency across each sensor. The results showed that there was some inconsistency between each sensor, ranging from 3 kΩ to 15 kΩ. Initially these inconsistencies were assumed to be due to sensor construction, so a new prototype was built, wiping down all surfaces with rubbing alcohol, carefully cutting uniform rectangles of Velostat, and all copper lines lined up on graph paper to ensure uniform intersections. This was measured, and the same inconsistency was there, pointing towards material inconsistency as the problem.

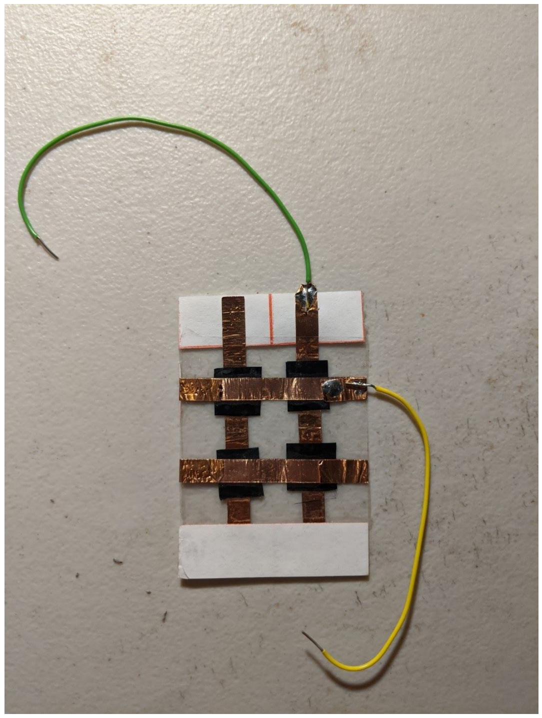


Fig. 27: *Grid Sensor prototype*

The final design prototype was built by using graph paper to line up all intersections, wiping down all contact surfaces, and using a leather punch to punch out uniform ⅜ in circles to ensure uniform coverage of all intersections. This yielded resistances values that averaged 27.1 +/- 8.1kΩ with no force applied. The resistance with a 3 pound load averaged 45.53 +/- 17.9Ω. The resistance average for 6 pounds of load was 39.5 +/- 18.3Ω, and 30.6 +/- 15.4Ω for the 9 pound load.

The final sensors that were used for the brace testing were manufactured in the same way, this time yielding average unloaded baseline values 2.58 +/- 0.34kΩ; 3 lb weighted values averaged 1.32 +/- 0.20kΩ; 6 lb weighted values averaged 1.167 +/- 0.19kΩ; and 9 lb weighted values averaged 1.09 +/- 0.17kΩ. The vast difference between the final design prototype and the final sensors is unclear. The hypothesis is there could be some environmental factors at play such as humidity in the air when the sensors were produced, however this is only a theory. The final two sensors that were built were considerably more consistent between each sensor, and showed less significant drop off in resistance between loaded and unloaded. This gradual drop off would in theory allow more accurate mapping between force and resistance.

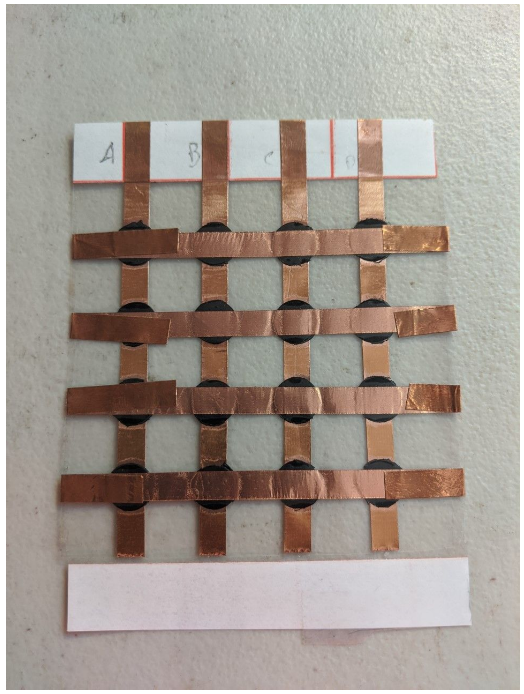


Fig. 28: *Final Grid Sensor*

4. Testing

In order to evaluate whether or not the brace was effective and viable for use, a series of tests were conducted on the brace.

The first of these tests was an impact test on the side delt pad using the pendulum test rig, described in Section 4.1. This test was done to simulate a common collision that a football player would experience that could result in shoulder separation and AC joint injury.

The second test measured the compression that the shoulder brace generates on the AC and glenohumeral joints. Our goal was to compress the general area of the shoulder by 45N, since this has been shown to reduce the chances of shoulder dislocations as discussed in Section 3.1.

The third test measured the ROM of a person wearing the brace. This test was conducted to determine if the brace met the preliminary target ROMs set in Table 4. By measuring ROM our team could decide whether or not the brace performed well at restricting the wearer from reaching vulnerable positioning of the shoulder, consequently lowering chances of injury.

The fourth and final test performed on the brace was to evaluate its ease of use and comfort. It is important to note that these tests were conducted with the brace fully built and functional.

Safety protocol was implemented into the pendulum testing due to the injury risk associated with swinging weights on a steel arm.

4.1 Impact Test Modifications and Setup

To test the impact absorption capabilities of our shoulder brace, we used a pendulum test rig used in previous projects (Buckley et al, 2019; Merchant et al, 2019). This test rig allowed our team to test the functionality of the brace’s side delt padding. The original pendulum rig was made with 3/16” thick, 2” x 2” mild steel square tubing. The 2” x 2” tubing was cut to the appropriate sizes and welded together to create the pendulum frame. The frame had a total height of 9 feet. The pendulum arm was created with 1” x 1” mild steel square tubing and had a total length of 6 feet. The arm was welded to a 0.065” thick steel pipe with an outer diameter of 1.25”. The length of this pipe was 2”. The arm slid onto another 0.065” thick steel pipe with a slightly smaller outer diameter of 1” to create a rotating joint. A contact head was bolted onto the end of the pendulum arm with a weight rack to adjust the mass of the pendulum. The original contact point was 32 inches from the ground.

To secure the shoulder brace and create a realistic shoulder collision with the pendulum rig, our team decided to use a BOB Dummy or Body Opponent Bag, which is designed to receive impacts from punches and kicks. A BOB Dummy has a torso and rounded shoulders, thus allowing the brace to be fully secured to a torso with accurate shoulder dimensions. Furthermore, the BOB Dummy has an adjustable height and can be filled with 240 lbs of water, equivalent to a medium to large sized football player that our brace is designed for. To account for the knock-back of a player during a football collision, our team strapped the BOB Dummy to a furniture dolly. This allowed the Dummy to be pushed back upon impact with the pendulum.

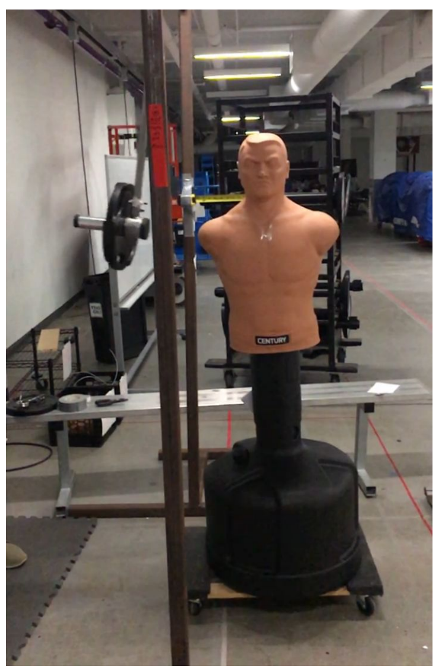


Fig. 29: *Baseline test rig configuration*

Our team made slight adjustments to the original pendulum test rig to account for a different contact point height and a wobble in the original arm. Our contact point height was 56 in from the ground, so we created a new arm with 1” x 1” low carbon steel square tubing that has a length of 42.5 inches. To improve the wobble of the original arm, which led to inaccurate contact points, our team increased the length of the outside pipe of the rotating joint. As the drawing in Appendix 4 shows, we increased the length of the pipe from 2” to 8”. Tests of the adjusted rotating joint confirmed that there was very little wobble and still an easy rotation, proving that the new arm would provide our team with more consistent testing results.

4.2 Impact Test Modeling

In order to conduct the final impact test with forces that did not exceed the limit of our accelerometers, we calculated the rig arm weight that would equate to forces below the limit of 16g as detailed in Section 4.3, which is roughly equivalent to 500 N. To validate our calculations, we first ran a baseline test to determine the actual impact time of the collision between our test rig arm and the shoulder of the BOB Dummy. We used a 240 FPS GoPro camera to record the impact in slow motion. We conducted three tests with 30 lb (133 N) of arm weight and three tests with 40 lb (178 N). To determine the impact time, we looked at the slow motion video for each test and counted the number of frames that it took for the pendulum to reach a velocity of 0 in the direction of impact. The average impact time with 30 lb (133 N) was 0.13s and with 40 lb (178 N) was 0.173s. Each of these impact times fell between 0.1-0.2s which our team’s research revealed to be the duration of football collisions (Gay, 2004; Schwarz, 2009). Therefore, the impacts resulted in realistic football collision movements of the BOB Dummy.

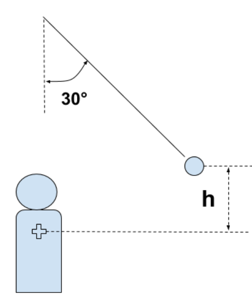
Fig. 30: *Baseline impact test setup*

Table 11: Relationship between Total Pendulum Mass* and Impact Time

Test	Impact Time (s)
30 lbs Test 1	0.11
30 lbs Test 2	0.12
30 lbs Test 3	0.16
30 lbs avg	0.13
30 lbs st. dev.	0.026
40 lbs Test 1	0.17
40 lbs Test 2	0.18
40 lbs Test 3	0.17
40 lbs avg	0.17
40 lbs st. dev.	0.0058

**Bob (5lbs) + added gym weights*

We tested the shoulder brace with forces ranging from 200N to 500N to closely resemble the impact force of a football collision. The calculations to determine the weight needed to create impacts with each of these force increments are below. The pendulum arm was released from an angle of 30 degrees for ease of testing and safety purposes.



To find Δv of the pendulum set PE and KE equal to each other and assume no friction loss

$PE = KE$

$mgh = \frac{1}{2} mv^2$

The PE and KE equation can be simplified through simple math to:

$v = \sqrt{2gh}$

$v = \sqrt{2(9.81m/s^2)(0.2286m)} = 2.1178m/s$

Velocity (v) is equal to initial velocity (v_i), the velocity immediately before impact of the arm. Assume v_f is equal to 0 because the collision comes to a dead stop.

Therefore:

$v_i = \Delta v = 2.1178m/s$

Use momentum equations to find force

$\Delta P = m\Delta v = F\Delta t$

Use Pendulum Force Equation to find Δt with momentum equations

$F = mgsin(\theta)$

$m\Delta v = F\Delta t$

$m\Delta v = mgsin(\theta)\Delta t$

The masses cancel out giving us:

$\Delta v = gsin(\theta)\Delta t$

Therefore:

$\frac{\Delta v}{gsin(\theta)} = \Delta t$

$\Delta t = \frac{2.1178m/s^2}{9.81m/s^2 * sin(30)}$

$\Delta t = 0.11s$

This Δt value is consistent with our 240 FPS recorded baseline tests that resulted in impact times between 0.1s and 0.2s.

Plug Δt into the momentum force equation with predetermined forces to find mass.

Solve for Forces of 200, 250, 350, and 500 N.

$F = \frac{m\Delta v}{\Delta t} => m = \frac{F\Delta t}{\Delta v}$

$m = \frac{F(0.11s)}{2.1178m/s^2}$

Table 12: Total Pendulum Mass and Impact Force Matrix

Weight to Test With Matrix	
Force (N)	Weight (lbs)
200	23
250	29
350	40
500	57

4.3 Pendulum Tests

This process was followed for testing of forces up to 500N of magnitude. Starting at 200N, and increasing to 250, 350, and finally 500N. The accelerometer chosen to measure the impact force applied to the dummy was the Adafruit LSM6DS33, chosen for the sampling rate of 1.3kHz and measurable range of force up to 16g, as well as supporting files that made for easy implementation.

1. Safety procedures (Appendix 5) read and followed by each member prior to testing.
2. Removed the test rig and BOB dummy from the sectioned off area.
3. Setup and assembled the test rig and positioned the BOB dummy in the designated testing area.
4. Ensured the BOB dummy was filled with water and no leaks had sprung.
5. Aligned dummy so that the test rig arm hit the shoulder of the dummy. The impact point was when the arm was vertical and hit the BOB dummy square.
6. Taped the accelerometer onto the back of the BOB dummy and ensured wires were connected to a computer running an Arduino sketch to monitor the accelerometer.
7. Fit shoulder brace onto BOB dummy. The shoulder brace could be fit onto the BOB dummy during the beginning of the testing period and stay on for all tests.
    a. Velcroed down straps and fully secured the brace.

8. Loaded the proper weight to the pendulum for appropriate force being tested.
    a. Secured weights using bar clips.
9. Setup Slow Motion Camera.
    a. Positioned the camera facing the front of the BOB dummy, or along the side of the test rig to measure displacement of BOB dummy.
10. Two team members ensured proper positioning of the BOB dummy and test rig pendulum. The third held the test rig arm at a 30-degree angle to be dropped and released.
    a. Team member 1 was perpendicular to the drop path of the pendulum to make sure the pendulum was released from a 30-degree angle. This team member lined up the end of the pendulum with a designated tape mark on the ground ensuring a 30-degree angle.
    b. Team member 2 ensured the pendulum arm connected with the BOB dummy and that both were aligned for impact. Tape was placed on the ground simulating the test rig arm path to align the BOB dummy.
    c. Team member 3 ensured that the force sensors were located in the correct position and that they were reacting correctly before impact. Also this team member did a final check on the camera to make sure it was recording and positioned correctly.
    d. Team member 4 held the pendulum at a 30-degree angle waiting for confirmation from team members 1, 2, and 3 that the arm could be released and the trial was properly executed. After releasing the pendulum this team member swiftly stepped back well out of the path of the test rig arm.
11. All team members waited until the dummy and test rig arm reached a complete stop before entering the testing zone.
12. Repeated steps 7-11 with different weights to simulate varying forces.

4.4 Compression Test Setup and Procedure

To test compression acting on and around the shoulder joint while wearing the brace, a small loop was attached to the center of the left shoulder of the brace. This side of the brace was not constructed with the side delt padding for baseline impact testing so that the loop could be attached directly to the neoprene. The three materials needed for the compression tests include a pull scale, the loop material that was sewn onto the shoulder of the brace, and the brace itself.

The testing process was followed for each trial of compression testing to gather consistent results for the compressive forces acting on the shoulders of the wearer of the brace. First, one person would put on the shoulder brace completely, with all straps in place. Next, the Operator of the test standing on the side of the person wearing the brace, hooked a pull scale through a loop located on the brace sewn to the shoulder. The Operator then pulled the pull scale out and away from the surface of the shoulder. When the wearer of the brace no longer felt compression from the brace and the brace visibly lifted off of the shoulder, the wearer verbally indicated that the compression was gone to the Operator. At this point the Operator and a Spotter, who stood in front of the wearer of the brace to ensure that the pull scale was being pulled in the right direction, looked at the pull scale and saw how much force was measured. The force the pull scale measured was then recorded by the team. This process was repeated with and without the optional strap, and also for the AC joint strap. Every step stayed the same for testing AC joint compression, except where the pull scale was hooked. For testing the AC joint strap compression, it was hooked on the AC joint strap and pulled straight up off the shoulder. Testing was conducted in the x and y directions. Section 3.1 explains that compression in the x-direction supports the glenohumeral joint and compression in the y-direction supports the AC joint.

Fig. 31: *Pull loops on brace, and AC compression test*

4.5 ROM Test Setup and Procedure

Certain upper limit ranges of motions increase the likelihood of shoulder dislocation and soft tissue damage by putting the shoulder and arm into more vulnerable positions (Sheehan et al, 2013). To test whether or not the shoulder brace would limit the wearer from reaching extreme ranges of motion, the team followed a set of procedures. The testing process was followed by our team to gather consistent, reliable measurements and ranges of motions. Step one of testing range of motion was to have a person put on the shoulder brace, and secure every strap in place. After the brace was put completely on, the person wearing the brace was instructed by another team member what position to move their arm to. These movements included but were not limited to abduction, flexion, extension, adduction, and rotation. All ranges of motion that the brace wearer tried to reach can be found in Table 4: Preliminary Design Constraint. Once the person wearing the brace reached their maximal range of motion for the given movement, the position was held in place and measured by a second team member. The ranges were measured using a goniometer, and recorded in degrees. Finally, after all the ranges of motions had been measured and recorded they were compared to the ranges of motion of a healthy shoulder found in Table 1.

Fig. 32: *Vertical Flexion, Horizontal Adduction, and Lateral Rotation ROM test (Pictured left to right respectively)*

4.6 Ease of Use and Comfort Test Setup and Procedure

After surveying the WPI football team it became evident that how easy the brace is to put on and how it feels to wear, is a large consideration when deciding whether or not to use a brace. Specific answers to our initial survey can be found in Section 3. The following steps were taken to test how long the brace took to put on and how comfortable it was to wear. First, the brace was set up in the orientation that it would be before an athlete would put it on. The starting brace setup is shown in Figure 33. Next, a team member held the brace as an athlete would, to get ready to put it on. A second team member prepared to start a timer. On the count of three, the first team member began to put on the brace while the other team member started the timer. Once the brace was on and all straps were velcroed down the test was over and the time was recorded. After the times were recorded, the person who put on the brace was asked a series of questions regarding its comfort while still wearing the brace. Finally, all responses to the questions were recorded. These questions and their answers can be found in Appendix 6. As shown in Appendix 6, a series of questions were conducted after just putting on the brace, with and without an undershirt on, with shoulder pads, and after performing a period of light physical activity for 10 minutes, similar to a warmup.

Fig. 33: *Starting brace setup for ease of use tests*

Fig. 34: *Ease of use test, no help*

Fig. 35*: Ease of use test, additional help*

4.7 Grid Sensor Testing

The Grid Sensor developed to measure the force delivered to the shoulder underneath the deltoid padding in the Pendulum Test was tested for its effectiveness in four different situations: static force applied on a flat and rigid surface, impact force applied on a flat and rigid surface, impact force applied on a non-rigid surface, and unloaded resistance while bent over varying radii of curvature.

The first test was the calibration tests performed to see the resistance behavior of the sensor versus static forces. The sensor was laid flat on a table with weights applied to a small circular piece of plastic to apply the weight more directly to each cell. These resistance values were recorded and graphed to demonstrate the initial resistance versus force curve.

The second test used the Instron 9400 Series Drop Tower to apply known forces to the sensor. The resistance values gathered here would be used to try to correlate force to the reported resistance from the sensor. These tests were performed with the same material that was used for the deltoid padding, layered on top of the sensor. Several layers were used to reduce the amount of force applied to the Grid Sensor. This was done to protect the load cell of the drop tower, as well as lowering the force applied to the sensor into the range of force more similar to that of a football collision.. This test was performed to see if the sampling rate of the sensor was high enough to detect impact as well as build initial correlation between force and resistance.

The third test was part of the pendulum testing, repeating the test procedure with two Grid Sensors attached to the dummy, one on top of the deltoid padding and one underneath the deltoid padding at the same time, with three levels of force applied. An accelerometer was placed in the center of the back of the dummy as a comparison value to the read out of the Grid Sensor. The intent behind using the two sensors simultaneously was to get a measurement before and after the deltoid padding. This test was performed to see whether or not the sensor could detect impacts on a non-rigid surface, to see if the sensor could be used to measure force magnitudes based on the correlation found in the first test, as well as the deltoid padding for its effectiveness at absorbing force.

The fourth and final test performed on the Grid Sensor was measuring the unloaded resistance on three surfaces of different radii of curvature, being a table, a basketball with a radius 4.7 inches, and a lacrosse ball with a radius of 1.25 inches. This was done to see if there was a correlation between resistance and the amount the sensor was bent after complications arose during the pendulum test.

4.7.1 Piezoresistive Grid Sensor Calibration

This process was used to find the level of consistency of each sensor's resistance. This was done for checking the prototypes to find the best design and manufacturing process.

1. An ohmmeter was connected to the first column and the first row.
2. The unloaded resistance with no force applied to the sensor was recorded, then repeated for each column and each row.
3. Weights of 3, 6, and 9 pounds were applied, measuring resistance and recording at each weight, then repeated for each column and row, applying each weight to each sensor.

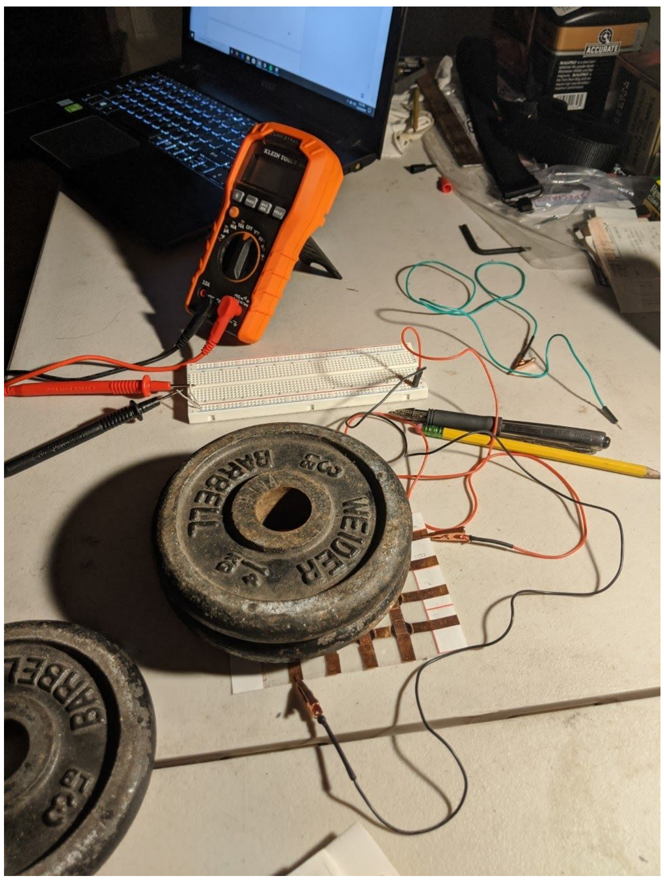


Fig. 36: *Grid Sensor calibration*

4.7.2 Grid Sensor Drop Tower Testing

This test was used to make sure the processing speed of the microcontroller was capable of detecting impact force, which included the general limits of force the sensor could handle, as well as if the sensor's sampling rate exceeded the necessary 1 kHz. as well as looking for the trend lines of how the sensors reacted to impact force. These trend lines were used to try to correlate forces to resistance values for each sensor.

The Grid Sensor was first taped down to the force plate of an Instron 9400 Series Drop Tower. The corners were secured so that the sensor was lying flat. Three pieces of EVA foam were laid on top of the Grid Sensor to protect the load cell and lower the forces into the range we wanted to test at, between 100 and 500 lbf. Forces of ~175 lbf, ~300 lbf, and ~500lbf were applied, recording the resistance and voltage reported at each sensor through the serial monitor. Step 2 was repeated for the second Grid Sensor. The Resistance vs. Force curve for each sensor of each grid was plotted to find a correlation between force and resistance.

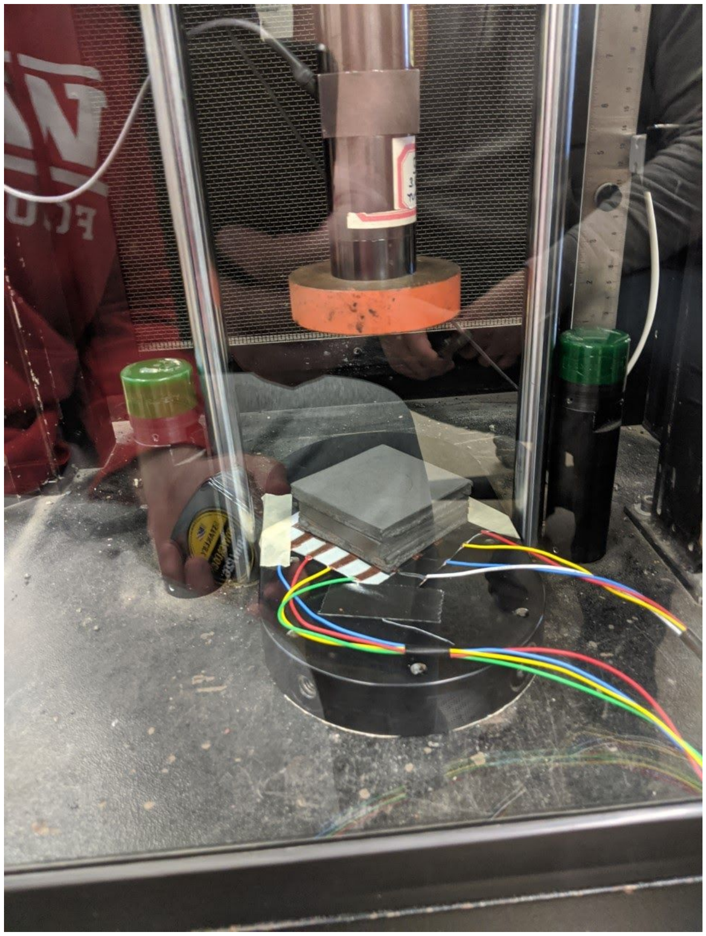


Fig. 37: *Grid Sensor drop tower setup*

4.7.3 Grid Sensor Pendulum Testing

This testing was done in conjunction with the pendulum testing previously described for the deltoid padding. If successful, the Grid Sensor placed underneath the padding would have read the same forces as the accelerometer, using the accelerometer to fact-check the Grid Sensor and validating the hypothesis that impact force applied to the sensor could be correlated to the resistance reported by the monitoring software.

The accelerometer was the Adafruit LSM6DS33, chosen for its sampling rate of 1.3kHz and measurable range of force up to 16g, as well as supporting files that made for easy implementation. The accelerometer was placed in the middle of the dummy's back, directly in line with the impact point. The accelerometer measured in three axes, which allowed us to see whether the force was being directly applied along the axis we were measuring. The maximum force tested at was 500 N so as to not exceed the limits of the accelerometer. If the Grid Sensor failed, the accelerometer would be used to measure the force applied to the dummy.

The first Grid Sensor was attached underneath the brace on the impact point, and the second was attached on top of the brace at the impact point. The resistances from each trial of the testing were recorded, then compared to the resistance measured in the drop tower testing.

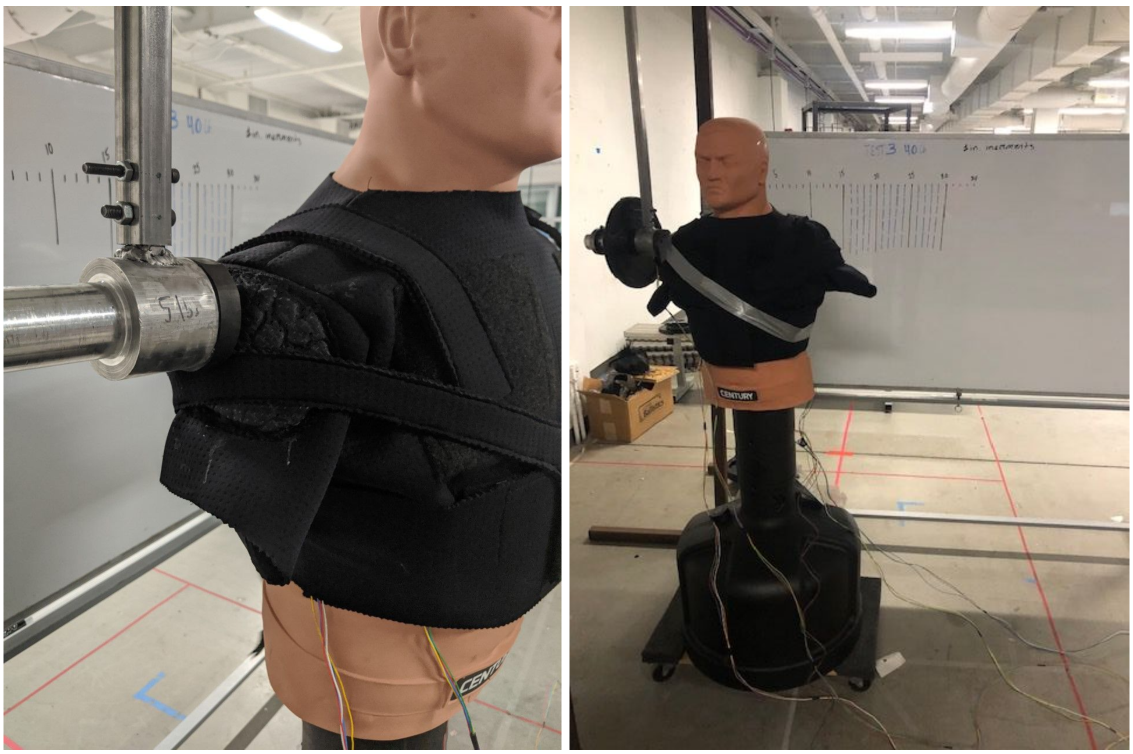


Fig. 38: *BOB dummy setup for pendulum testing*

4.7.4 Grid Sensor Bend Testing

This test was used to see how the sensor's unloaded resistance changes due to flexure over a known radius. After anomalies were found when testing with the dummy, this procedure was performed to investigate possible reasons. These tests were performed with a digital multimeter to remove error due to any inconsistency of current supplied by the microcontroller.

1. Measured the unloaded resistance of the inner four sensors, B2, B3, C2, C3 (These are the sensors that were the most routinely impacted so they are the data points most necessary to examine), by securing the sensor to a flat surface and measuring using a digital multimeter.
2. Bent the sensor at a radius of 4.7 inches by securing the sensor to a basketball and measured the resistance of the inner four sensors.
3. Bent the sensor at a radius of 1.25 inches by securing the sensor to a lacrosse ball and measured the resistance of the inner four sensors.

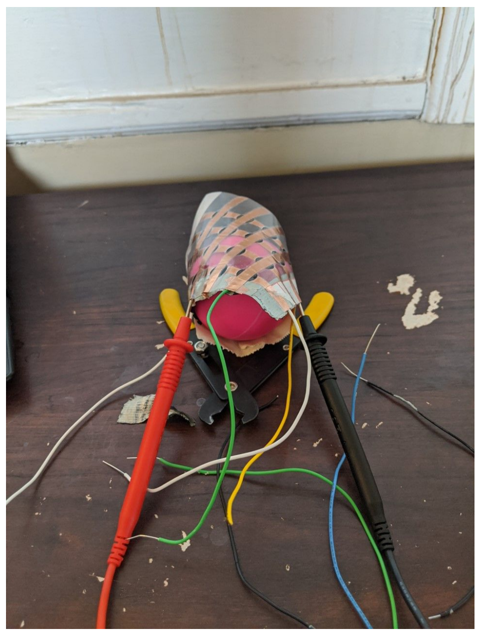


Fig. 39: *Bend test setup*

5. Test Results

5.1 Pendulum Test Results

The forces transferred from the pendulum to the testing dummy were measured using an accelerometer taped to the back of the BOB dummy. Raw output acceleration data from one of the 200N impact tests can be found in Appendix 7. Tests were run both with and without the shoulder brace on the BOB dummy allowing our team the ability to compare accelerations and forces felt with and without the side delt pad. The weight of the pendulum corresponded to the calculations made for theoretical forces that the arm would exert on the BOB dummy. Data from the accelerometer was analyzed in a text file where the difference between the pre-impact reading and maximum impact reading from the accelerometer was recorded.

Table 13: Accelerations Recorded by the Accelerometer During Pendulum Impact

Accelerations Felt by Accelerometer						
	With Brace On				Without Brace	
Theoretical Applied Forces	200	250	350	500	200	250
Trial 1	14.79	8.95	9.04	11.43	13.9	14.69
Trial 2	11.4	6	12.94	11.49	-	-
Trial 3	13.93	5.51	-	-	-	-
Avg	13.37	6.82	10.99	11.46	13.9	14.69
St. Dev.	1.76	1.86	2.76	0.0424	-	-

Table 14: Transferred Forces Calculated from Accelerometer Data

Actual Forces Felt by Accelerometer						
	With Brace On				Without Brace	
Theoretical Applied Forces	200	250	350	500	200	250
Trial 1	150.94	101.49	164.02	298.11	141.86	166.58
Trial 2	116.35	68.04	234.78	299.68	-	-
Trial 3	142.17	62.48	-	-	-	-
Avg	136.49	77.34	199.4	298.9	141.86	166.58
St. Dev.	17.98	21.1	50.03	1.11	-	-

Tests were first conducted with the brace on the BOB dummy. Once data from three trials at theoretical forces of 200N and 250N were gathered, our team noted a wide range of values that could point to inconsistent acceleration and force values. To calculate the average forces felt by the accelerometer, the accelerations were multiplied by the weight of the swinging pendulum arm. This calculation is quite simply F=ma. After one test without the brace for both theoretical forces of 200N and 250N, our team determined that the pendulum tests were both inconclusive and inconsistent. At 200N of theoretical applied force, some accelerations felt by the accelerometer were higher with the brace on the dummy than without the brace. Tests without the brace did not produce data we were expecting. Accelerometer readings became sporadic and unpredictable. Data was unreliable during tests without the brace, and it was suspected that our team the accelerometer could have been damaged. Single tests for 200N and 250N were not sufficient enough to draw meaningful conclusions, as single data points could be considered outliers.We believed also that the physical makeup of the BOB dummy could be a reason as to why data was inconsistent. With each impact the BOB dummy would cushion and bend with the pendulum arm. A potentially damaged accelerometer combined with the makeup of the BOB dummy showed results that were inconsistent.

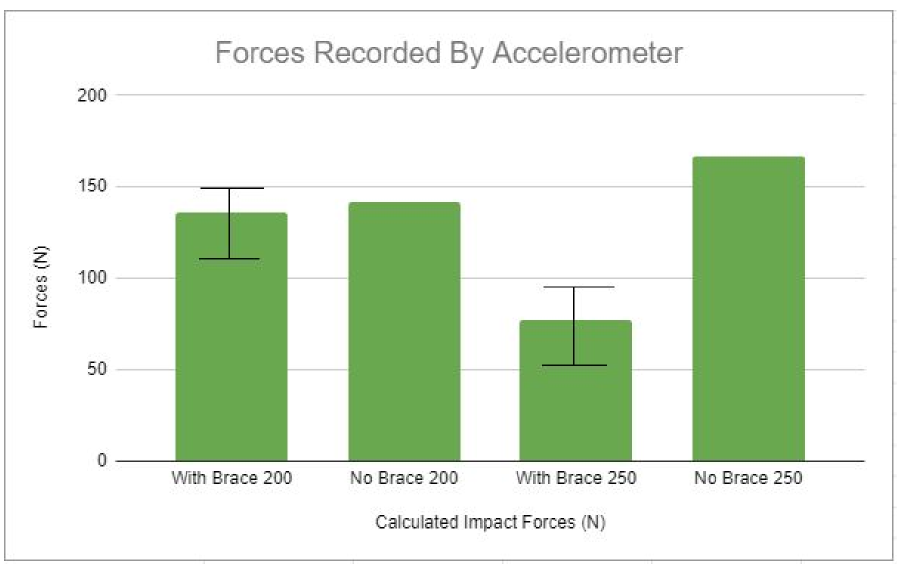


Fig. 40: *Forces recorded by accelerometer during pendulum impact tests*

5.2 Compression Test Results

Table. 15: Compression Test Results

Compression Test Results			
Force Test	Shoulder (N) [Horizontal and perpendicular to shoulder]	Shoulder w/ Optional Strap (N) [Horizontal and perpendicular to shoulder]	AC Joint (N) [Vertical]
Test 1	20	33	25
Test 2	20	33	25
Test 3	23	28	25
Test 4	23	34	25
Test 5	N/A	N/A	20
Test 6	N/A	N/A	21
Test 7	N/A	N/A	25
Average	21.5	32.0	23.7
St. Dev.	1.7	2.7	2.2

Table 15 shows the data that our team was able to measure and collect when running compression tests of the brace. Our team is confident in the data as it was both consistent and repeatable for seven different trials of testing on the AC joint, and eight different trials of testing on the shoulder. The average compression on the shoulder was tested to be approximately 50% greater with both tri-straps compared to one. The compression applied to the AC joint was similar to the compression applied to the shoulder by a single tri-strap.

5.3 ROM Test Results

Table 16: Range of Motion Test Results

Range of Motion Test						
	Healthy Non-Brace (Degrees)	Healthy With Brace 1 strap (Degrees)	Healthy With Brace 2 Strap (Degrees)	1 Strap Difference (Degrees)	2 Strap Difference (Degrees)	Healthy Shoulder Range of Motion
Flexion*	157	132	91	25	66	180
Extension*	53	33.5	21	19.5	32	45-60
Vertical Abduction*	128	113	84	15	44	150
Vertical Adduction	0	0	0	0	0	0
Horizontal Abduction*	110	103	103	7	7	150
Horizontal Adduction	75	68	72	7	3	75
Medial Rotation	77.5	77.5	77.5	0	0	90
Lateral Rotation*	53.5	43	33	10.5	20.5	70
External Rotation*	89	70	52	19	37	90
Internal Rotation*	51	34.5	24	16.5	27	90

**Dangerous Ranges of Motion*

The measurements found in Table 16 show the differences in shoulder range of motion when wearing no brace, our brace without the optional strap, and finally our brace with the optional strap. The first test was done on a healthy shoulder without the brace, to act as a baseline to compare ranges of motion with the brace on. The WPI athletic training staff confirmed that limiting range of motion to 10-20 degrees below the healthy ROM would greatly reduce the risk of injury. Flexion, Extension, Vertical Abduction, Horizontal Abduction, Lateral Rotation, External Rotation, and Internal Rotation were confirmed by the training staff to be most susceptible to injury. Without the optional strap, wearing the brace decreased the shoulder range of motion about 10°-25° in the most dangerous positions. Adding the second strap to the brace decreases the range of motion even more, nearly doubling the reduction in most cases.

5.4 Ease of Use and Comfort Results

Table 17: Times to Put on the Brace with and Without Additional Help

Time to Put on Brace				
	Trial 1 No Optional Strap, No Help	Trial 2 With Optional Strap, No Help	Trial 3: No Optional Strap, With Help	Trial 4: With Optional Strap, With Help
Time (s)	22.02	38.37	14.68	23.91

The times found in Table 17 show how long the brace takes to put on given different circumstances. The first two timed trials of the brace were done just by the athlete with no additional help. Oftentimes when gearing up for a football practice or a game, a player can ask for help in putting on equipment. Our team wanted to test how long it would take in situations where a teammate or trainer could help in putting on the brace. To test this our third and fourth timed trials were done with the aid of another person.

Before testing, our team developed hypotheses that the addition of the optional strap would increase the time it took to put on the brace, and that help from another person would drastically cut down the time to put on the brace. Both hypotheses proved to be true, as we see an increase of 16.35 seconds and 9.23 seconds when timing with the optional strap, and drastically lower times with the help of another person. Without the optional strap, there was a 33.3% decrease in time to put the brace on with help when compared to putting it on without help. With the optional strap, there was a 37.69% decrease in time to put the brace on with help when compared to putting it on without help. Our team believes the reason the brace took longer to put on with the optional strap in every test was due to the positioning of the strap on the lower back portion of the brace. This position is the hardest to reach with the brace on. We believe that with more experience and the brace breaking in over time, these times to put on could drop significantly.

The comfort test validated a significant number of our team's design parameters for the shoulder brace including comfort, breathability, and wear resistance. According to the wearer of the brace, before physical activity, it fit comfortably, correctly, had good compression on the shoulders, and was not too hot, restrictive, or bulky. However, the neck was a little tight and the armpits bunched up. When the additional strap was added, the wearer felt no extra weight or restriction, and felt greater compression. When asked if the wearer of the brace would use the optional strap, he responded, “for most practices and since I have relatively healthy shoulders I feel that one strap will provide enough protection… if I had injured my shoulder before or am playing in a game I’d consider wearing the optional strap for more compression”. This statement confirms the functionality of the optional strap and the reasoning for making it removable by being velcroed to the front and back of the brace. Additionally, after 10 minutes of physical activity with only the shoulder brace, the wearer of the brace noted that the brace felt good and had no restriction to running or necessary football movements. In addition, the straps stayed secure in the correct spots, showing the brace’s strong structure. Furthermore, the wearer of the brace did not get too hot and predicted they would be able to wear the brace for prolonged use.

Fig. 41: *Right and left shoulder view of brace under shoulder pads*

The comfort test with shoulder pads proved that the shoulder brace worked cohesively with other pieces of football equipment and was suitable for contact situations. When wearing the brace underneath shoulder pads and before physical activity, the wearer of the brace stated that the brace fit comfortably, the shoulder pads fit correctly, there was no slippage between the two, and that there was no interference with the strapping mechanisms. In addition, the wearer was able to put on and remove the shoulder pads with no additional help, and felt more protected than with just shoulder pads and no brace. The only negative was that the neck of the shoulder brace rode up and got a little tight. After 10 minutes of physical activity with the brace and shoulder pads, the shoulder pads stayed in place, the brace felt comfortable, was not too restrictive, and the wearer did not overheat. The wearer of the brace stated that he had “a little sweat going as expected” and that he did not overheat “more than usual” when compared to wearing just shoulder pads. Breathability is one of the largest concerns for most shoulder braces, and this statement confirms that the perforated neoprene makeup of our shoulder brace proved effective. Furthermore, the shoulder brace straps stayed more secure under the added compression of the shoulder pads, and all but the AC straps were adjustable from underneath the shoulder pads. The full list of questions and answers can be found in Appendix 6.

Fig. 42: *Front view of brace under shoulder pads*

5.5 Grid Sensor Test Results

5.5.1 Grid Sensor Calibration

The initial curve from the calibration was promising, showing the general trend that as force increased resistance fell. This static loading was generally consistent across both sensors. Below is a graph of all cells averaged, as each cell had the load directly applied to it, so the expectation was that each cell would behave relatively similarly.

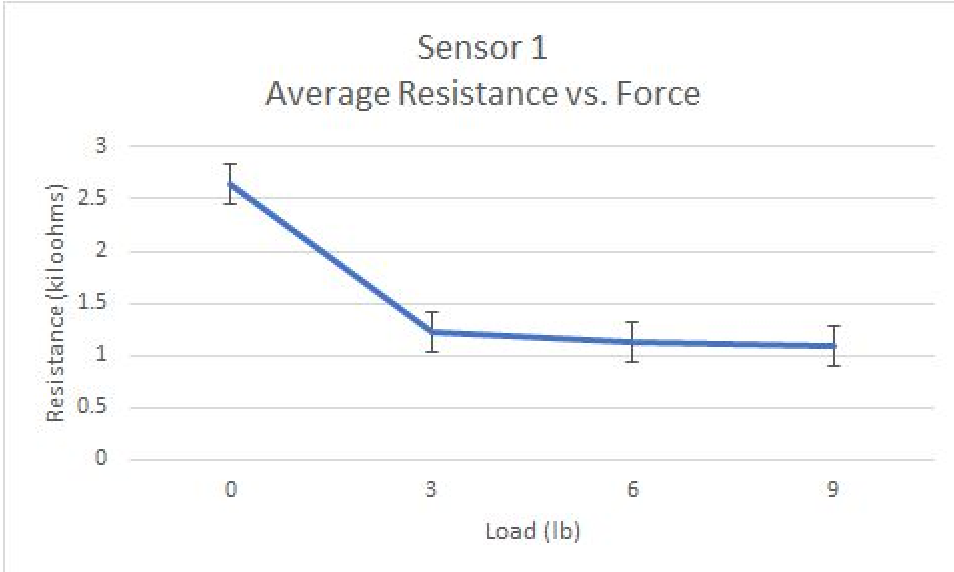


Fig. 43: *Grid Sensor calibration results (Sensor 1)*

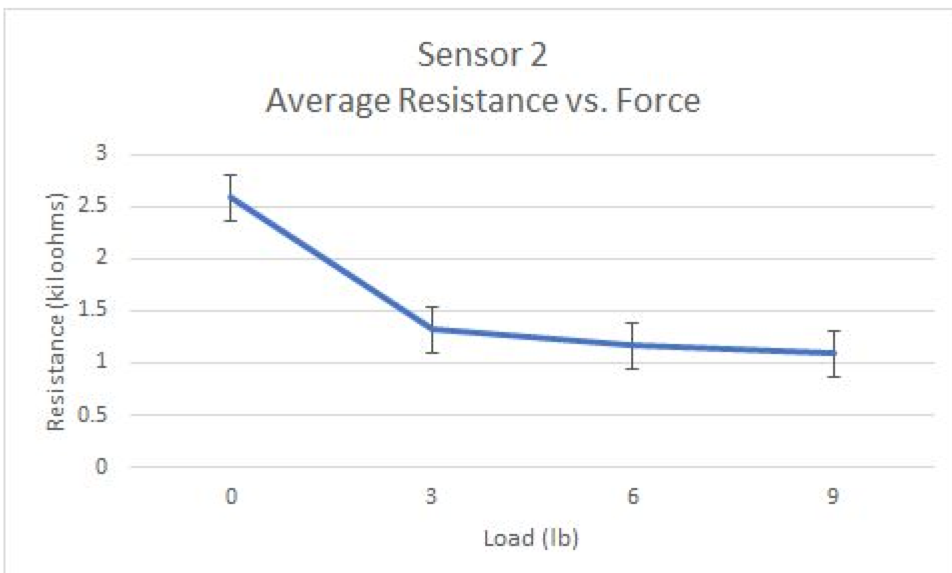


Fig. 44: *Grid Sensor calibration results (Sensor 2)*

The resistance readings were very consistent between each cell, with a standard deviation of less than 0.2 kΩ once the load was applied. As far as static loads go, it appeared that the Grid Sensor measured different levels of pressure consistently across the whole grid. This test accomplished the goal of checking for consistency across the sensors and getting an initial correlation between force and resistance.

5.5.2 Grid Sensor Drop Tower Testing

The results of the Drop Tower testing can be seen in Figures 45 and 46 below, presented as an average of the cells that would be most directly impacted during the pendulum test versus impact force applied. These cells would be the interior cells: B2, C2, B3, and C3.

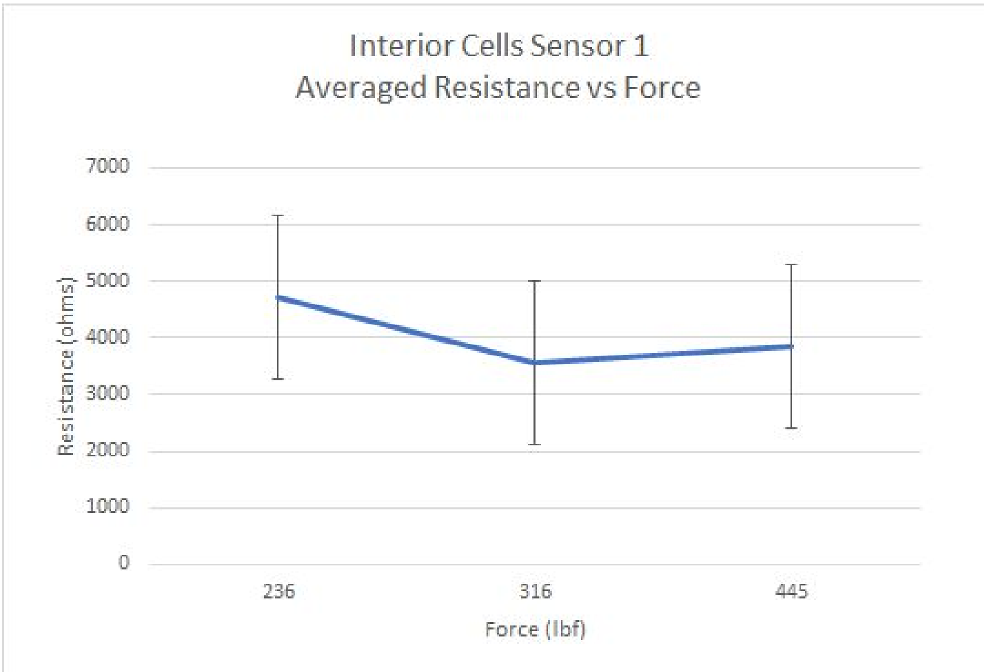


Fig. 45: *Drop tower results (Sensor 1)*

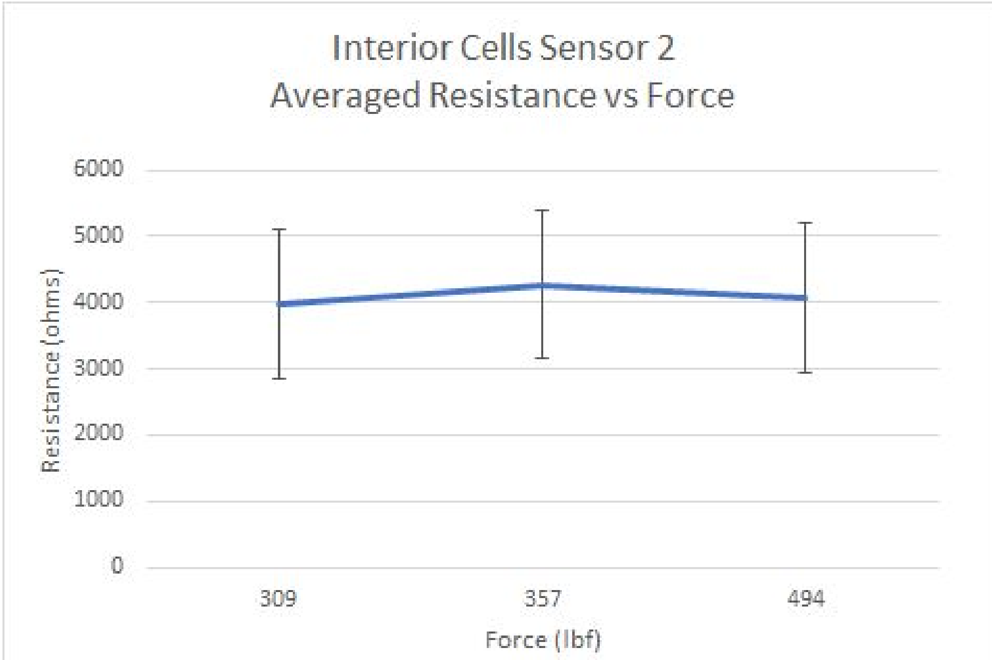


Fig. 46: *Drop tower results (Sensor 2)*

These averaged cell results showed a massive amount of variance across the cells. This was a persistent problem, showing up in both sensors with a standard deviation at each applied force of over 1000 ohms. These results showed an inconsistent ability to detect difference in force applied, as neither graph featured the curve that was expected out of them, shown in the calibration tests to be consistently decreasing resistance versus force.

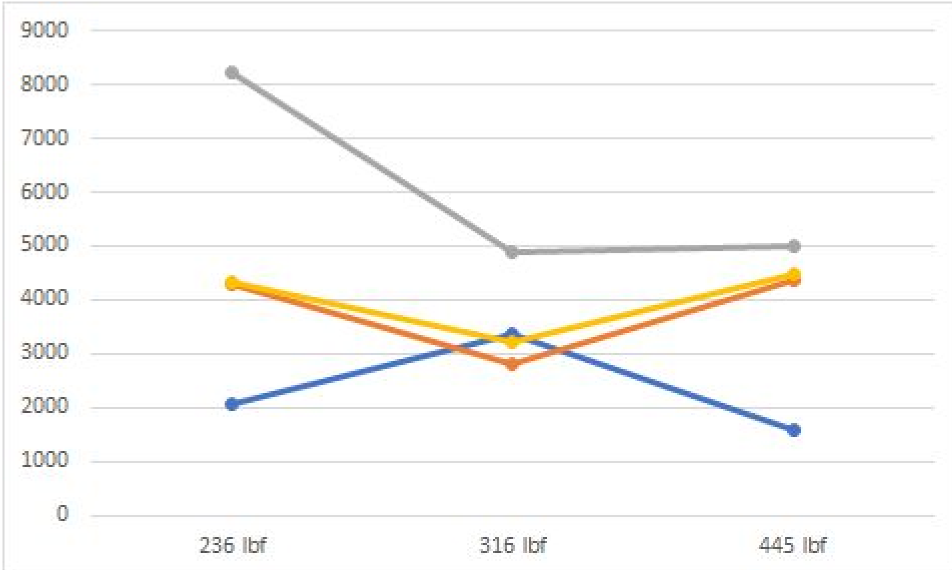


Fig. 47: *Drop tower test resistance versus force graph*

In Figure 47 sensor cells B2, B3, C2, and C3 resistance versus force graphs were plotted, and there was no discernible trend, so correlating force to a resistance level was not possible. The takeaway from this test was that when the sensor was laid flat on a hard surface, the sensor was capable of detecting that it had been impacted and reporting that back to the monitor, but it could not discern between different levels of force. One possible hypothesis is that these forces exceeded the threshold where the material can detect differences in force, and that at lower forces the sensor could theoretically be capable of correlating force to resistance, however these were the lowest forces that we were able to test with the equipment on hand.

5.5.3 Grid Sensor Pendulum Test Results

The following are the results of the pendulum testing. The expectation was that as a higher force was applied, the sensor values would decrease, as Velostat decreased in resistance as a function of force. The interior four cells of the sensor, B2, B3, C2, and C3 were the values used in further analysis, as those are the cells that the pendulum hammer was centered over.

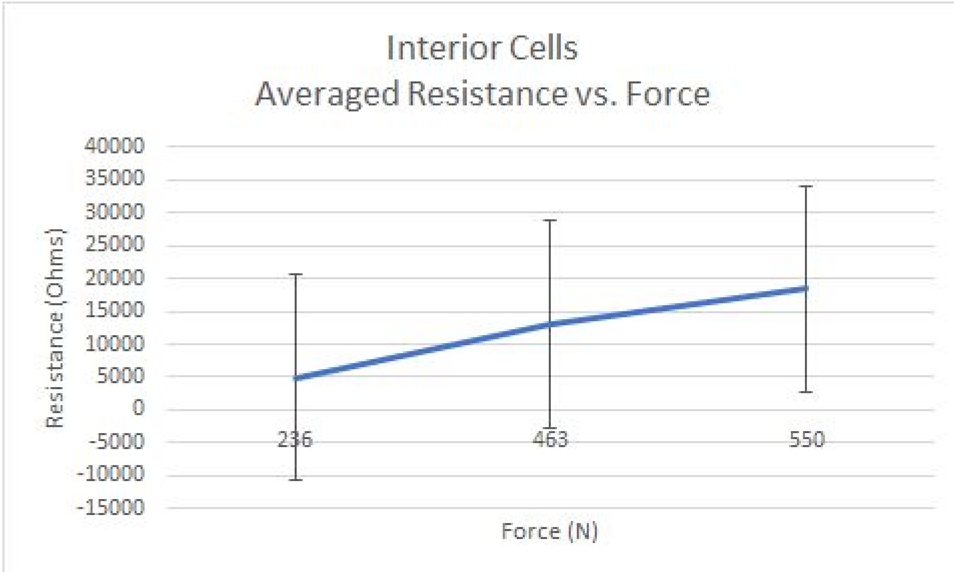


Fig. 48: *Pendulum test average resistance vs. force*

As the data illustrates in Figure 48, there is no discernible trend between forces just as the drop tower data in Figures 45 and 46 suggest.

5.5.4 Grid Sensor Bend Testing

The following are the results of the bend test performed on the Grid Sensor to measure the resistance versus radius of curvature.

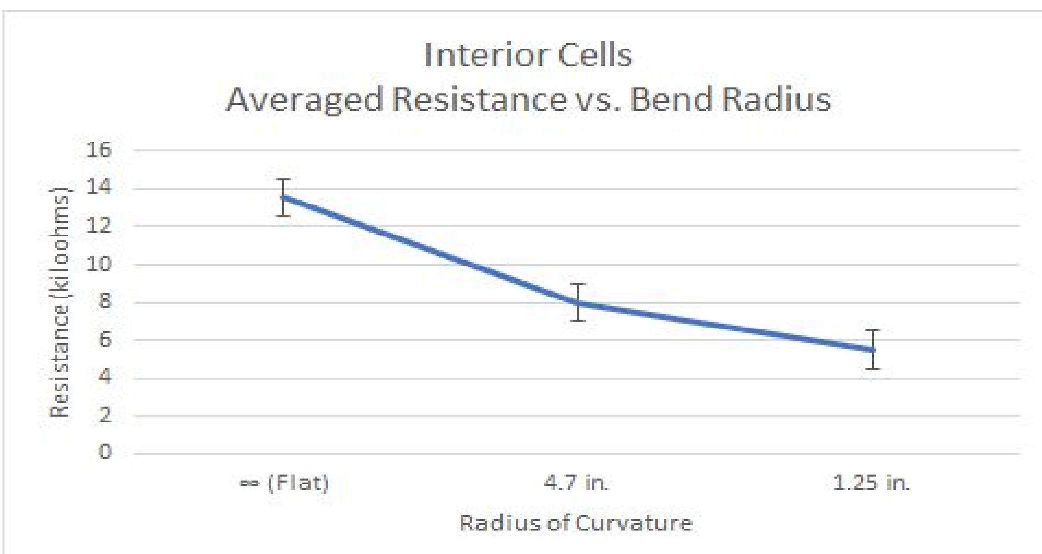


Fig. 49: *Grid Sensor bend testing results*

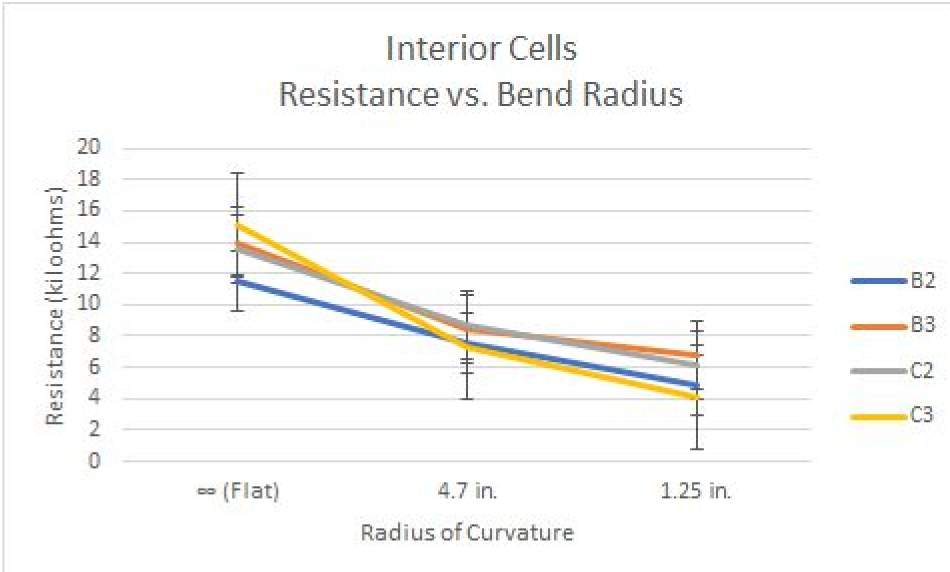


Fig. 50: *Resistance vs. radius of curvature of B2, B3, C2, C3 cells*

The bend test results shown in Figures 49 and 50 illustrate that the sensor is actually very responsive to flexure, showing a consistent change in resistance across all four cells measured as the angle the sensor is bent gets larger. This could be a useful application for this sensor with more testing done to build a correlation.

6. Discussion

6.1 Shoulder Brace Discussion

As shown in Section 5, the shoulder brace proved effective at compressing the shoulder joint, limiting ranges of motion, and providing superior comfort to that reported of current shoulder braces. Also, the side delt padding proved effective at absorbing impact through the drop tower tests.

Results of the pendulum test showed signs of promise, but were ultimately inconclusive due to the lack of consistent data. However, the drop tower test during our material selection indicated that the shoulder brace achieved the function of reducing impact forces that could cause shoulder separation and AC joint injuries. Since the force plate of the Instron drop tower was very sensitive, we were unable to test the impact force with no padding in fear of damaging the machine. In addition, we were unable to test the impact force felt on a realistic shoulder model because it was not adaptable with the drop tower. Nonetheless, the results from the test showed that EVA foam padding, with the same thickness as the shoulder brace padding, had a reactionary impact force of 324.27 lbf ± 4.79 when having 15.28 lbs dropped on it from a height of 10 cm. Polyurethane foam padding of the same thickness and under the same conditions resulted in a reactionary impact force of 1,589.39 lbf ± 20.12. This means that EVA foam had a force reduction of 79.6 % when compared to PU foam. Our initial goal was to reduce impact felt on the shoulder by 22.6 %. The reduction of 79.6 % in the drop tower test was the result of comparing different pad materials and does not account for the geometries and anatomy of an actual shoulder or football collision. The incorporation of this padding makes the brace the only one our team could find that has foam padding on the side delt specifically to reduce chances of AC joint injuries and shoulder separations, which produced favorable reductions in force and was the first brace to incorporate this technology into a shoulder brace.

Results of the compression test revealed that our shoulder brace achieved one of it's functional requirements of compressing both the AC joint and glenohumeral joint. Therefore, it would take a higher force applied on the shoulder to dislocate it if wearing this shoulder brace.

The optional strap system on our team's shoulder brace allowed for additional compressive forces to be applied parallel to the shoulder joint. Our research showed that 45 Newtons of compression improves the dislocation force of a shoulder from 525 N to 625 N (Gutiérrez, Keller, Levy, & William E. Lee, 2008). With the optional strap, our shoulder brace had a compressive force of up to 32 N. Through linear interpolation we determined that 32 N of compression may increase the dislocation force of a shoulder from 525 N to an upper limit of 596 N. While the compression of both the shoulder and AC joint did not achieve the goal magnitude of 45 N on the AC joint and perpendicular to the shoulder, the shoulder brace did achieve a favorable compression that increased dislocation forces significantly and with the addition of padding on the deltoid, reduced the risk of shoulder separation even further. One hypothesis that our team made, following the conclusion of compression testing, was if the straps were constructed of a stronger material then the compression force would most likely increase. The counterpoint to a stronger strap material is the possibility of compromising comfort of the brace.

From the ROM tests our team concluded that the brace did an effective job at limiting vulnerable ranges of motion. Our research showed that the more that a shoulder is abducted, the fewer soft tissue stabilizers are functionally contributing to anterior stability (Weise et al, 2004), and the easier it becomes to dislocate the shoulder from abrupt forces. Since the shoulder brace reduced dangerous ranges of motion to 10-20 degrees below the hazardous limit with one strap, thereby decreasing the dislocation effect of abrupt forces, we concluded that football players with no history of injury would benefit from using one strap to limit ROM, giving them the most lightweight solution to minimizing injury without compromising effectiveness. However, players returning from injury can use two straps for added protection since the range of motion limitation was nearly doubled.

With vertical abduction, the weakest point where the least amount of stabilizing muscles are activated is at 90 degrees. Anything below 90 degrees of vertical abduction significantly increases the reactionary forces that the shoulder is able to generate against the forces that cause dislocations (Weise et al, 2004). To most effectively limit dislocations, a brace should not let the wearer be able to reach or surpass 90 degrees of vertical abduction. Our brace accomplished this by limiting vertical abduction to 84 degrees.

Additionally, we concluded that the brace is not difficult to put on and does not hinder the ability of the athlete to get geared up in a timely manner. As shown in Table 3, one of the parameters for enhancing ease of use was that the brace should take less than 30 seconds to completely put on. Shown by our data, we were able to accomplish this in three out of the four trials. The only trial over 30 seconds was conducted with the optional strap and no help. We believe that the additional 8 seconds is miniscule in terms of the extra amount of protection and support the optional strap gives to the shoulders. Also, it is very rare that a football player is unable to ask for help with putting on a brace, however the extremely low times recorded concluded that the brace can be put on by the athlete alone or with one other person. These timed trials confirmed that the brace was simple, straightforward, and easy to put on. One consideration that could be made from the timed tests was that the placement of the optional strap was in a difficult position to reach on the lower back.

Also, Section 5.4 proved that the shoulder brace was comfortable and worked cohesively with other pieces of football equipment. Results from the football survey in Section 3 showed that 88.6% of WPI football players with a history of shoulder injury did not wear a shoulder brace. Reasons for not wearing a shoulder brace included, “most are uncomfortable and restrict a lot of mobility”, they are “too bulky”, and they are “too hot”. The comfort test confirmed that the shoulder brace was breathable, comfortable, not too bulky, and did not restrict needed mobility. During physical activity, the team member was able to perform all necessary football movements, and did not overheat or become irritated. In addition, the brace fit comfortably underneath shoulder pads, with the functionality of neither the shoulder pads nor brace being hindered. During physical activity with both the brace and shoulder pads, the team member felt more protected, did not overheat or become irritated, and was once again able to perform all football movements. Throughout each of the tests, the brace remained intact and all of the straps stayed secure, thereby demonstrating the brace’s functionality. In conclusion, the shoulder brace was shown to be suitable for use in actual football activity and provided comfort for the athlete, that of which most shoulder braces on the market have been proven to lack.

Overall, the project was successful because our team was able to design, construct, and test the shoulder brace, as well as improve upon a testing rig to better simulate football collisions involving the shoulder. Our shoulder brace achieved most of the necessary functional requirements our team identified, but it excelled through aesthetics, stacking up favorably versus professionally manufactured braces on the market.

Our team identified the customization of the brace to be one of its best qualities. For example, in instances where an athlete does not have AC joint pain, the AC joint straps can be fastened loosely to the brace. In instances where an athlete's shoulder needs more compression and protection the optional strap can be velcroed onto the brace. With athletes with one healthy shoulder and one injured shoulder the brace serves as a twofold injury protection and prevention mechanism. These are just some of the ways the brace exemplifies its adaptability to the athlete using it. Finally, this brace can transcend past the sport of football and be useful in applications in other areas such as lacrosse, hockey, military operations, and manual labor professions, thereby expanding useful applications of our brace.

6.2 Sensor Discussion

The calibration of the Grid Sensor showed that the initial hypothesis that the piezoresistive nature of Velostat could be used to measure force versus resistance was true at least in concept. The drop tower test suggested that that could continue to be true within the force limits of about 600 lbf (2669 N). However, this test also suggested that the material may not respond well to impact.

During the initial stages of testing while we tried to find the force range we could test with the drop tower, certain cells were returning maximum resistance values which indicated that no voltage was being read at the input pin by the processor. This suggested that this was likely the saturation point of the material, as we were able to get a full sensor readout below that threshold of 600 lbf. It was reasonable to believe that this was actually the high end of where the saturation point could be, as the graph was showing an irregular pattern for force versus resistance. It was hypothesized, were the applied force to be reduced, a correlation between force and resistance could be found, however this cannot be addressed as we tested at the lowest force the drop tower can test at. From what can be seen from this test, there was no discernible trend between impact force and resistance.

Successfully detecting impact, however, meant the microcontroller was polling the sensors fast enough to detect impacts and the triggering function was effective at sending values to the serial monitor only when impact was detected. This meant a sampling rate of at least 1 kHz was achieved, which was no small feat.

The shoulder brace impact testing brought on several complications for the sensor. Velostat needs to be squeezed for it to change resistance, and the shoulder of the dummy was too soft to register the correct response from the material. In this particular application for impact detecting, the sensor had trouble picking anything up. This was partially due to having pressure applied from the straps of the brace, which alter the reported resistance from the sensor, as well as the sensor being bent over the shoulder of the dummy. As seen in the bend testing, flexure consistently altered the resistance of the sensor. This in turn rendered the trigger function, the method used in the monitoring software to exit the resistance sampling loop, near useless as the while loop used to detect outlier values from impact relied on a predictable unloaded resistance from the trigger cell in the grid. When the sensor was taped flat to a hard surface the trigger cell, B2, usually sat at an unloaded resistance of 2500 ohms. Then the trigger function could be set at about 2200 ohms so that when the sensor was impacted, and the resistance dipped below that threshold, the program exited the sampling loop and printed the measurement. However, when the sensor had been placed under the brace and strapped in, the resistance ranged between 900 and 1500 ohms, and that variable resistance prevented any useful threshold resistance from being set.

Unfortunately, this exact purpose of sensing impact on the dummy was what the sensor had been designed for. This made the measuring of force with and without the deltoid padding difficult. Our methodology for that test was that we had calculated the force the pendulum was delivering, and the accelerometer should have been returning the force that was felt by the dummy. Then we compared the forces measured with the deltoid padding and compared that to the force felt without the deltoid padding.

Once it was determined that the Grid Sensor could not be relied on for the impact data we were looking for, the accelerometer was relied on as our only source of data collection. This was originally supposed to primarily be a fact checking device, allowing us a comparison value between something we could expect to be reliable (the accelerometer), and something we were still figuring out (the Grid Sensor). This is largely why only one accelerometer was used, as the Grid Sensors were expected to be the primary measuring device.

7. Conclusions

7.1 Shoulder Brace Conclusions

The following conclusions were made by our team following completion of material testing, testing of the brace, and analysis of its performance.

1. The side delt padding appeared to reduce forces felt during impact.
2. Ranges of 20-23 N and 28-34 N of compression were exerted on the shoulder with one and two straps respectively. In addition, a range of 21-25 N of compression was exerted on the AC joint.
3. It is expected that using the brace would reduce the chances of AC joint injuries and shoulder separation. This is due to the predicted force needed to dislocate the shoulder increasing.
4. The brace reduced dangerous ranges of motion to 10-20 degrees below hazardous limits, thereby it decreased the chances of dislocations and subluxation.
5. The brace was fast and easy to put on with or without help from another individual.
6. The shoulder brace was comfortable and worked cohesively with other pieces of football equipment.

7.2 Sensor Conclusions

The following conclusions were made by our team following completion of testing of the sensors and analysis of its performance.

1. The Grid Sensor could measure the difference between different levels of static load.
2. The Grid Sensor could also detect when it had been impacted when placed on a hard, flat surface.
3. The Grid Sensor software could be used to poll the sensor at a high enough sampling rate to be used in impact testing environments.
4. It could not detect impact on a softer surface.
5. The sensor could not measure the amount of force applied to it.

6. The sensor could potentially measure bend radius.
7. The accelerometer was successful at measuring the force experienced on the dummy, until we exceeded the force rating of 16g during the pendulum testing.

8. Recommendations

8.1 Brace Testing Recommendations

Our team recommends further testing on the brace by implementing an IRB approved test where different test subjects put on the brace and are tested for ROM, ease of use, comfort, and compression. This would give a larger sample size to draw more conclusions. In addition, we recommend implementing an IRB approved on-field test. This test would start with football players using the brace during actual light contact practices to determine its functionality throughout the duration of a practice. These tests would ideally scale up to full contact practices and eventually games, allowing meaningful conclusions and alterations to be made on the brace. The goal of the additional tests would be to have a final shoulder brace product that is ready for market and immediate full contact use.

Another future test of the brace could be conducted on the velcro itself, determining how long the velcro stays strong and capable of withstanding constant use. This could be done counting how many times the velcro can be attached and detached until the velcro has lost its ability to hold together. Another way to go about this test could be through an active player using the brace, counting each time they attach and unattach the velcro per day for a week, and using that number to multiply by the amount of days until the velcro wears out.

8.2 Brace Design Recommendations

Using the feedback from the comfort and ease of use test, our team would have the armpits of the brace cut out. Our reason for keeping the armpits sewn and intact was to have no losses of compression in the shoulder joint. After analyzing the responses from the test it was clear the comfort of the brace would benefit from eliminating material from the armpit. Other responses from the tests showed that the wearer of the brace became concerned that the straps (red and green straps in Figure 14), when directly in contact with the shoulder, would slip up or down the shoulder when moving. We recommend securing the straps directly to the side of the shoulder, possibly with an extra piece of velcro. In addition, the largest concern from the tests was that the neck rode up and was too tight. Thus, we would cut the neck larger to improve comfort and prevent it from riding up. While this did not affect the functionality of the brace it did affect brace comfort. In addition, changes to the neck and armpit area of the brace would warrant an analysis of tensile loading to determine how the brace would react to stresses with this material now gone.

As discussed in Section 3, the team recommends using Ventiprene for increased airflow while maintaining the same mechanical properties as perforated neoprene (SHEICO Group, 2020). Our team believes that by using Ventiprene instead of perforated neoprene we would have even higher air flow through the brace, and even higher comfort responses during testing.

Finally, in full scale manufacturing of this brace we recommend custom sizing to meet athlete's needs of all shapes and sizes. To accomplish this a sizing chart would be implemented for athletes to choose which size fits best based on measurements around the chest, shoulder, and arms. Continuing with the customizability of the brace, we also recommend custom strapping solutions if needed per request. This would give the opportunity to have all the straps including the optional strap sewn in place for better ease of use. Another option would allow for ordering braces with less straps in cases where either the AC joint straps or tri-straps are unwanted.

8.3 Recommendations for Use of Brace

We recommend not using the optional tri-strap in situations where the extra compression will not be needed. These situations include light contact practices, or on-air drills where forces high enough to dislocate the shoulder will not be felt by the player. This would improve comfort and increase the longevity of the velcro while still providing adequate compression. In situations such as fully padded practices, live drills, and games, the optional tri-strap is recommended for use due to the higher compressive force it exerts on the shoulder. In addition, our tests confirmed that the brace limits the dangerous ranges of motion to 10-20 degrees below the healthy limit with one strap. With the optional strap, that limitation nearly doubles. Therefore, we acknowledge that players with no history of shoulder injury (wearing brace for prevention) can wear the brace with one strap to improve comfort, and football players returning from shoulder injury looking for maximum protection should wear the brace with the optional tri strap.

Finally, our team recommends keeping the side delt padding in any and all versions of a shoulder brace. Not only is it aesthetically pleasing, but also functional in reducing the chance of injury. While full scale pendulum tests were inconclusive, testing impact with the Instron drop tower proved the pad's force reduction capabilities, as the padding is made of EVA foam which our team also proved was the best force absorbing foam of our samples gathered.

8.4 Sensor Recommendations

The sensor is clearly not usable for detecting and measuring the magnitude of impacts on non-rigid surfaces. However the drop tower tests suggest that it could be used as a lower cost method to measure if a rigid surface is impacted. The calibration also showed that at lower forces where the contact is not high speed, there is promise in the sensor being able to measure forces, but the applications are certainly more limited than initially hoped.

With that said, Figures 49 and 50 show that the sensor responds fairly consistently to bending. Each sensor cell has a similar resistance versus radius of curvature response, which suggests that with further testing the Grid sensor could potentially be used in applications where tracking flexure is important. There appears to be a fairly consistent correlation between the resistance of the sensor and the flexure.

The sensor could be used for detecting pressure on rigid surfaces, just not measuring the magnitude of the force. So it would be reasonable to assume it could be used for situations where you need to know if something is resting on top of the sensor, for example a doormat that alerted the occupants of the house if something was on the doormat.

9. Acknowledgments & Reflections

Our team would like to first and foremost acknowledge Professor Fiona Levey for guiding us through the entirety of the MQP process. With her guidance, we were able to turn our idea for a shoulder brace that would benefit the people around us, into a functional prototype. We would also like to acknowledge Joseph from Design by Joseph for his help in sewing and tailoring the brace together. Additionally, we would like to acknowledge Russel Lang for his help with the impact drop tower testing and the WPI Athletic Training Staff for their input in determining vulnerable shoulder ranges of motion.

Looking back, our team learned that jumping into the design process before identifying customer needs slowed progress and wasted time. Each of us came into the design process with unique pre-set notions and ideas of how we wanted the brace to function and what it would look like. We subsequently learned how to take a step back and identify the needs of the athletes that we were designing the brace for. The customer needs could be collected from the customers themselves, and after these needs were identified the design of the brace became much more clear. With jumping into the physical design first, our team had to eventually go back and rethink the design over because an idea that seemed useful at first would conflict with too many customer needs not yet identified.

One of the most helpful things that we did as a team that fostered a good design was carry out many brainstorming sessions. The time spent brainstorming immensely helped with our creativity and allowed us to rank different ideas against each other and decide as a group which design aspects to move forward with.

Our team also learned the importance of modeling. By being able to model the side delt padding in solidworks, the neoprene material in solidworks, and the pendulum impact tests with calculations, we were able to justify our decision making and incorporate the engineering thought process into our design. Modeling lowered the risk of performing futile tests and improved the validity and reasoning behind our final results.

Finally, our team most importantly learned how to ask why. The turning point to our project came to us when we started to ask why for each and every design aspect: “Why does the brace need straps?" "Why should we build it out of perforated neoprene?" "Why should it be comfortable?" and finally, "Why are we designing this improved shoulder brace in the first place?" By asking why, our team was able to concretely formulate our plan, put that plan and the little details of the brace into perspective, and establish functions that the brace must accomplish.

Seeing our shoulder brace become a working prototype that actually exceeded our expectations was the most rewarding part of this MQP process. This project was over a year in the making with the initial idea for a shoulder brace being brainstormed in the spring of last year and research beginning at the start of the summer. Each step of the process including brainstorming, designing, modeling, building, and testing our shoulder brace had its challenges, but having each step be cross checked and verified in a number of ways proved to have astonishing results.

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Appendix 1. WPI Football Team Survey

QUESTIONS RESPONSES 51

Section 1 of 6

Shoulder Injury History Survey

Form description

What is your primary position?

- QB
- RB/FB
- OL
- TE
- WR
- DL
- LB/OLB
- DB/S
- K/P

How long have you played football?

- 0-1 yrs
- 1-2yrs
- 2-5yrs
- 5-10yrs
- 10+ yrs

Have you ever injured your shoulder playing football?

- Yes
- No

Section 2 of 6

Non-Injured

Description (optional)

Would you consider wearing a shoulder brace for shoulder injury prevention?

- Yes
- No

After section 2 Go to section 6 (Untitled Section)

Section 3 of 6

Injury History

Description (optional)

How many shoulder injuries have you had throughout your career?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5

Have you injured just one or both shoulders?

- ○ Just One
- ○ Both

Do you wear a shoulder brace because of said shoulder injury?

- ◯ Yes
- ◯ No

After section 3 **Continue to next section**

Section 4 of 6

Shoulder Bracing

Description (optional)

What kind of shoulder brace do you use?

Long answer text

What do you like/dislike about using the brace and what improvements do you think could be made to it?

Long answer text

Section 5 of 6

Non-Shoulder Brace

Description (optional)

Why do you not wear a shoulder brace? (What are your complaints with them)?

Long answer text

Would you consider wearing a shoulder brace if it was a better more comfortable design?

- ◯ Yes
- ◯ No
- ◯ Other...

Section 6 of 6

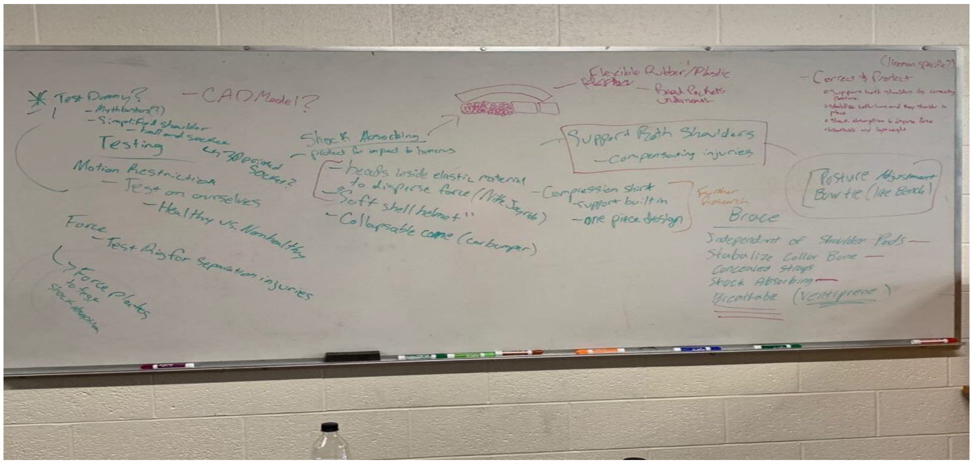
Untitled Section

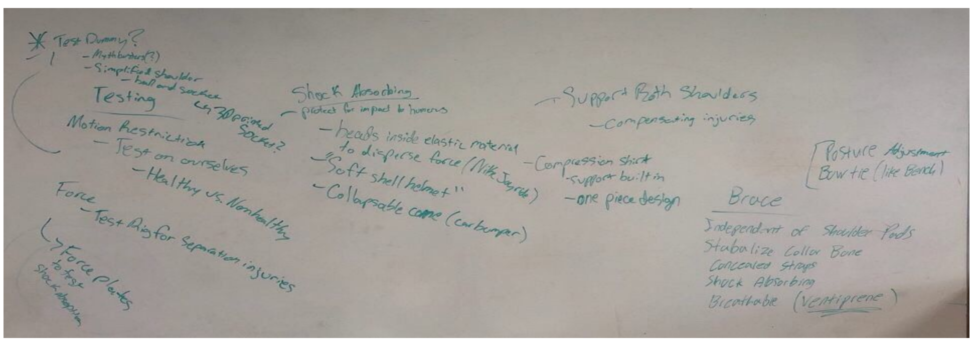
Description (optional)

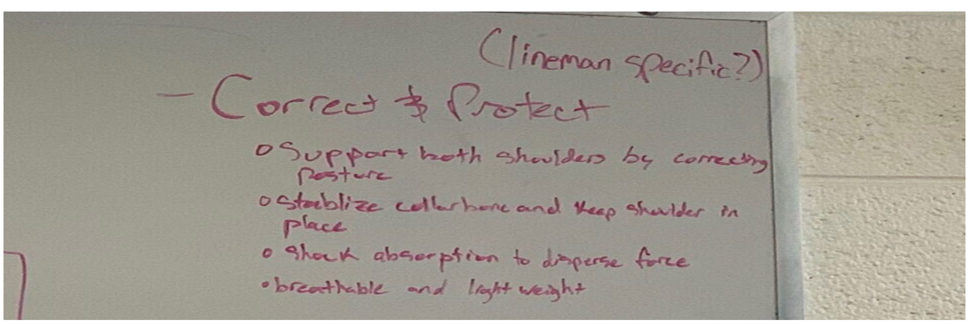
Why or why not would you wear a shoulder brace for injury prevention?

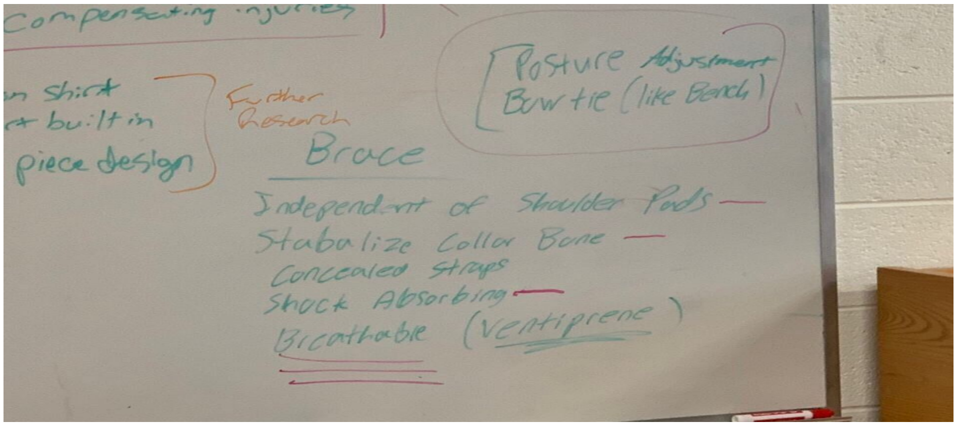
Long answer text

Appendix 2. Brainstorming








Compensating injuries
Posture Adjusment
Bowtie (like Bench)
n shirt
t built in
piece design
Further Research
Brace
Independent of Shoulder Pads
Stabalize Collar Bone
Concealed straps
Shock Absorbing
Breathable (Ventiprene)

Appendix 3. Grid Sensor Monitoring Application Source Code

```
//status LED
const int LED_BUILTIN = 2;
//assigning input and output pins
const int ap1 = 36;
const int ap2 = 39;
const int ap3 = 12;
const int ap4 = 13;
const int di1 = 23;
const int di2 = 22;
const int di3 = 1;
const int di4 = 3;
//storage variable declarations
int sv1 = 0;
float ov1 = 0;
int sv2 = 0;
float ov2 = 0;
int sv3 = 0;
float ov3 = 0;
int sv4 = 0;
float ov4 = 0;
int sv5 = 0;
float ov5 = 0;
int sv6 = 0;
float ov6 = 0;
int sv7 = 0;
float ov7 = 0;
int sv8 = 0;
float ov8 = 0;
int sv9 = 0;
float ov9 = 0;
```

```
int sv10 = 0;
float ov10 = 0;
int sv11 = 0;
float ov11 = 0;
int sv12 = 0;
float ov12 = 0;
int sv13 = 0;
float ov13 = 0;
int sv14 = 0;
float ov14 = 0;
int sv15 = 0;
float ov15 = 0;
int sv16 = 0;
float ov16 = 0;
int a1 = 0;
int a2 = 0;
int a3 = 0;
int a4 = 0;
int b1 = 0;
int b2 = 0;
int b3 = 0;
int b4 = 0;
int c1 = 0;
int c2 = 0;
int c3 = 0;
int c4 = 0;
int d1 = 0;
int d2 = 0;
int d3 = 0;
int d4 = 0;

//constants for calculation
int R2 = 550;
```

```
int Vin = 3.3;
int hi = 4095;

void setup() {
  // initialize serial communications at 38400 bps:
  Serial.begin(38400);
  pinMode(LED_BUILTIN, OUTPUT);
  pinMode(di1, OUTPUT); //set dig I/O to output
  pinMode(di2, OUTPUT);
  pinMode(di3, OUTPUT);
  pinMode(di4, OUTPUT);
}

void loop() {
  Serial.println("Begin Measuring" );
//initialize variable for exiting sampling loop
int n = 0;

  digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on, testing to see if code has uploaded

  // Sampling section, once outlier value is detected break the loop
  while(n == 0){

  digitalWrite(di1, hi); //set di1 to high
  digitalWrite(di2, 0); //set di2-4 to 0
  digitalWrite(di3, 0);
  digitalWrite(di4, 0);

  delay(1); //timing delays after each digWrite

  sv1 = analogRead(ap1); //read voltage at ap1
  ov1 = (sv1 * 3.3) / 4095; //convert from dig voltage to an Voltage, 4095 bits, reference voltage
3.3 V
```

```
delay(1); //timing delays for each anRead

sv2 = analogRead(ap2);

ov2 = (sv2 * 3.3) / 4095;

delay(1);

sv3 = analogRead(ap3);

ov3 = (sv3 * 3.3) / 4095;

delay(1);

sv4 = analogRead(ap4);

ov4 = (sv4 * 3.3) / 4095;

delay(1);

digitalWrite(di1, 0);


digitalWrite(di2, hi);

delay(1);

sv5 = analogRead(ap1);

ov5 = (sv5 * 3.3) / 4095;

delay(1);
```

```
sv6 = analogRead(ap2);

ov6 = (sv6 * 3.3) / 4095;

b2 = ((Vin-ov6)*R2)/(ov6); //voltage divider equation, checking "trigger" value

delay(1);

sv7 = analogRead(ap3);

ov7 = (sv7 * 3.3) / 4095;


delay(1);

sv8 = analogRead(ap4);

ov8 = (sv8 * 3.3) / 4095;

delay(1);

digitalWrite(di2, 0); //set di2 to 0

digitalWrite(di3, hi);

delay(1);

sv9 = analogRead(ap1);

ov9 = (sv9 * 3.3) / 4095;

delay(1);
```

```
sv10 = analogRead(ap2);

ov10 = (sv10 * 3.3) / 4095;

delay(1);

sv11 = analogRead(ap3);

ov11 = (sv11 * 3.3) / 4095;

delay(1);

sv12 = analogRead(ap4);

ov12 = (sv12 * 3.3) / 4095;

delay(1);

digitalWrite(di3, 0); //set di3 to 0

digitalWrite(di4, hi);

delay(1);

sv13 = analogRead(ap1);

ov13 = (sv13 * 3.3) / 4095;

delay(1);

sv14 = analogRead(ap2);
```

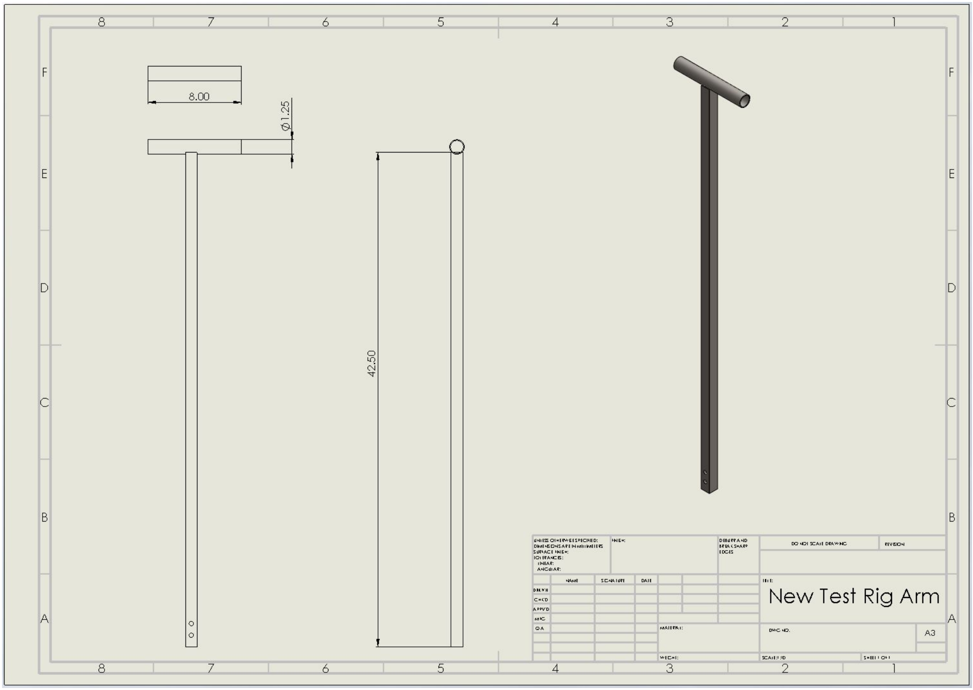
```
ov14 = (sv14 * 3.3) / 4095;

delay(1);

sv15 = analogRead(ap3);

ov15 = (sv15 * 3.3) / 4095;

delay(1);

sv16 = analogRead(ap4);

ov16 = (sv16 * 3.3) / 4095;

delay(1);

digitalWrite(di4, 0); //set di4 to 0

if( b2 < 3200)(          //checks "trigger sensor", if resistance is below trigger threshold, exit loop
                          //Sensor 2 trigger = 3500
        n++              //sensor 3 trigger = 3200

        );
};

//calculation
a1 = ((Vin-ov1)*R2)/(ov1);  //voltage divider calculations for the rest of the grid
a2 = ((Vin-ov2)*R2)/(ov2);
a3 = ((Vin-ov3)*R2)/(ov3);
a4 = ((Vin-ov4)*R2)/(ov4);
b1 = ((Vin-ov5)*R2)/(ov5);

b3 = ((Vin-ov7)*R2)/(ov7);
```

```
b4 = ((Vin-ov8)*R2)/(ov8);
c1 = ((Vin-ov9)*R2)/(ov9);
c2 = ((Vin-ov10)*R2)/(ov10);
c3 = ((Vin-ov11)*R2)/(ov11);
c4 = ((Vin-ov12)*R2)/(ov12);
d1 = ((Vin-ov13)*R2)/(ov13);
d2 = ((Vin-ov14)*R2)/(ov14);
d3 = ((Vin-ov15)*R2)/(ov15);
d4 = ((Vin-ov16)*R2)/(ov16);


// after exiting sampling loop, print the results to the serial monitor:

Serial.print("Resistance at A1 = " );
Serial.println(a1);
Serial.print("Voltage at A1 = ");
Serial.println(ov1);

Serial.print("Resistance at A2 = " );
Serial.println(a2);
Serial.print("Voltage at A2 = ");
Serial.println(ov2);

Serial.print("Resistance at A3 = " );
Serial.println(a3);
Serial.print("Voltage at A3 = ");
Serial.println(ov3);

Serial.print("Resistance at A4 = " );
Serial.println(a4);
Serial.print("Voltage at A4 = ");
Serial.println(ov4);
```

```
Serial.print("Resistance at B1 = " );
Serial.println(b1);
Serial.print("Voltage at B1 = ");
Serial.println(ov5);

Serial.print("Resistance at B2 = " );
Serial.println(b2);
Serial.print("Voltage at B2 = ");
Serial.println(ov6);

Serial.print("Resistance at B3 = " );
Serial.println(b3);
Serial.print("Voltage at B3 = ");
Serial.println(ov7);

Serial.print("Resistance at B4 = " );
Serial.println(b4);
Serial.print("Voltage at B4 = ");
Serial.println(ov8);

Serial.print("Resistance at C1 = " );
Serial.println(c1);
Serial.print("Voltage at C1 = ");
Serial.println(ov9);

Serial.print("Resistance at C2 = " );
Serial.println(c2);
Serial.print("Voltage at C2 = ");
Serial.println(ov10);

Serial.print("Resistance at C3 = " );
Serial.println(c3);
Serial.print("Voltage at C3 = ");
```

```
  Serial.println(ov11);

  Serial.print("Resistance at C4 = " );
  Serial.println(c4);
  Serial.print("Voltage at C4 = ");
  Serial.println(ov12);

  Serial.print("Resistance at D1 = " );
  Serial.println(d1);
  Serial.print("Voltage at D1 = ");
  Serial.println(ov13);

  Serial.print("Resistance at D2 = " );
  Serial.println(d2);
  Serial.print("Voltage at D2 = ");
  Serial.println(ov14);

  Serial.print("Resistance at D3 = " );
  Serial.println(d3);
  Serial.print("Voltage at D3 = ");
  Serial.println(ov15);

  Serial.print("Resistance at D4 = " );
  Serial.println(d4);
  Serial.print("Voltage at D4 = ");
  Serial.println(ov16);

  Serial.println("END DATA SET" );


}
```

Appendix 4. New Test Rig Arm Drawing



Appendix 5. Pendulum Safety Guidelines for Impact Testing

The following details safety guidelines for impact testing using a BOB dummy and pendulum test rig. All team members are required to read and familiarize themselves with these guidelines before any tests can be conducted.

At least three (3) people must be present in order to conduct any tests or operate the test rig and BOB dummy.

All people present or within vicinity must wear safety goggles during all tests

Operator of the test rig arm must wear a hard helmet with an attached face mask while testing.

Only one person is allowed within the blue tape line during testing. This is the operator.

Restricted zone marked by blue tape must be clear of any and all foreign objects

The operator of the test rig arm must lift the arm with their arms outstretched, keeping the weight and test rig arm in front of their body.

All people must stay outside the tape restricted zone.

Before releasing the test rig arm the operator must ensure the restricted area is clear from any person or foreign object and must give a verbal cue when lifting the test rig arm and releasing the test rig arm.

The operator must lift the test rig arm in a slow controlled manner and ensure they have control over the arm before release.

Once the test rig arm is lifted by the operator, the operator gives a ‘ready to release’ command.

Once the operator is ‘ready to release’ and all persons and foreign objects are clear from the restricted area the operator can release the arm.

Upon release the operator should step back out of the restricted zone as soon and as safely possible.

No food or drink is allowed in the restricted zone.

This safety plan shall be posted in a location visible to all people in and around the testing area.

Appendix 6. Comfort Test Questions & Answers

Questions directly after putting the brace on.

Without optional strap

1. **Can you put the brace on by yourself or do you need help?**
    a. Yes, I can put the brace on by myself
2. **How does the brace feel? (fit, feel, weight, irritative) Please explain.**
    a. Fits comfortably. Definitely feel the compression in the shoulders. The neck is a little tight and the armpits bunch up a little , but besides that everything fits great. Not too bulky, and not too hot
3. **Does the brace feel restrictive**
    a. Not too restrictive
4. **Do you feel compression on your shoulders?**
    a. Yes, I feel compression on both shoulders
5. **Do you feel compression on your AC joints?**
    a. Yes, both AC Joints
6. **Is the side delt pad centered on your side delt?**
    a. Yes, the pad fits correctly on the side of my delt
7. **Do you have any suggestions for improvement of the brace?**
    a. Trim the neck area and remove material from armpits. I'd also find a way to secure the strap in place on the shoulder joint itself maybe with an additional piece of velcro

With optional strap

1. **Does the optional strap provide any more compression?**
    a. Yes, I feel noticeably more compression with the extra strap
2. **Does the optional strap add any significant weight?**
    a. Not at all
3. **Would you wear the optional strap? Always?**
    a. I feel like the optional strap is not always necessary. For most practices and since I have relatively healthy shoulders I feel that one strap will provide enough protection. If I had injured my shoulder before or am playing in a game I'd consider wearing the optional strap for more compression.
4. **What would you improve about the optional strap?**
    a. I like that it can be removed, I can't think of anything to improve.
5. **Are you capable of putting the optional strap on yourself?**
    a. Yes, after a little bit of practice

With shoulder pads

1. **Does the brace fit comfortably underneath the shoulder pads?**
    a. Yes, not bad but the neck portion of the brace rides up in front. Everything else but the front of the neck feels good. Does not feel bulky. Can definitely tell the brace is there. Shoulder pads sit like normal on the shoulder. It feels more protective than if I was just wearing the shoulder pads without the brace.
2. **Do the shoulder pads fit correctly?**
    a. Yes shoulder pads fit correctly. I can tighten them all the way as normal.
3. **Do the shoulder pads slip on top of the brace?**
    a. Shoulder pads do not slip, it is like I am wearing an undershirt. No slip at all.
4. **Do the pads interfere with the straps or vice versa?**
    a. No not at all, if anything it secures the straps better. Shoulder pads go over the velcroed sections making sure they don't come loose.
5. **Are you able to put on and take off the shoulder pads without additional help?**
    a. Yes I can take them off and on. It's not that hard.

Brace With Undershirt

1. **How does the brace feel with the undershirt on? (fit, feel, weight, irritative) Please explain.**
    a. The brace fits very comfortably on top of an undershirt. No additional weight, the compression keeps the undershirt in place, and there's no irritation at all.
2. **Does the undershirt interfere with any straps or velcro?**
    a. Not at all
3. **Does the undershirt cause brace slippage?**
    a. Not any noticeable slippage

Questions after 10 mins of physical exertion including football stretches, warmups, and technique drills

Without Shoulder Pads

1. **How does the brace feel during and after physical activity?**
    a. Feels good. Running is fine, no restriction and I can run as normal. Weight of the brace is good, I can tell I am wearing the brace but not anything I couldn't deal with to save my shoulders.
2. **Have some straps loosened?**
    a. No, straps have not loosened. Still feel secure both the AC and the shoulder joint. Side delt pad doesn't get in the way and doesn't move during activity.
3. **Is the brace breathable enough for prolonged use?**

    a. I think so, not any worse than any other shoulder braces out there for sure.

4. **Would you worry about becoming too hot while wearing the brace?**
    a. No
5. **Based on your experience with the brace would you be able to wear it during practices and games?**
    a. Yes, definitely would be able to wear it during practice and games. During practice I feel that just the one tri-strap would provide enough protection.

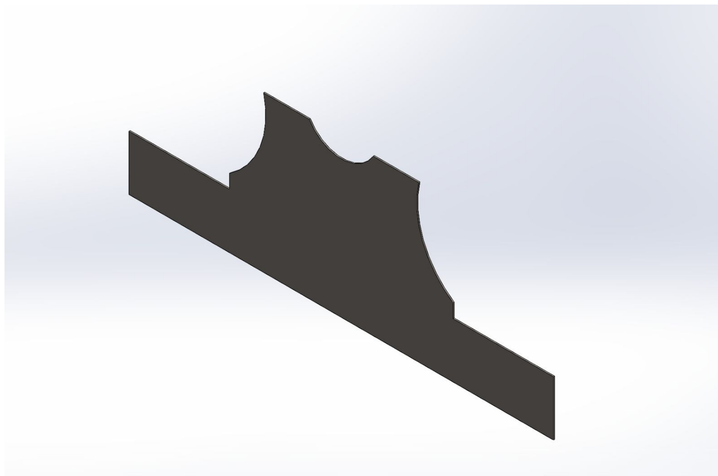
With Shoulder Pads

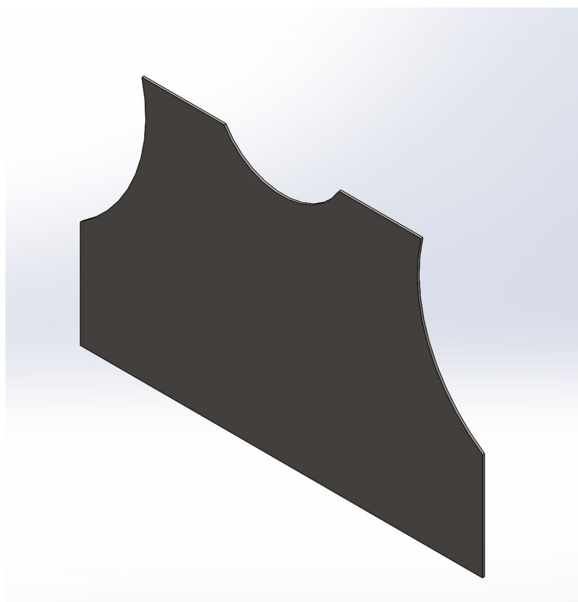
1. **Do the pads stay in place?**
    a. Shoulder pads stay in place as they would normally.
2. **How does the brace feel under the shoulder pads during and after physical activity?**
    a. I feel super protected like I could run through a wall. During it feels pretty good but the neck rides up a little bit. Not too restrictive, and not too hot. After feels the same as before. Little sweat going as expected.
3. **Did any shoulder brace straps loosen or come loose?**
    a. No. Straps are still secured and in the right places.
4. **Can you reach the shoulder brace straps if needed?**
    a. I can reach all straps but the AC joint straps.
5. **Would you worry about overheating with the brace and pads on during activity?**
    a. No. Not more than usual.

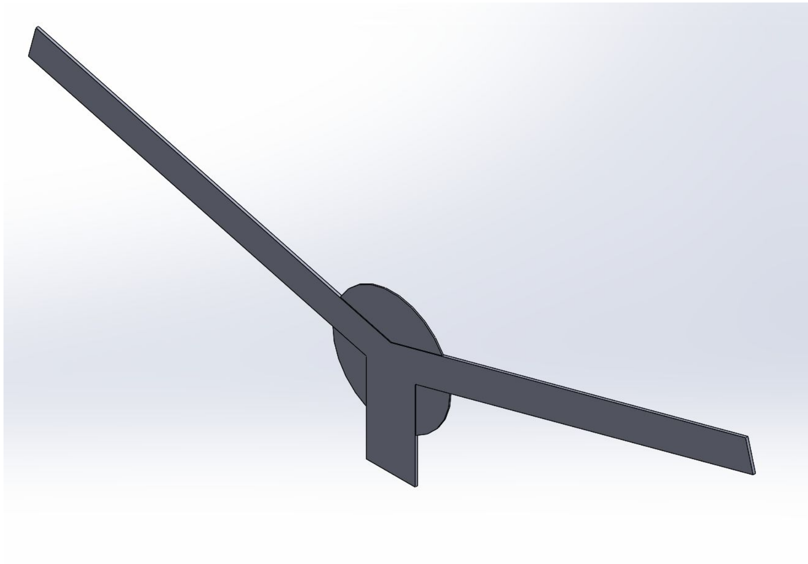
Appendix 7. Raw Output Accelerometer Data

```
2020-02-26 10:42:14     Adafruit LSM6DS33 test!
2020-02-26 10:42:14     Read ID 0x69
2020-02-26 10:42:14     7       Accel X: 9.21   Y: -2.61        Z: 1.95 m/s^2
2020-02-26 10:42:14                     Gyro X: 0.02    Y: -0.02        Z: -0.01 radians/s

2020-02-26 10:42:17
2020-02-26 10:42:17                     Temperature 24.57 deg C
2020-02-26 10:42:17                     Accel X: 9.38   Y: -2.60        Z: 1.63 m/s^2
2020-02-26 10:42:17                     Gyro X: 0.02    Y: -0.02        Z: -0.01 radians/s
2020-02-26 10:42:17
2020-02-26 10:42:17                     Temperature 24.57 deg C
2020-02-26 10:42:17                     Accel X: 9.53   Y: -3.63        Z: 1.86 m/s^2
2020-02-26 10:42:17                     Gyro X: 0.02    Y: -0.02        Z: -0.01 radians/s
2020-02-26 10:42:17
2020-02-26 10:42:17                     Temperature 24.57 deg C
2020-02-26 10:42:17                     Accel X: 5.47   Y: -14.01       Z: 1.19 m/s^2
2020-02-26 10:42:17                     Gyro X: 0.12    Y: -0.22        Z: 0.07 radians/s
2020-02-26 10:42:17
2020-02-26 10:42:17                     Temperature 24.57 deg C
2020-02-26 10:42:17                     Accel X: 13.83  Y: 0.97         Z: 3.23 m/s^2
2020-02-26 10:42:17                     Gyro X: 0.02    Y: 0.05         Z: -0.15 radians/s
2020-02-26 10:42:17
2020-02-26 10:42:17                     Temperature 24.57 deg C
2020-02-26 10:42:17                     Accel X: 7.59   Y: -1.06        Z: 3.62 m/s^2
2020-02-26 10:42:17                     Gyro X: 0.04    Y: -0.04        Z: 0.10 radians/s
2020-02-26 10:42:17
```

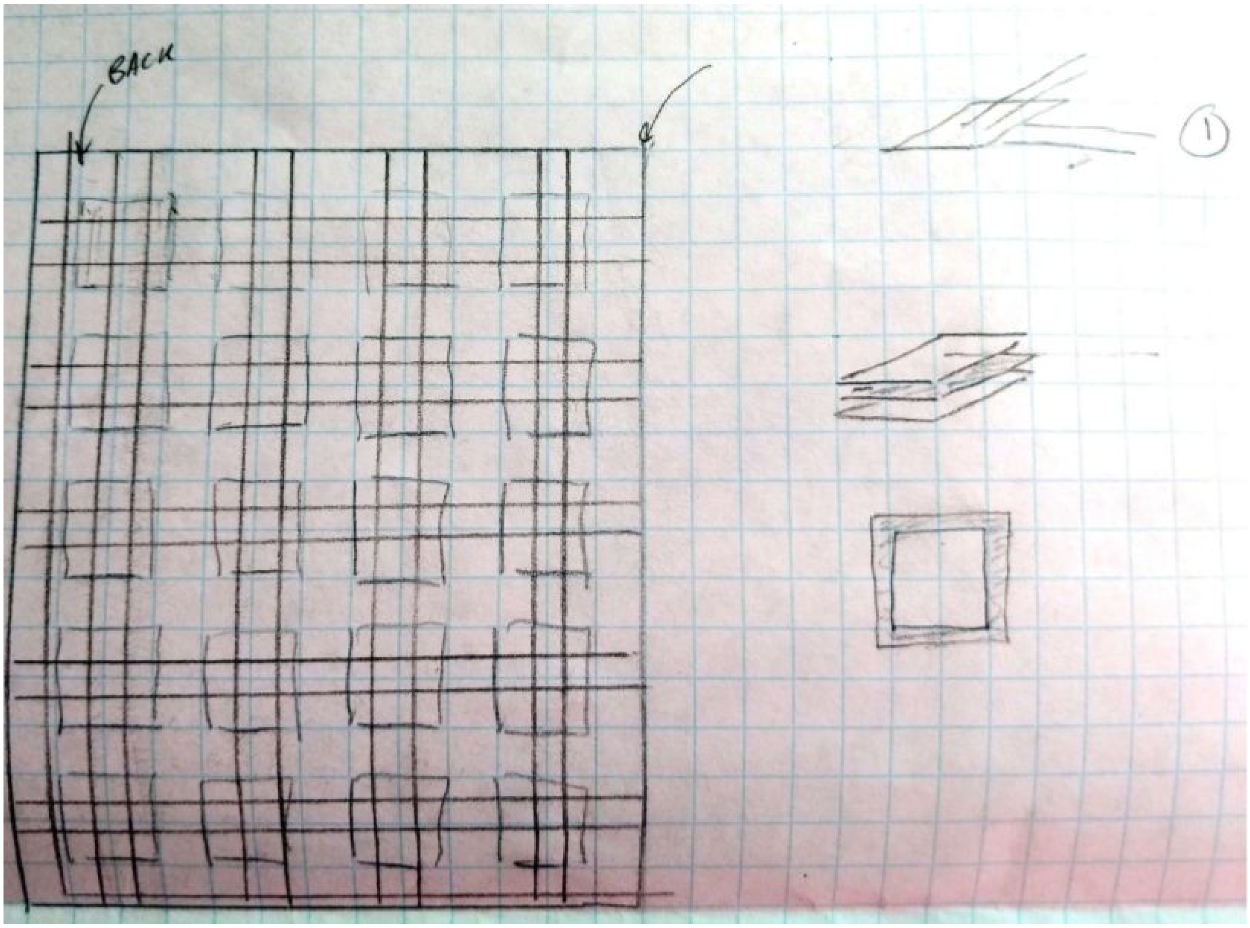
Appendix 8. Shoulder Brace Component Models







Appendix 9. Sensor Construction Rough Sketch



Appendix 10. Sensor Calibration Test Results

Final Design Prototype

Baseline							
A1	24 kΩ	B1	25 kΩ	C1	24 kΩ	D1	19 kΩ
A2	27 kΩ	B2	24 kΩ	C2	16 kΩ	D2	40 kΩ
A3	21.5 kΩ	B3	49 kΩ	C3	24 kΩ	D3	33 kΩ
A4	33 kΩ	B4	25 kΩ	C4	19 kΩ	D4	29.5 kΩ
Weight 1	3 lb						
A1	64 Ω	B1	52 Ω	C1	66 Ω	D1	37 Ω
A2	77 Ω	B2	79 Ω	C2	26 Ω	D2	35 Ω
A3	50 Ω	B3	52 Ω	C3	25 Ω	D3	45 Ω
A4	40 Ω	B4	23 Ω	C4	35 Ω	D4	22.5 Ω
Weight 2	6 lb						
A1	26 Ω	B1	52 Ω	C1	29 Ω	D1	60 Ω
A2	28 Ω	B2	97 Ω	C2	33 Ω	D2	36 Ω
A3	26 Ω	B3	39 Ω	C3	25 Ω	D3	56 Ω
A4	26 Ω	B4	34 Ω	C4	35 Ω	D4	30 Ω
Weight 2	9 lb						
A1	20 Ω	B1	43 Ω	C1	22 Ω	D1	45 Ω
A2	28 Ω	B2	82 Ω	C2	29 Ω	D2	24 Ω
A3	22 Ω	B3	25 Ω	C3	22 Ω	D3	36 Ω
A4	17 Ω	B4	26 Ω	C4	29 Ω	D4	20 Ω

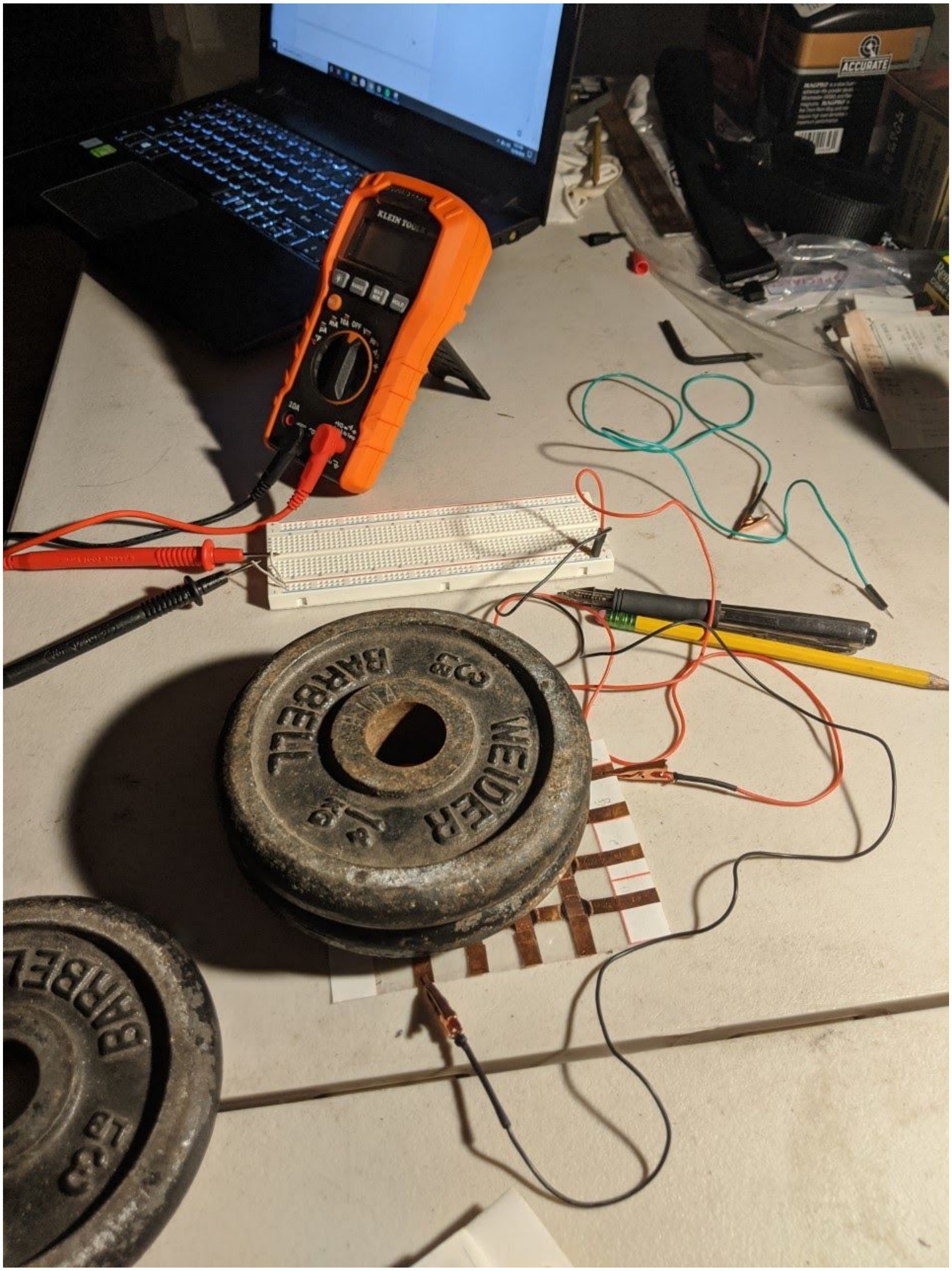
Final Sensor 1

Baseline	units in kΩ						
A1	2.2	B1	2.47	C1	2.2	D1	2.52
A2	2.8	B2	2.5	C2	2.5	D2	2.23
A3	2.75	B3	2.6	C3	2.92	D3	2.1
A4	2.85	B4	2.9	C4	3.45	D4	2.33
Weight 1	3 lb						
A1	1.4	B1	1.42	C1	1.1	D1	1.32
A2	1.15	B2	1.29	C2	1.43	D2	1.44
A3	1.28	B3	1.35	C3	1.87	D3	1.3
A4	1.05	B4	1.3	C4	1.47	D4	0.94
Weight 2	6 lb						
A1	1.16	B1	1.13	C1	0.95	D1	1.22
A2	1.28	B2	1.27	C2	1.37	D2	1.29
A3	1.15	B3	1.07	C3	1.6	D3	1.15
A4	0.9	B4	0.9	C4	1.38	D4	0.82
Weight 2	9 lb						
A1	1.16	B1	1.11	C1	0.95	D1	1.14
A2	1.23	B2	1.1	C2	1.15	D2	1.27
A3	1.1	B3	0.95	C3	1.44	D3	1.07
A4	0.86	B4	0.85	C4	1.29	D4	0.78

Final Sensor 2

Baseline	units in kΩ						
A1	2.8	B1	2.34	C1	1.8	D1	2.15
A2	2.02	B2	2.17	C2	2.32	D2	2.36
A3	2.85	B3	2.78	C3	2.5	D3	2.85
A4	2.35	B4	2.5	C4	2.47	D4	2.27
Weight 1	3 lb						
A1	1.29	B1	1.01	C1	1.15	D1	1.01
A2	0.77	B2	1.31	C2	1.39	D2	1.98
A3	1.09	B3	1.2	C3	1.2	D3	1.34
A4	1.12	B4	1.06	C4	1.08	D4	1.67
Weight 2	6 lb						
A1	1.16	B1	0.8	C1	0.83	D1	0.93
A2	0.71	B2	1.12	C2	1.15	D2	1.58
A3	0.8	B3	1	C3	0.85	D3	1.12
A4	1.01	B4	0.91	C4	0.93	D4	1.25
Weight 2	9 lb						
A1	1.121	B1	0.76	C1	0.72	D1	0.85
A2	0.63	B2	1.03	C2	0.83	D2	1.24
A3	0.79	B3	0.92	C3	0.79	D3	0.85
A4	0.92	B4	0.86	C4	0.83	D4	1.12

Appendix 11. Sensor Test Setup



Appendix 12. Grid Sensor Breadboard Set Up