Baseball Injury Prevention and Pitching Biomechanics

A Major Qualifying Project
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Abstract

In the past decade, baseball pitchers have been incentivized to throw harder, and this has come with a dramatic increase in elbow-related injuries, specifically regarding the UCL. There has been a strong rise in Tommy-John surgeries, from 27 in 2000 to 166 in 2015 in the MLB plus MiLB. With this throw harder mentality spreading down to amateur and youth leagues, teams are becoming more invested in trying to prevent these injuries in the first place. The use of motion capture has been on the rise, and while it aids in helping pitchers throw harder, it does not have the thorough capability to measure injury risk and prevent injuries.

The goal of the project is to develop a wearable sensor-based system that measures metrics of interest (i.e., linear acceleration, angular velocity) to estimate elbow injury risk that occurs as a result of baseball pitching, with respect to pitch types. The design incorporates inertial motion sensors attached to the forearm that have Bluetooth transmitting capability, for real-time feedback, that sends data to a MATLAB script that takes the measurements and estimates injury risk, based on the pitcher's physical attributes. Literature suggested that the UCL experienced an upper limit of 60 Nm of torque per pitch.

The sensors were verified when attached to a wheel moving at a fixed velocity of 5 mph (2.23 m/s), where the angular velocity was expected to be 4.68 degrees per second, and the IMU calculated 4.63 degrees per second. Once it was verified that the sensors were collecting accurate data it then validated the data analysis system in MATLAB. Preliminary data was then collected from the team throwing pitches to detect any issues that could arise. These data were used to calculate the force and torque at the elbow when the pitch was thrown. Both calculations were the same and were within the expected range of force and torque. The sensors were then validated with a pitcher human subject who wore the sensors and threw several pitches to develop a healthy baseline of force and torque experienced. Then, the pitcher was fatigued and

threw again in order to create a fatigued baseline. The force and torque collected were analyzed to determine what the expected "drop" was to be between each baseline. If there is more fatigue there would show a greater amount of torque, which could lead to a higher risk of injury. The average fastball torque increased from 42.53 Nm to 45.41 Nm with fatigue and the average curveball torque decreased from 49.29 Nm to 47.37 Nm with fatigue. While the fastball results were expected, the curveball results were not.

While the results were not expected, the limitations can be addressed to optimize the system overall. The project was able to demonstrate a proof-of-concept that a real-time feedback capability is feasible and that different pitch types could be accounted for.

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Glossary

Ulnar Collateral Ligament (UCL) - ligament running on the inside of the humerus providing stability to the elbow when performing throwing

Fastball - the primary pitch for a pitcher; when released, the baseball travels with a high speed in a mostly straight trajectory when it crosses home plate; thrown in order to reach home plate before the batter is able to swing the bat

Breaking ball - the secondary pitch for a pitcher, when released, the baseball travels with a relatively lower speed than a fastball, but with an increased deviation in from mostly straight trajectory; thrown in order to fool the batter into swinging at a pitch that is not the location of the pitch

Inertial Measurement Unit (IMU) - an electronic sensor that detects, measures, and reports a body's force, acceleration, and/or orientation using accelerometers and gyroscopes

Accelerometer - a tool that detects, measures, and reports linear acceleration

Gyroscope - a tool that detects, measures, and reports angular acceleration

Chapter 1: Introduction

The role of the pitcher has changed throughout the history of baseball from a play initiator to a specialized role. This change in roles has led pitchers to change their mechanics to throw harder than ever before. This new pitching environment where throwing harder is incentivized has come with a dramatic increase in elbow-related injuries, specifically regarding the ulnar collateral ligament (UCL). There has been a rise in UCL reconstruction surgeries, also known as Tommy-John surgeries, especially at the turn of the century, from 27 in 2000 to 166 in 2015 [2]. Because these surgeries often will put the pitcher on the shelf for at least the end of the season, teams are invested in trying to prevent these injuries in the first place.

The elbow joint consists of ligaments to “connect” the arm bones together and to define their range of motion, all in order to prevent dislocation. One of those ligaments is the ulnar UCL. The UCL connects the humerus (upper arm bone) to the ulna (outer-elbow, pinky-side, lower arm bone). In order to define the movement, the ligament is made of three bands of tissue that extend and contract in different directions. The bands are made of Type I collagen, which has specific material properties that don’t adjust based on dynamic changes. This means that the UCL is meant more as a static restraint to stabilize the elbow. Further, it suggests that if the UCL were to experience large, repetitive valgus stresses (such as pitching a baseball), the UCL will begin to experience failure. The elbow can experience up to 60 Nm when throwing, far above the UCL’s 34 Nm limit [22].

The mechanics of a baseball pitch are complex, as each pitch delivered uses the entire body to develop forces to push the ball forwards. There is a complicated set of internal forces and torques applied to not only the arm but the entire body, organized into five phases: wind-up, stride or early cocking, late cocking, acceleration, and deceleration or follow-through.

The late arm cocking phase is where the highest risk of injury exists [22]. After the body rotates to generate the energy necessary to throw the ball hard, almost all the energy is transferred into the arm, where it experiences stress. Proper technique is needed in order to perform. However, if a pitcher is fatigued, as he does as he continues to pitch, his technique becomes poor, and throws less hard.

Motion tracking has become a popular way to study pitching mechanics in order to find ways to get better in their biomechanics. The two main ways to track motion are video capture and inertial motion sensors. Video motion capture has been known as a more accurate way of collecting biomechanics data. Although this can be more accurate, this method requires many resources. Inertial motion sensors track the motion of a pitcher’s arm. The inertial motion sensors are able to detect linear acceleration and angular velocity with a total of six degrees of freedom.

The rise in motion tracking came around the early 2000s. Consequently, pitch speeds increased along with the rise in UCL injuries [30, 31]. If the increased use of motion tracking indirectly led to a rise in elbow injuries, perhaps it could also be used to understand and possibly prevent elbow injuries.

The goal of the project is to develop a worn sensor-based system to prevent elbow injury that occurs as a result of baseball pitching with the following criteria: The sensor should be wearable, the system should provide real-time biofeedback on injury prevention, and the system should differentiate the biofeedback in different types of pitches.

The project goals are broken down into three main aims: to develop free body diagrams to analyze the equations of motions, to develop a wearable sensor system software that will flag dangerous levels of injury risk on the elbow in real-time, to conduct human testing to analyze the variability in pitch types when arm and whole-body fatigue is induced.

The design uses inertial motion sensors that have Bluetooth transmitting capability. These sensors have a built-in Bluetooth transmitter in the microcontroller that transmits the raw data to a computer wirelessly. The raw data are inputted into MATLAB to be analyzed. The analysis of the pitch happens in real-time feedback. The real-time feedback analysis should allow the pitcher and coach to make "game time" decisions on whether to remove a pitcher from a game before injuring themself.

In order to verify that the hardware was working correctly, the team performed a test to see if the data received was what was expected. The team placed the sensor in the middle of a car wheel and drove the car at about 5 mph, or 2.24 m/s. Using the radius of the car wheel and the speed of the car was calculated the expected angular velocity. The team found the expected value to be 4.68 degrees per second, and the IMU calculated 4.63 degrees per second. This is within range to verify our sensor, as the calculated value only has a 1.07% error to the expected value.

Once it was verified that the sensors were collecting accurate data it then validated the data analysis system, which is in MATLAB. In order to do this, the team collected data on themselves. These data were used to calculate the force and torque at the elbow when the pitch was thrown. These calculations were done on paper, as well as done in the analysis software, MATLAB. Both calculations were the same and were within the expected range of force and torque.

Collegiate baseball pitchers volunteered to test the sensor system in an IRB approved protocol. The pitchers wore the sensors and threw several pitches to develop a healthy baseline of force and torque experienced. Then, the pitchers were fatigued and threw again in order to create a fatigued baseline. The force and torque collected were analyzed to determine what the expected "drop" was to be between each baseline.

Chapter 2: Literature Review

2.1: Role of the Pitcher

Baseball is considered one of the world’s most popular sports, with major influence in areas such as East Asia, Latin America, and North America. In 1875, the National Association became the first professional baseball league. Needing a standard set of rules, the National Association adopted the Knickerbocker Rules, which would lay the foundation for today’s game. Considered a “gentleman's game,” the Knickerbocker Rules stated that pitchers were only allowed underhanded throws, hence, pitches. However, the National Association reversed the rule in 1884 and overhand pitches were allowed. Over time, the role of the pitcher position changed from a ninth fielder to a specialized role. Initially, the pitcher’s role was as an initiator, throwing the ball in good faith with no intention of tricking the batter. Then, the pitching role became more specialized as the rules changed to give the pitcher the ability to produce outs [1].

In the modern-day game of baseball, popularized with Major League Baseball (MLB), the pitcher’s main goal is to prevent hitters from getting on base. They can do so in two ways:

1. Weak contact - throw pitches that the batter is not able to hit well, making it easy for the fielders to get the batter/runners out when the ball is in play.
2. Strikeout - The strikeout occurs when the batter acquires three strikes. A strike is acquired in three ways: when the batter swings and misses, hits the ball foul (for the first two strikes), or called strikes, when the ball enters a discretionary “strike zone,” (see Figure 1) usually around the batter’s knee to midsection level and above home plate.

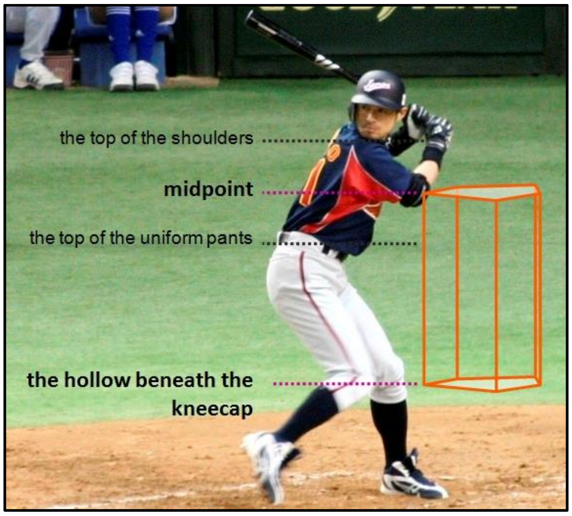


Figure 1: Strike Zone [2]

The ideal result for a pitcher in every situation is a strikeout because a strikeout does not put the ball in play. Pitchers have developed different types of pitches with different purposes to get the batter out:

1. Fastball: The fastball is self-explanatory; the pitcher throws the ball as hard as he can in hopes that the speed is too fast for the batter to swing or to induce a swing and miss by the batter. The fastball often has little to no additional movement. However, this pitch is predictable with speed and location in terms of the strike zone.
2. Change-up: The change-up is designed to appear as a fastball, however, the speed of this pitch is much slower than that of the fastball. Because of the lack of movement, the location is still predictable along a straight-line trajectory, but the sudden drop in speed disrupts the batter’s timing and makes him either swing earlier and miss or cause weak contact.
3. Breaking ball: The breaking ball, like a change-up, is designed to appear as a fastball until it approaches home plate, where it has increased movement, either sideways or downward. While the speed drops throughout the whole pitch, the increased movement

changes the location of the ball from a straight-line trajectory. The two most common breaking balls are the curveball and slider.

Having a good combination of these three pitch types makes a pitcher more valuable. While there are other pitches, modern-day pitchers rely heavily on these three types of pitches to get the batter out.

Over the years, because fastballs are the primary pitch of almost every pitcher, pitchers are throwing harder than ever. Before the 2000s, it was only occasional that a pitcher's fastball reached 95 mph consistently. Now, a 95+ mph fastball is common. Fangraphs, a baseball analytics site, notices these pitching trends in MLB from 2008 to 2018. The percentage of fastballs thrown at 95+ mph has gone from 12% to 22%. The percentage of pitchers throwing an average 95+ mph fastball increased from 9% to 20%. The average fastball speed jumped up by 1.5 mph [3]. This rise in pitch speed is likely in part due to the increased focus on pitching biomechanics and data analytics after the Steroids Era in the early 2000's. In a league where roster spots are extremely competitive each year, pitchers know that an increased speed will gain them a competitive edge.

2.2: Pitching Injury Statistics

Youth athletics have become a much more competitive environment when comparing the early 2000s to now. This competitive environment has led to much more rigorous baseball seasons for youth all the way through college. Baseball players are playing a lot more throughout the year and this is causing a lot of overuse of the arm. There are some surveys given to baseball players aged 9-18 in which 43.5% of the respondents said they pitched on consecutive days, 19% pitched in multiple games in the same day, and 13.2% pitched competitive baseball for more than 8 months in a year [4]. The culture of baseball to play throughout the year and neglect resting at young ages has become increasingly popular.

Pitchers are pitching more than in prior years, while not performing the proper preventive techniques. These techniques can include properly warming up before pitching as well as improving flexibility and strengthening [5]. When a player performs a proper warm-up before throwing, the injury risk for the arm will significantly decrease. Improving the flexibility and strength of the arm is also helpful because as a pitcher throws more, fatigue will set in based on how well conditioned the arm is.

When a pitcher neglects to rest their arm, fatigue builds up, no matter how much of the preventive techniques are used. This leads to more stress being put on different parts of the arm. When a pitcher is throwing more than 8 months of the year, they are 500% more likely to get surgery on the elbow [6]. This shows a correlation between the amount of work the arm does in a year and the injuries that occur when throwing too much. Therefore, the main cause of arm injury is overuse. These injuries can occur in the shoulder and in the elbow. The majority of shoulder injuries are muscle-related, while elbow injuries are ligament-related [7]. As a pitcher throws more the muscles surrounding the elbow become increasingly fatigued. This fatigue causes the mechanics of the throwing motion to break down. As the mechanics break down there will be much more stress on the elbow. This fatigue and stress on the elbow are also associated with a decrease in pitching speed. When looking at a pitcher throwing for an extended period of time, there was a significant decrease in speed in all of the pitcher’s pitches leading up to a UCL injury [7].

As baseball is being played more year-round, UCL reconstruction numbers have been skyrocketing since the early 2000s. The most common type of UCL reconstruction surgery is called Tommy John surgery. In a study done that surveyed baseball players through the years 2002-2011, they found there was a 193% increase in Tommy John surgeries [6]. These UCL injuries are not just happening at the youth through college levels, they are happening at professional levels as well. Shown in Figure 2, the chart shows the amount of Tommy John surgeries in Major League Baseball Plus Minor League Baseball (MiLB), as a function of year.

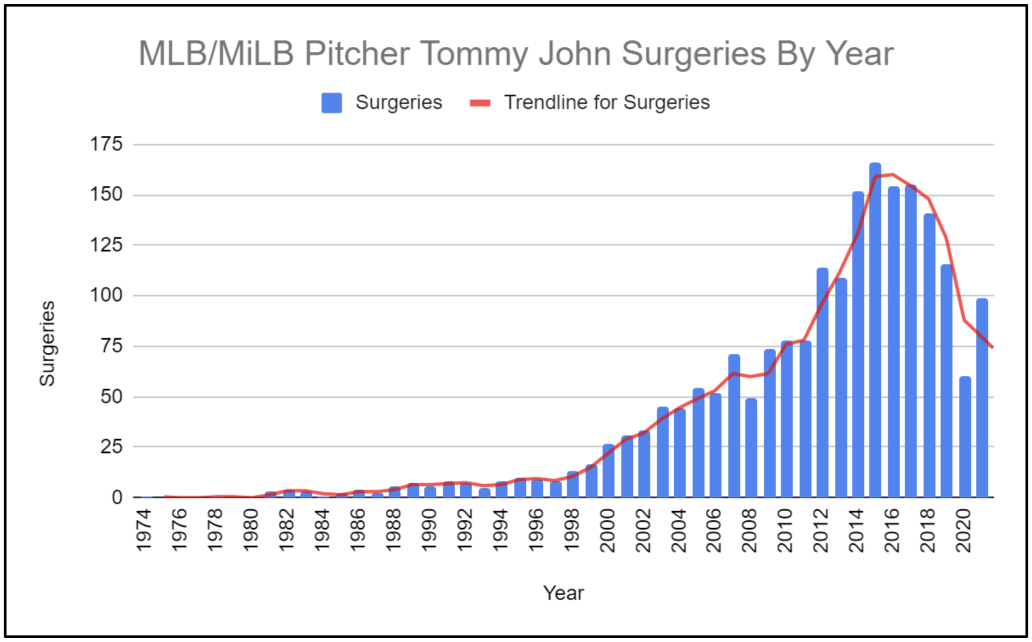


Figure 2: MLB Plus MiLB Pitcher Tommy John Surgeries by Year based on [9]

From the 1990s through the present day, Tommy John surgeries have increased dramatically, from 27 in 2000 to 166 in 2015. This can be attributed to these pitchers throwing a lot more when they are younger before they play professionally, as well as throwing a lot more when they are playing professionally. As seen in Figure 2, surgeries did peak in 2015 and have slowly decreased since then. Preventative techniques have come out and this helps reduce the risk of injury for the elbow, but Tommy John surgeries are still at alarmingly high rates in professional baseball.

2.3: Elbow Anatomy

Any person looking into the biomechanics of the arm needs to know how the arm is designed. The arm is designed with four primary joints that connect bones together and create its range of motion: the acromioclavicular joint (shoulder-body), the glenohumeral joint (shoulder-upper arm), elbow joint (upper arm-lower arm), and the wrist joint (lower arm-hand). The elbow joint is the one being focused on in this project. The elbow joint consists of two primary ligaments (Figure 3), or pieces of tissue that connect bones. These ligaments have two primary functions. The first is to connect the humerus (upper arm bone) to the radius and the ulna (lower arm bones). The other function is to connect the lateral collateral ligament (LCL) and four primary joints that connect the ulnar collateral ligament (UCL). Ligaments stabilize the joint to prevent bone dislocation. The UCL is made up of three bands, or bundles, of tissue that hold it together: the anterior (front) (AB), posterior (back) (PB), and transverse (across) bands (TB). The anterior band is important in maintaining UCL stability, as the largest of the three [10].

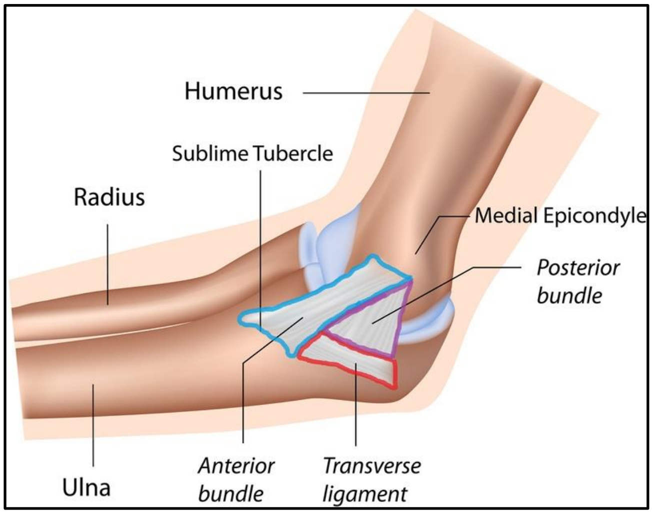


Figure 3: Elbow Joint [11]

The elbow, like any joint, moves when the muscles, bones, and ligaments work together. The arm muscles, controlled by electrical signals originating in the brain, contract in order to create movements for the limbs. The forearm and upper arm bones move relative to the elbow joint. The elbow joint is broken into three sections. The humero ulnar joint connects the humerus and ulna and allows flexion and extension of the arm. The humeral radial joint connects the radius and humerus and allows the motions of flexion, extension, supination, and pronation. The radioulnar joint connects the radius and ulna and allows for lower arm rotation [12]. Altogether, it allows the elbow to move and rotate. To prevent friction between the two bones, the elbow contains cartilage lines or a slippery surface that acts as a shock absorber and cushion to the bones if and when the bones make contact [13].

The UCL contains Type I collagen fibers (~70% of its dry weight) that passively stretch and contract in order to allow the bones to move relative to each other and to stabilize the joint from dislocating if bones are separated too far [14]. This occurs primarily with the anterior band, which is considered the primary stabilizer. UCL mechanical responses are mostly linked to the static (unloaded) collagen microstructural organization, which is bundle specific. It is not linked to large-scale dynamic changes in collagen fiber alignment during tensile loading. This implies that the UCL serves as a static restraint for the elbow that is not well suited to adjust its microstructural organization to repetitive tensile loading. The UCL anterior bundle is stiffer and more strongly aligned than the posterior bundle [15]. The limited degree to which microstructural changes occur because of the alignment suggests that if the UCL experiences too much valgus stress, especially repetitively, the UCL will begin to tear [16]. The elbow can experience up to 60 Nm when throwing, far above the UCL’s 34 Nm limit [17]. When the UCL tears to the point of failure, it may feel as a “pop” occurs and inner elbow pain is prominent (from the anterior band). UCL tears range from a first-degree tear, which has no changes to the UCL to a third-degree tear, which has significant changes to the UCL, affecting function. While a UCL tear does not affect mundane tasks such as carrying groceries, it does affect a person’s ability to throw a ball 80-100 mph consistently [18]. The torque the elbow experiences between the two tasks is significantly greater during a baseball pitch.

2.4: Pitch Mechanics

The movement and mechanics of a baseball pitch are some of the most studied movements in all sports. The mechanics of a baseball pitch are complex, as each pitch delivered uses the entire body to develop forces to push the ball forwards. There are a complicated set of internal forces and torques applied to not only the arm but the entire body. The neuromuscular facilitation for a baseball pitch is usually developed at a young age [19]. Neuromuscular facilitation is the process in which one's muscles become familiar with motor skills. Properly taught pitching mechanics at a young age are vital to preventing injury during one's baseball career [19]. Pitching mechanics are described by Calbrese as a coordinated sequence of body movements and muscular forces that have an ultimate goal of high ball velocity and target accuracy [20]. To properly understand the pitching mechanics of an overhead pitch, the mechanics have been classified into five different phases. These five phases are wind-up, stride or early cocking, late cocking, acceleration, and deceleration or follow-through [21]. For a baseball pitch to be properly thrown, forces and torques are developed from the lower extremities and transferred throughout the entire body, creating the term Kinetic Chain.

2.5: Phases of the Pitch

The five phases of the baseball pitch are shown below in Figure 4.

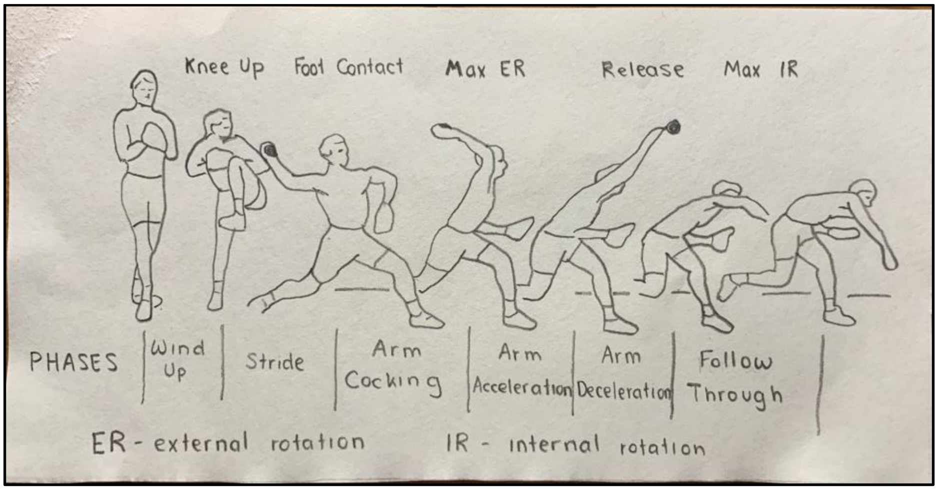


Figure 4: Pitching Phases based on [21]

The wind-up and stride phase of the baseball pitch generate the forces and energy required to create pitching velocity. The phase begins with an initial movement of the contralateral lower extremity. This is paired with the lead leg raising to its highest point [21]. The final position of the wind-up is when the baseball glove is brought across the body and the pitching arm is slightly cocked; this is called the balance point. The total time of the wind-up is estimated to last between 0.5 and 1.3 seconds. During the wind-up phase, through electromyography, it has been reported that the rotary cuff receives below 21% maximal voluntary contraction. As a result of this, the risk of injury during the wind-up phase is low compared to the remaining phases of the pitch [21].

The stride or early cocking is the second phase of pitching mechanics. The phase begins with the pitcher at the balance point and ends once the lead leg comes in contact with the ground. The stride phase generates approximately 50% of the ball velocity in the pitching motion. The stride phase also causes the pelvis to rotate at 400-700 degrees per second. During this rotation, the upper extremities remain still, creating spinal rotation [21]. The stride is essential to create proper positioning of the lower extremities and the trunk. Increasing the distance of the stride allows for a greater transfer of energy through the trunk to the upper extremities. A shorter stride decreases the potential energy created from the lower extremities. On the other hand, overstriding can result in throwing off the kinetic chain. If a pitcher over strides, then potential energy will be lost. This could result in transferring a dangerous amount of energy to another part of the body resulting in an injury.

The next phase of pitching mechanics is late cocking. The late cocking phase is initiated when the lead leg just becomes in contact with the ground, and the shoulder is at maximum external rotation. The trunk, shoulder, and elbow patterns lead the pitching motion of this phase. During this phase, the shoulder is abducted at 90 to 100 degrees and horizontally abducted at 20 degrees [21]. As the late cocking phase proceeds, the elbow experiences approximately 64 Nm of torque, and the shoulder experiences approximately 67 Nm of internal rotation torque. Studies have shown the majority of injuries during a baseball pitch occur during the late cocking phase. [22].

Following the late cocking phase, is the acceleration phase of pitching mechanics. The arm acceleration phase begins when the arm is at a maximum external rotation and is concluded at the release of the baseball. During the acceleration phase, the elbow is experiencing its maximum amount of torque and reaches approximately 2251-2728 degrees per second of internal rotation and horizontal adduction. The maximum amount of torque is found to be when the arm is completely stretched at 90 degrees [21]. The arm acceleration phase lasts approximately 42-58 ms of the total pitch sequence. As a result, it is known to be one of the fastest movements in all sports activities [21]. A comparative study of amateur and professional pitchers found amateur pitchers will exceed three times greater bicep and rotator cuff muscular activity than professional pitchers, during this phase [23]. This has become a leading factor in rotator cuff and UCL injuries in youth pitchers.

The final phase of pitching mechanics is the deceleration or follow through. The phase begins at the initial release of the baseball and is concluded when the pitcher is assumed in a ready-to-field position. The deceleration phase results in maximal dominant shoulder internal rotation and 35 degrees of horizontal abduction [21]. The decrease in joint loading and the small amount of forces acting on the body results in a minimal risk of injury during this phase.

2.6: The Kinetic Chain

Some believe the baseball pitch generates force solely from a pitcher's arm; this is incorrect. The force required to deliver a baseball pitch is a full-body movement, known as the kinetic chain. The kinetic chain of a baseball pitch is generated from the lower extremities of the body. The forces generated from the lower extremities are then transferred up through the body overall propelling the ball forwards [21]. Shown below in Figure 5 is a force vs time graph of the kinetic chain of a baseball pitch. The figure shows how all forces are transferred throughout the body over time within one baseball pitch.

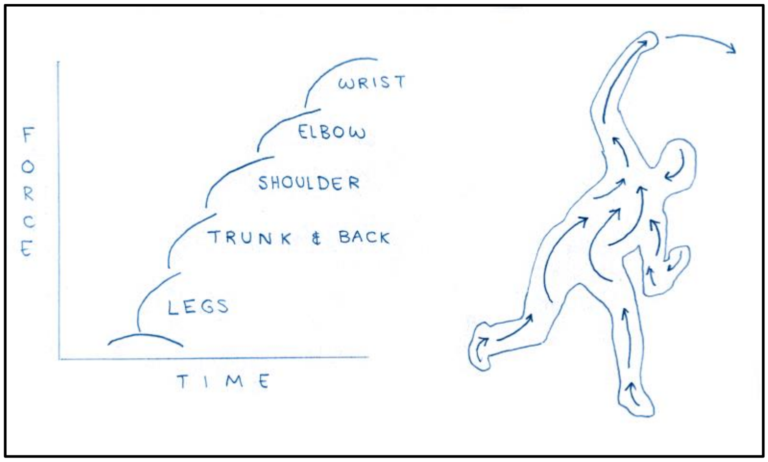


Figure 5: Transfer of Force vs Time Graph of the Kinetic Chain of a Baseball Pitch based on [24]

The lower extremities, pelvis, trunk, and back establish support that is then transferred to potential energy through the body, primarily into the shoulder and elbow. The kinetic chain creates a summation of the speed principle which has been investigated in pitching mechanic injuries. The summation of the speed principle states if the rotational movements between segments are faulted, then the transfer of potential energy throughout the body will be unproductive.

Due to the sequential movements of the kinetic chain, if one segment does not produce enough energy, the entire chain will be ineffective. The rapid rate of movement in a baseball pitch results in assessments being extremely difficult. The complete total time elapsed from the stride foot in contact with the ground to the release of the baseball is approximately 0.145 seconds. During this short time, the maximum humeral internal rotation velocity will reach 7500 to 7700 degrees per second. The kinetic chain proves that the excessive external rotation in the shoulder paired with linear trunk motion results in a greater velocity of the baseball. The relationship between the dynamic stabilizers is required to supply the force and stability for the glenohumeral joint and the UCL [25]. Understanding the components of the kinetic chain may prevent injury in the shoulder and elbow joints.

Analyzing the kinetic chain of baseball pitchers has allowed for further research upon shoulder and elbow injuries induced from throwing. High-speed 3-dimensional video analysis has proven crucial in investigating the kinetic chain. Video analysis helped discover that lead knee flexion, forward trunk tilt, peak elbow extension, maximum shoulder external rotation, and maximum pelvis angular velocity are correlated with greater ball velocity.

2.7: Pitch Types

To be a successful pitcher at any competition level, one must acquire the ability to alter their pitch velocity and ball movement characteristics in hopes the batter will swing and miss. The most common pitches thrown by a baseball pitcher are the fastball, the slider, the changeup, and the curveball. Each of these pitches has its own ball movement characteristic, ball grip by the pitcher, and ball velocity.

The fastball is the most common pitch thrown at any competition level. The fastball is gripped with the index and middle fingers located in the 3 and 9 o'clock positions. The pitch is thrown by supinating the forearm until the release of the ball. At the peak elbow extension velocity of a fastball, a pitcher's arm is rotating at 2317.6°/s [26]. The slider is a pitch with a "breaking" characteristic. The pitch is thrown to appear as a fastball; however, it is decreased in ball velocity and breaks (i.e., curves) on the horizontal plane. The changeup is also thrown similarly to the fastball. The only difference with this pitch is the ball is positioned deeper in the pitcher's palm to decrease the ball velocity, throwing off the timing of the hitter. At peak elbow extension velocity of a changeup, a pitcher's arm is rotating at 2141.8°/s [26]. The curveball is similar to the slider in the "breaking" aspect. However, the curveball is gripped with the fingers located in the 12 to 6 o'clock location. The pitch is thrown with a different spin and trajectory, creating a "break" in the ball flight from the 12 to 6 o'clock positions [27]. At the peak elbow extension velocity of a curveball, a pitcher's arm is rotating at 2226.2°/s [26].

Four of the professional baseball pitchers with the highest average fastball velocities throw their fastball approximately 60-65 percent during the season [27]. A study conducted on 18 professional pitchers showed during the release of the baseball, the shoulder internal rotation angular velocity was 11 to 18 percent greater in the fastball than compared to the slider, changeup, and curveball. The study also showed that knee flexion was 18 percent greater in the changeup compared to the fastball [28]. Shoulder and elbow forces and torques cause a great risk of injury depending on pitch mechanics and pitch types. Each pitch type uses different mechanics, and if the kinetic chain is off, then the transfer of energy will be ineffective and may result in injury.

2.8: Injury Research

There has been some research done on the topic to help detect and prevent UCL injuries while throwing a baseball. The studies that have been done looked at the biomechanics of the body as well as the result of the pitches that are thrown. This has most likely played a role in the slight decrease of the UCL reconstructions over the past few years, after its peak in 2015 in professional baseball.

A study by W. Carroll looked at the different velocity and spin rate trends in MLB pitchers in the previous 15 games pitching before tearing their UCL. The study found that when a pitcher is fatigued their pitches tend to slow down, showing that fatigue plays a role in UCL injuries. The data found that the velocity of all the pitches did decrease leading up to the time of the injury. When looking at the spin rate, the fastball spin rate went down in the games leading up to the injury. [29]

Another study by Mayberry et al., was performed that looked at data from a pitcher's vertical jump and then looked at if the pitcher went on to have a shoulder injury. The study found that the strength levels of the pitchers play a role in their elbow injury risk. The study had over 500 professional pitchers perform countermovement jumps in the preseason during the years of 2013 to 2018. They measured the eccentric rate of force development, average vertical concentric force, and concentric vertical impulse, while also keeping track of their workload. When looking at all these factors they found that the combinations of low average vertical concentric force along with high concentric vertical impulse and the opposite showed a heightened risk of an elbow injury [30].

A third study at UC Davis looked at how fatigue affects the mechanics of collegiate baseball pitchers. The study found that as a pitcher gets more fatigued, their mechanics change overall. This can lead to more stress on the elbow leading to injury risk. In this study, they used high-speed motion cameras to record the kinematics of NCAA Division I pitchers while they were pitching in-game. They looked at the 1st, 15th, and 30th pitch as the game proceeded. There were some overall mechanics changes as more pitches were thrown in each game and as the season went along. Also, as pitch counts for the pitchers increased throughout the season, elbow flexion decreased [31]. When a muscle is fatigued it is unable to protect the connective tissue, leading to more of the load being transferred to these connective tissues [31]. This increases injury risk in these areas.

Coincidentally, as seen in Figure 2, the rise in Tommy John surgeries started to dramatically increase around the early 2000s, around the same time the use of biomechanics became popular amongst pitchers. When pitchers are competing each year to secure their roster spot, finding small details that could help you throw the ball faster made a difference. With the average fastball speed increasing at such a dramatic pace, Caroll's study supports the intuitive suggestion that throwing harder leads to greater fatigue and a greater likelihood for injury [29]. Mayberry's study supports the suggestion that poor form increases the likelihood for injury. UC Davis supports the suggestion that a high pitch count contributed to increase in injury likelihood.

2.9: Motion Tracking

In the post-Steroids Era, motion capture rose up as a tool to better pitching. Two of the main ways of tracking biomechanics for athletes are with video motion capture and inertial motion sensors. Video motion capture involves setting up cameras around the test subject and putting visual markers on them to track their movements. Motion cameras are able to record the motions of athletes. Then with the help of computer software, the accelerations and angular velocities are able to be processed and analyzed. Video motion tracking systems are very accurate, which results in them currently being the prominent measuring system for this data compared to the other options [32]. Video motion systems require a lot of resources, as seen in Figure 6.

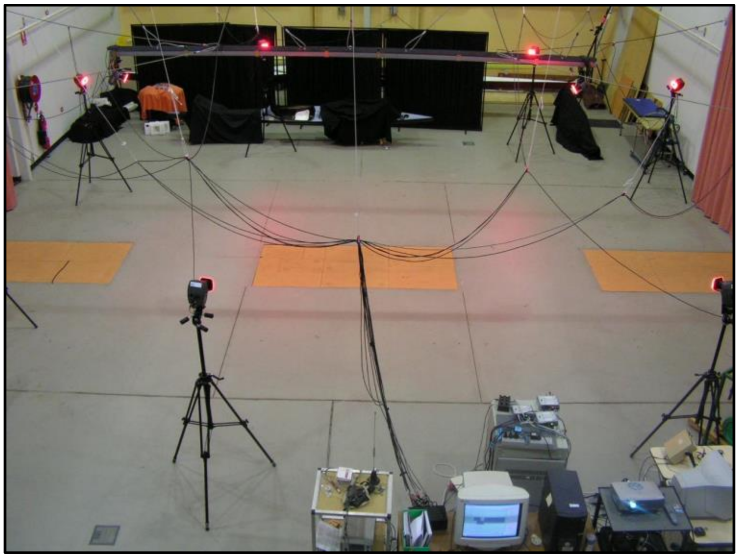


Figure 6: Video Motion Tracking Lab [33]

Another option of motion tracking is through inertial motion sensors (IMU). This type of sensor is a much more cost-effective option [34]. Inertial motion sensors are a relatively small size which makes this type of sensor able to be put on different parts of a test subject's body with limited effect on any movements. This makes them effective when tracking the biomechanics of a test subject. These sensors are built-in with an accelerometer, a gyroscope, and sometimes a magnetometer [35]. The accelerometer is responsible for tracking the linear acceleration of the sensor. This can be found in 3 degrees of freedom. When the sensor moves, the capacitance in the plate's changes, and the acceleration can be calculated [36]. The gyroscope measures the angular velocity about three axes. Gyroscopes consist of a mass that when it has a particular angular velocity applied to it the mass is displaced. The capacitance can be measured from this mass displacement and the angular velocity can be found [36]. Then the magnetometer tracks the earth's magnetic field and with this and the data from the other sensors, making it so body orientation can be found [35]. This also uses the x, y and z axes. The magnetic field can be found by having voltage run through a conductive plate. When the plate goes near a magnetic field, the current flow is disrupted. This change is used to find the magnetic field strength [36]. The data that the sensors produce can be used to estimate torques and forces throughout the body. This is calculated by putting the data into certain algorithms that output the desired values. Obtaining accurate data can be difficult when using inertial motion sensors because they have a lack of absolute positioning [33]. They also pick up on all movements that the arm is making even when they are not pitching. When using IMUs, it is important to track the right movements with the sensor to obtain accurate data. Another issue that can arise is the sensor can move on the arm [35]. If the sensor is in the wrong place, then data collected is wrong.

For the device to accurately tell whether a pitcher is at risk of injury while pitching, it is important for the device to give real-time feedback. The sensor system on the arm can measure the needed data, but a computer software system is needed to actually process and analyze the data. This means the device needs to wireless transmit data to the computer software. Two of the main ways that this can be done are through Wi-Fi and Bluetooth. Data can be uploaded to the internet and then another connected device can access this data. This allows for longer range communication, as it can be accessed anywhere with Internet access. The range of the sensor is still limited as it must be always connected to Wi-Fi. The other way, Bluetooth, allows data to be sent from one Bluetooth-capable device to another. This is a much smaller range, as Bluetooth Class 2 devices can communicate within only 10 meters [37]. Though the range is smaller, this can be done in all places if both devices are Bluetooth capable.

One of the most popular inertial motion sensor systems currently on the market for sports tracking is the MotusBaseball wearable sensor. This is an inertial motion sensor that is placed into a baseball arm sleeve and is used to track the readiness of a pitcher to enhance their performance. The sensor is very small, weighing 0.25 oz with a volume of 0.6 in^3. The sensor is made of a 3-axis accelerometer and a 3-axis gyroscope. The sensor is equipped with Bluetooth and has a storage capacity of 450+ throws [38]. The sensor tracks arm speed, arm angle compared to the floor, arm rotation, arm stress, and various torques on the arm. All of this data is sent to a mobile app and is used to determine if a pitcher is ready to pitch. There is a question of how accurate this sensor is in calculating these values, as the sensor is placed directly on the elbow. This placement makes it difficult to find each of these data points correctly. The current price of the MotusBaseball complete package is $149.99.

2.10 Current Needs

After the Steroid Era ended in baseball, some (if not most) pitchers suddenly had lost one of their best “tools” to pitch better. The rise of biomechanics rose from the demand for a new tool to improve pitching. The demand to incorporate biomechanics led to an understanding of how each body part, including the elbow, should move in order to become better pitchers. This demand also indirectly contributed to more pitching elbow injuries. The problem started from one extreme, where pitchers were not throwing hard enough, to the other extreme, where pitchers are getting hurt. Teams and players are looking for ways to slow down the rise of elbow injuries in the UCL. If biomechanics were able to determine how to throw faster, perhaps it could also be used to understand and prevent elbow injuries. Despite the increase in the use of biomechanics in pitching, there has yet to be a stage where biomechanics can be used to determine injury risk.

Chapter 3: Project Strategy

3.1: Initial Client Statement

The initial client statement was developed by the faculty advisors and project sponsor: Professor Karen Troy, and Dr. David Magit respectively. The scope of the project is as follows:

Develop a worn sensor-based system to prevent elbow injury that occurs as a result of baseball pitching with the following criteria:

1. *The sensor should be wearable*
2. *The sensor should provide real-time biofeedback on injury prevention*
3. *The system should differentiate the biofeedback in different types of pitches*

3.2: Design Objectives

After analyzing the initial scope of the project, the following design objectives were developed to meet the objectives and constraints.

3.2.1: Hardware Objectives

In order to achieve the criteria, the team came up with five hardware objectives.

<u>Accurate</u>

The device needs to be able to accurately measure the biomechanics of the baseball pitching motion. Previous biomechanics research has found the torque and force at the elbow during a baseball pitch. In order to confirm the accuracy, the team compared the data received from the sensor to the other measurement methods researched and got similar results.

<u>Pitch Detection</u>

The device must be able to detect differences in mechanics and tell whether they are related to fatigue or a different pitch type. When a pitcher throws a different pitch type the data is different from the data collected from another pitch type. The device should be able to detect this difference and not mistake it with fatigue.

Real-Time Interpretation

The device must be able to provide real-time feedback on the fatigue levels of the pitcher. This feedback should occur within ten seconds. This time should give the user enough time to see a dangerous level of risk and assess the pitcher whether it is during a game or in practice.

Wearable

The device must be able to be worn by the pitcher while they are pitching or in between pitches. The sensor can only collect the data from the arm if it is able to be worn on the body. It cannot move once put on the arm, as the data will be invalidated if the device moves while it is measuring data.

Ease of Use

The device must be easy for the pitcher to use, while not affecting the movement or mechanics of the pitcher's motion. The device must be simple enough to be used by someone who is not very familiar with these devices, such as a coach or a player.

3.2.2: Constraints

Time

The project must be completed in the allotted Major Qualifying Project time. The given time is from September-April.

Cost

The budget for the project is $250 per team member. Three team members means a total of $750.

Sensor Market

The project must rely on using sensors that are already on the market. Due to the time and cost constraints, the team built a custom design that is based on the sensor technology on the market.

Software

The project relied on a laptop software program to store and process the data. The program must be able to import and analyze the data using the equations. The data is stored locally from this program.

IRB Approval

In order to perform human subject testing, the WPI Institutional Review Board (IRB) must approve of the protocols involved. The procedure abides by the rules of testing for this board. The investigators must follow all the ethical and regulatory concerns, so the project has no issues.

Simple Set-up

The device setup should be quick and easy, roughly a minute to set up without too many complications so that it can be used in games, where there is limited time before the start. Also, it should be simple enough to set up, so that a user that is not very knowledgeable about sensors can use it.

No Pitching Motion Interference

The pitching motion while wearing the sensors should be the same as the motion without the sensor on. This allows for accurate fatigue and injury risk results.

3.3: Standard Design Requirements

The team was tasked with designing a sensor system that uses medical research involving the testing of human subjects. The project must follow the requirements laid out by multiple standard agencies. These agencies include the International Organization for Standardization (ISO), the Institute of Electrical and Electronics Engineers (IEEE), and the Federal Communications Commission (FCC). The standards involving the product are listed below.

ISO

This device falls under six categories of ISO standards:

1. ISO 13485 - Medical Devices - Quality Management Systems - This standard is how the medical devices need to be required to meet customer and regulatory needs.
2. ISO 14155 - Clinical investigation of medical devices for human subjects - This the standard for providing good clinical practices for human subject testing relating to design, conduct and recording the investigation.
3. ISO/IEC 17025 - Testing and Calibration Laboratories - This is to help results of certain testing be accepted by a wider range of people, including internationally.
4. ISO 21500 - Guidance on Project Management - This gives guidelines on how to have good practice when managing a project.
5. ISO/IEC 27001 - Information Security management - This standard is meant for optimizing security management systems. This is used to better protect information assets.
6. ISO/IEC 29182 - Information Technology - This refers to the standard set regarding sensor networks. It gives the organization of everything involved in a sensor network.

IEEE

IEEE - 360 - 2022 gives the overview and specifications for wearable consumer devices. It describes areas such as security, suitableness to wear, health, and fitness.

FCC

FCC Official Guideline - Part 15.247 Includes electronic devices used for wireless internet, wireless access points and Bluetooth transceivers. These are operated as a Digital Transmission System, Frequency Hopping Spread System or a hybrid system. These operate at Bluetooth/WLAN 802.11 or 2.4GHz.

3.4: Revised Client Statement

Based on the requirements and constraints the team was able to revise the client statement, resulting in the new one being:

The goal of the project is to develop a sensor system that is able to read raw data (data that has not yet been processed) as the pitcher is throwing the baseball. The system consists of an Inertial Motion Sensor in the middle of the forearm of the pitcher. Ultimately the IMU should calculate linear acceleration and angular velocity at the elbow to be transmitted to a serial port. The goal of the software should be to determine a dangerous level of injury resulting from torque on the UCL induced by fatigue in a baseball pitch in real-time. The device should be easy enough to use those coaches and players should be able to use it with little knowledge of sensors.

3.5: Project Goals

The project was designed to meet three goals:

1. *The sensor should be stable and wearable*
2. *The sensor should provide real-time biofeedback on injury prevention*
3. *The system should differentiate the biofeedback in different types of pitches*

Aim 1: *Equations of motion will be developed based off of free body diagrams*

Based on the initial design concept, the main metrics in UCL injuries should be analyzed in the system. These metrics include the average valgus force and torque produced at the elbow during a baseball pitch. Once determined, models were created to account for the metrics that account for the system, acting on the arm as the ball is pitched. The free body diagram models created display the arm as two segments, the upper arm and forearm. For the project, the forearm segment of the arm was focused on. The free body diagram generated of the forearm allowed the group to develop equations of motion. These equations were used in the software to calculate the force and torque at the elbow from raw data inputs during a baseball pitch. These metrics are analyzed to estimate their effects in the UCL.

Aim 2: *Develop a wearable sensor system software that will warn of dangerous levels of injury risk on the elbow in real-time*

A small wireless IMU was attached to the subject's lower arm segment. The accuracy of the sensor was tested before use on the subjects. Using the software component of the system, the team intended to use the raw data from the sensor and the developed equations of motion to calculate the metrics of interest for the pitcher in real-time, so the possibility of using in-game and in-practice exists. The software component should also determine the extreme values for each individual pitch in order to compare different pitches of the same type to each other more effectively within the session, i.e., fastball pitches are compared to each other, breaking ball pitches are compared to each other, etc. Each of the pitch type values were grouped in windows to compare the variability of the pitches against one another. Using the software, a healthy baseline and variability were established using the in-session data. The software compared the subsequent pitches against the baseline to warn of the risk based on the estimated fatigue.

Aim 3: *Conduct human testing to analyze the variability in pitch types when arm and whole-body fatigue is induced*

After validating the sensor system functioned properly, the team conducted human subject testing. The goal of human subject testing was to collect raw data to be processed through the software. The data from these sessions allowed the team to assess the system’s ability to measure fatigue. The analysis of fatigue was processed through the software after calculating baseline force and torque generated at the elbow. More specifically, the goals of the human subject testing include gather field data from pitching practices to test the abilities of the code, use the system in real-world operating conditions to analyze any hardware limitations, test the feasibility of the system's operation protocol, and conduct usability testing to assess the practicality of the physical system. To accomplish this, the team designed and facilitated three human subject testing protocols: baseline data collection, where real world pitching values are collected, induced arm fatigue data collection where fatigued data is collected, and a usability, design verification study where data is collected concerning the feasibility of the physical system. Following the human subject testing, the data collected was processed, analyzed, and used for further system validation testing.

Chapter 4: Design Process

4.1: Need Analysis

Based on the client statement and requirements provided by Professor Troy and Dr. Magit, the team developed the need analyses to ensure all requirements were met. The requirements provided in Chapter 3 of the report are that an elbow injury prevention system of multiple pitches with real-time feedback must be developed. After research, the team concluded the best solution for the requirement is to develop a real-time feedback sensor-software system. The system must have the ability to track a pitcher's movement and collect the data requirements discussed in Chapter 3. The sensor must also meet the requirements of wearability and ease of use. The sensor must be able to be worn during the pitching motion with minimal sensor movement during use. The sensor must also be comfortable enough that the pitcher does not change pitching mechanics due to the sensor. To accomplish the problem system requirements, the sensor must have the ability to measure raw data and wirelessly transmit the data to a computer. The sensor must also collect enough raw data to capture the pitching motion, meaning the sampling frequency must exceed that of a baseball pitch by a factor of two (Nyquist's criterion). The software must then have the capability to collect the raw data and calculate the force and torque at the elbow from the previous pitch. Finally, the software must have the ability to produce real-time graphs of the average force and torque on the elbow after every pitch. These sensor and software requirements can be shown below in Table 1**.**

Sensor Requirements	Software Requirements
Accurate (+/- 30 G’s and +/- 4000 degrees per second)	Collect raw data from sensor (in MATLAB files)
Wearable	Produce real-time feedback on joint force (Newtons) and torque (Newton-meters)
Adjustable	Flag pitches which are outside two standard deviations of baseline pitch

Table 1: Sensor and Software Requirements from Chapter 3

4.2: Alternative Designs

During preliminary research of the design section, the team developed a concept of the overall sensor system which can be seen in Figure 7 below.

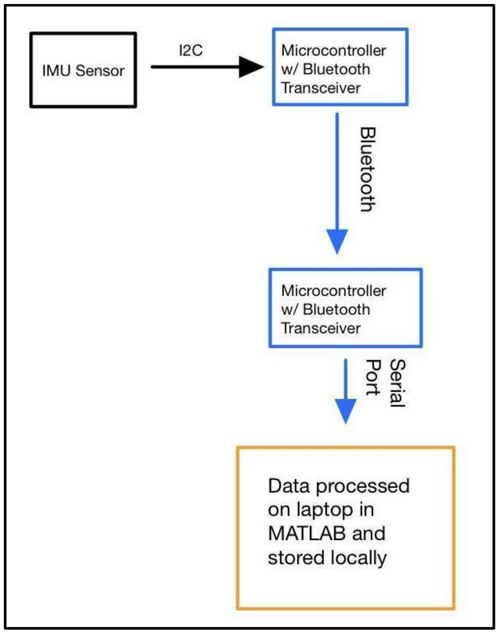


Figure 7: Data Processing System Outline

After analyzing the system outline, the team evaluated four main concepts developed from the team to meet the design requirements. This section outlines these four main concepts and analyzes the decision to develop one into the final design.

4.2.1: Wi-Fi Transceivers

The initial design concept to meet the system requirements was a Wi-Fi transceiver. The Wi-Fi transceiver can be shown in Figure 8 below.

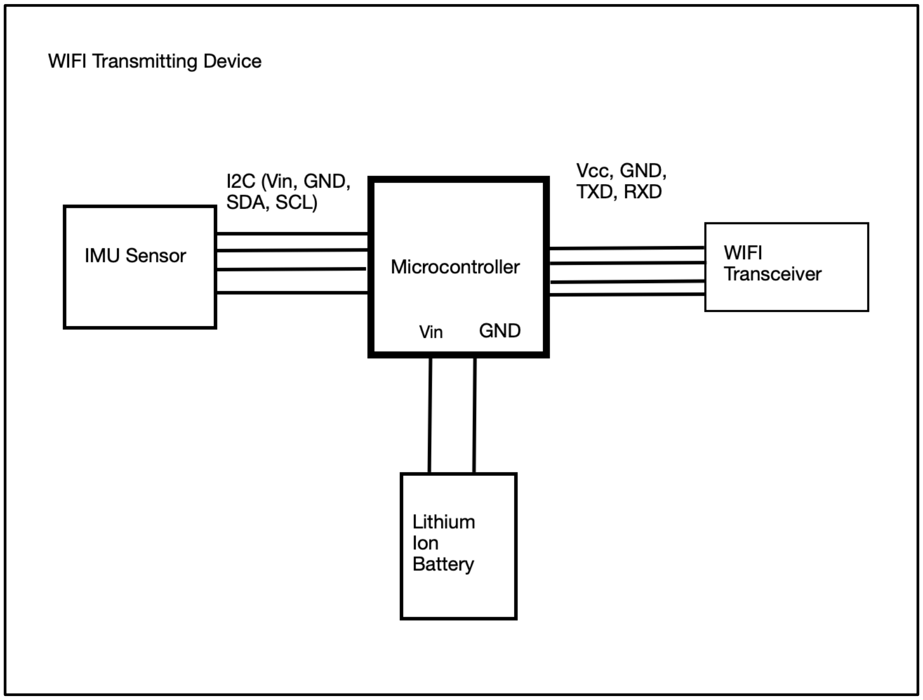


Figure 8: Wi-Fi Transceiver Attached to a Microcontroller System

The Wi-Fi transceiver device system can transmit raw data collected from the IMU sensor wirelessly. The system can transmit the raw data collected through the sensor to a computer using Wi-Fi capabilities.

The primary drawback of this system is the necessity of soldering the transceiver to the microcontroller. The Wi-Fi transceiver is a device in itself. When soldering the Wi-Fi transceiver to the microcontroller, this creates a larger sensor device system. A larger sensor device system may not meet the requirement of wearability. The larger the sensor device system, the more uncomfortable the sensor could be on the arm of the pitcher. Another drawback from the Wi-Fi transceiver is the need for Wi-Fi to transmit the data. Not all places where the system would be used (gym, baseball field, etc.) have a strong Wi-Fi signal. The lack of a strong Wi-Fi signal can result in a disconnection between the sensor and the computer. For these reasons previously mentioned, the Wi-Fi transceiver was not included in the design.

4.2.2: Bluetooth Transceiver

The second design concept is the Bluetooth transceiver. Like the Wi-Fi transceiver, the Bluetooth transceiver has the capability to wirelessly transmit raw data to the computer. The raw data is transmitted through Bluetooth to the computer to be processed. The Bluetooth transceiver system can be seen in Figure 9 below.

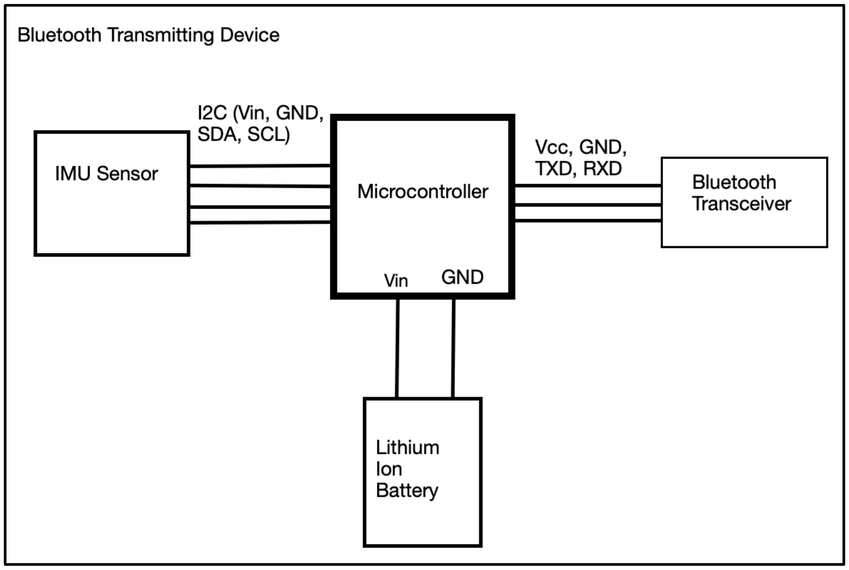


Figure 9: Bluetooth Transceiver Attached to the Microcontroller System

The primary drawback with the Bluetooth transceiver is similar to the Wi-Fi transceiver, the team must solder the transceiver onto the microcontroller. Soldering the Bluetooth transceiver to the microcontroller increases the size of the overall system. Increasing the size of the device could result in discomfort for the pitcher, leading to a change in their mechanics. Due to these drawbacks, the team did not choose this concept for the design.

4.2.3: Single Board Wi-Fi Transmitting Sensor

The third design concept is a Wi-Fi transmitting device. Differing from the previous two designs mentioned, this system has a built-in Wi-Fi transmitter into the microcontroller. The single board Wi-Fi transmitting device concept can be seen below in Figure 10**.**

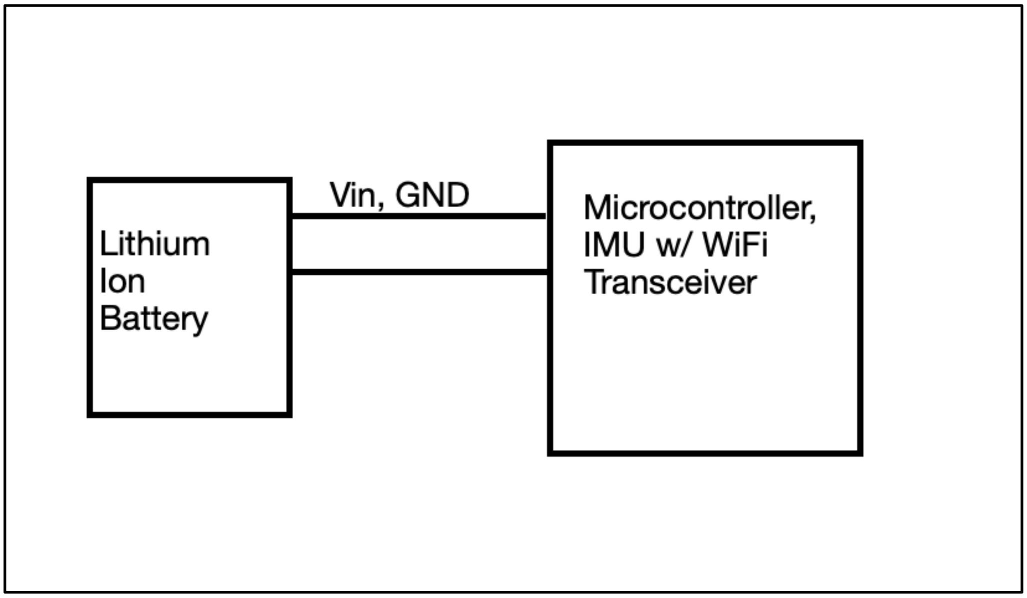


*Figure 10**:** Design Concept of the Single Board Wi-Fi Transmitting System*

The single board Wi-Fi transmitting system can wirelessly transmit the raw data without soldering on a separate transceiver board, as the transceiver is already soldered onto the circuit board before purchase. This allows for a smaller device to put onto the pitcher when collecting data.

The drawback of this design concept is the same as the previous Wi-Fi device. The lack of places that have Wi-Fi accessibility results in the data not being able to transmit correctly. Especially when testing outside on a baseball field, there is not always a Wi-Fi connection. This results in a limited number of places where this device could be tested. As a result of these drawbacks, the team did not choose this design concept.

4.2.4: Single Board Bluetooth Transmitting Sensor

The final design concept is a single board Bluetooth transmitting sensor. The Bluetooth transmitting sensor has a built-in capability of wirelessly transmitting raw data through Bluetooth. The single device Bluetooth transmitting system can be seen below in Figure 11**.**

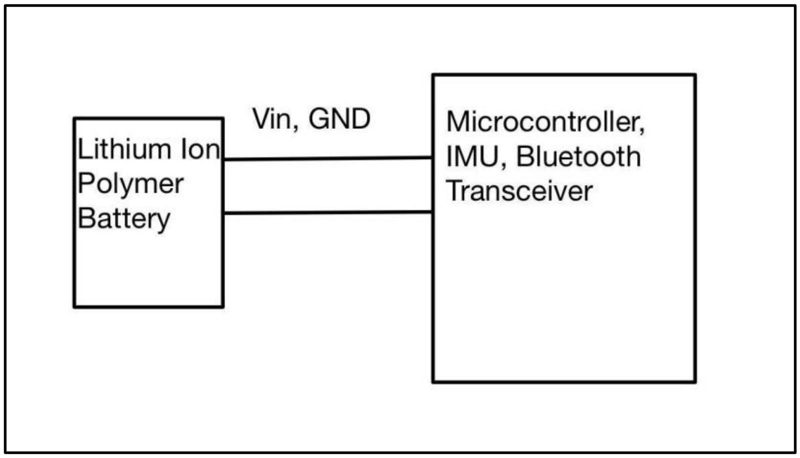


*Figure 11****:*** *Design Concept of the Single Board Bluetooth Transmitting System*

Same as the previously mentioned single board Wi-Fi system, the single board Bluetooth system has the capability to transmit data with a compact design as the microcontroller, IMU and Bluetooth transceiver are already soldered onto the circuit board before purchase.

The benefit of this single device Bluetooth system is the ability to wirelessly transmit raw data through Bluetooth. The team found it necessary for the sensor system to have the ability to transmit the raw data on a baseball field, which can be accomplished through Bluetooth. This cannot be said for Wi-Fi transmitters as baseball fields do not always have Wi-Fi capability. Another benefit of the single device Bluetooth system is the overall size of the system. Each piece being on the same board, allows for the devices to be centimeters in size along with an external battery. As stated in Chapter 3, one of the requirements the team needs to meet is developing a system that is wearable and comfortable for the pitchers. To meet the needs of the wearability and comfort for the design, the smallest system would best fit the requirements.

The preliminary design is using inertial motion sensors attached to a microcontroller with Bluetooth transmitting capability. These sensors have a built-in Bluetooth transmitter in the microcontroller that transmits the raw data to a computer wirelessly. The raw data is then inputted into MATLAB to be analyzed. The analysis of the pitch is done with real-time feedback. The real-time feedback analysis allows the pitcher and coach to make “game time” decisions on whether to remove a pitcher from a game before injuring themself.

4.3: Design Requirements

After conducting a need analysis, the specific design requirements were developed.

4.3.1: Sensor Requirements and Functions

Analyzing the design requirements stated in Chapter 3, the team defined the requirements for the hardware detailed below in Table 2**.**

Number	Hardware Requirement
1	Motion sensors shall record accelerations up to +/- 32 G’s
2	Motion sensors shall record motion up to an angular rate of 4000 degrees per second
3	Motion sensors shall record motion in 6 degrees of freedom; 3 translational and 3 orientational axes
4	The motion sensors shall have a sampling frequency of at least 120 Hz
5	The sensor system shall operate for a minimum of four hours straight and be rechargeable
6	The system of motion sensors shall weigh less than one pound
7	The motion sensors shall securely mount onto the body of the user
8	The sensor system shall transmit real-time data in outdoor and indoor conditions
9	The sensor shall report back motion data to microcontroller
10	The motion and time coordinates of the sensor system shall interface with the data collection to be put into a data analysis program
11	The sensor data shall be analyzed within 1 minute after the pitch that occurs
12	The sensor shall be capable of transmitting over a distance of up to 60 ft

*Table 2**:** Table of Hardware Requirements for the Wearable Sensor Device*

4.3.2: Software Requirements and Functions

After the team completed the need analysis and completed the hardware requirements, the software requirements were analyzed to meet the needs defined in Chapter 3. The software requirements were developed knowing the sensors need to calculate linear velocity and angular acceleration to calculate the force and torque at the elbow. A baseline value of force and torque was developed. As stated from Chapter 2, when the mechanics of the pitch break down, more stress is induced on the elbow. The software requirements for the system design are in Table 3**.**

Inputs	Linear Acceleration (±x, y, and z axes) in meters/second^2
	Angular Velocity (± azimuth, elevation, and roll) in degrees/ second
	Time values in milliseconds
	Subject Specifications (Height, weight, arm lengths, sensor location)
Source	The raw data from the sensor system will be sent wirelessly to a microcontroller plugged in the computer, which will upload the data into the MATLAB code, using the serial port.
Outputs	A 7-column array from with each of the raw data values occupying each column
	Force at the elbow during each pitch
	Torque at the elbow during each pitch
	Range of Torque
Pre-condition	The MATLAB script must be open and displayed on the user’s screen
Post-condition	The raw data .MAT file is unchanged, and new .MAT file of calculated values is stored locally on the user’s computer

Table 3: Table of Software Requirements for Sensor System

4.4: Conceptual Sensor Designs

After the team analyzed the hardware requirements outlined in Table 2, there were potential sensors that would meet the needs of the sensor system. The team researched four potential sensors to use in the device. The team then analyzed each of the potential sensors based on the hardware requirements shown above in Table 2**.**

- Nicla Sense ME: The Nicla Sense ME is a sensor that can measure both “motion” and “environment.” This sensor has nine degrees of freedom smart motion sensors and four degrees of freedom environmental sensors. The Nicla Sense has an AI sensor system with an integrated motion sensor (16-bit 3-axis accelerometer and gyroscope), magnetometer, pressure sensor, gas sensor with AI, humidity sensor, and temperature sensors. The Nicla Sense ME is small and compact, weighing a total of two grams with Bluetooth compatibility. This IMU has more than enough capabilities for the design, with each sensor costing $71 each [39].
- Adafruit Feather nRF52840 Express: The Adafruit Feather nRF52840 Express is a microcontroller with a built-in accelerometer and gyroscope that can measure in six degrees of freedom. The microcontroller runs at 64 MHz and has Bluetooth capability. Overall, the sensor weighs about 6 grams without soldering or wiring on a microcontroller. The Adafruit Feather uses SPI and I2C to connect the IMU outputs to the microcontroller. This IMU has enough capability to work for the design, each sensor costs around $24 [40].
- Arduino Nano RP2040 Connect with headers: The Arduino Nano RP2040 is an IMU that runs off the brain board of Raspberry Pi. This sensor has a built-in IMU that can measure six degrees of freedom at 2000 degrees per second. The Arduino Nano RP2040 has

wirelessly transmission capability through Wi-Fi, along with Bluetooth. This sensor also has a built-in microphone to wirelessly code the device. The sensor has a processing speed of 133 MHz and is lightweight around 6 g. In total, the Arduino Nano RP2040 Connect with headers cost $25.50 each [41].

- Adafruit ICM20649 Wide-Range 6-DoF IMU Accelerometer and Gyro: The Adafruit ICM20649 Wide-Range is an IMU with Bluetooth transmitting capability. This IMU can measure six degrees of freedom up to 30 g's and 4000 degrees per second. This sensor processes data through an I2C connection to the microcontroller. The Adafruit can be used through both Raspberry Pi and Arduino Uno. In total, the Adafruit ICM20649 Wide-Range sensors cost $15 each [42].

Analyzing the requirements outlined in Table 2, the team determined the Adafruit ICM20649 Wide-Range 6-DoF IMU Accelerometer and Gyro to be the best sensor for the system. The sensor was less expensive than the sensors by at least $10 per sensor. The Adafruit ICM20649 excelled over the other sensors in the capability to measure up to 4000 degrees per second. This would allow the team to capture more data during each pitch from the Adafruit ICM 20649 than the other sensors.

4.5: Design Calculations and FBD Modeling

The data collection to be analyzed by the team is the joint forces and torques at the elbow. To estimate the joint forces and torques, the sensors must have the capability to measure the linear acceleration and angular velocity. To evaluate the equations of motions of the arm during a baseball pitch, free body diagrams (FBDs) were developed for segments of the arm. Figure 12 shown below displays the sensor location on the arm for data testing.

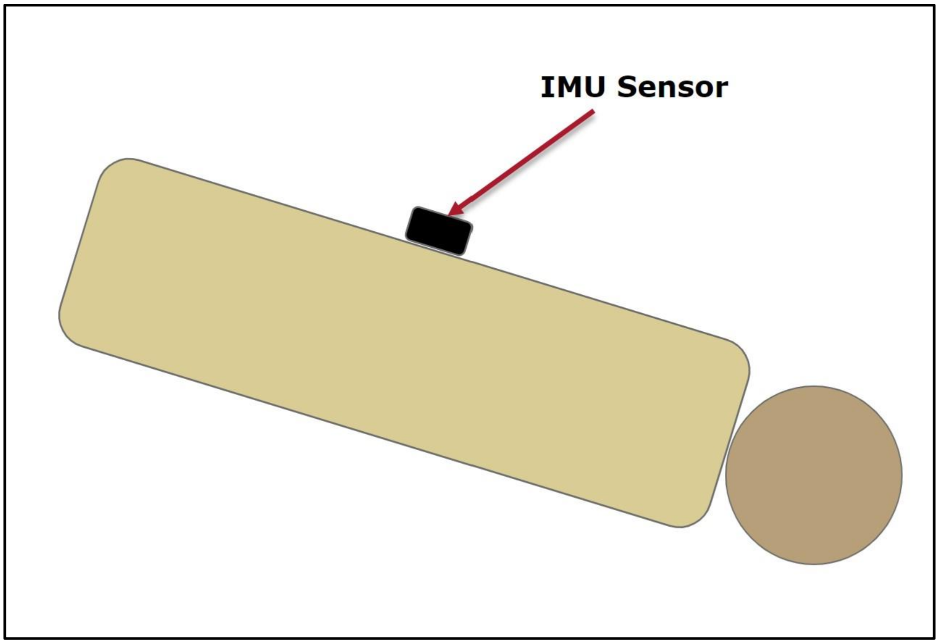


Figure 12: Diagram of the Forearm Showing the Sensor Location during Data Testing

From Chapter 2, the maximum force and torque on the elbow during a baseball pitch occurs when the arm is at 90 degrees. Demonstrating the 90-degree arm angle and local coordinate system of the sensor system is shown below in Figure 13**.**

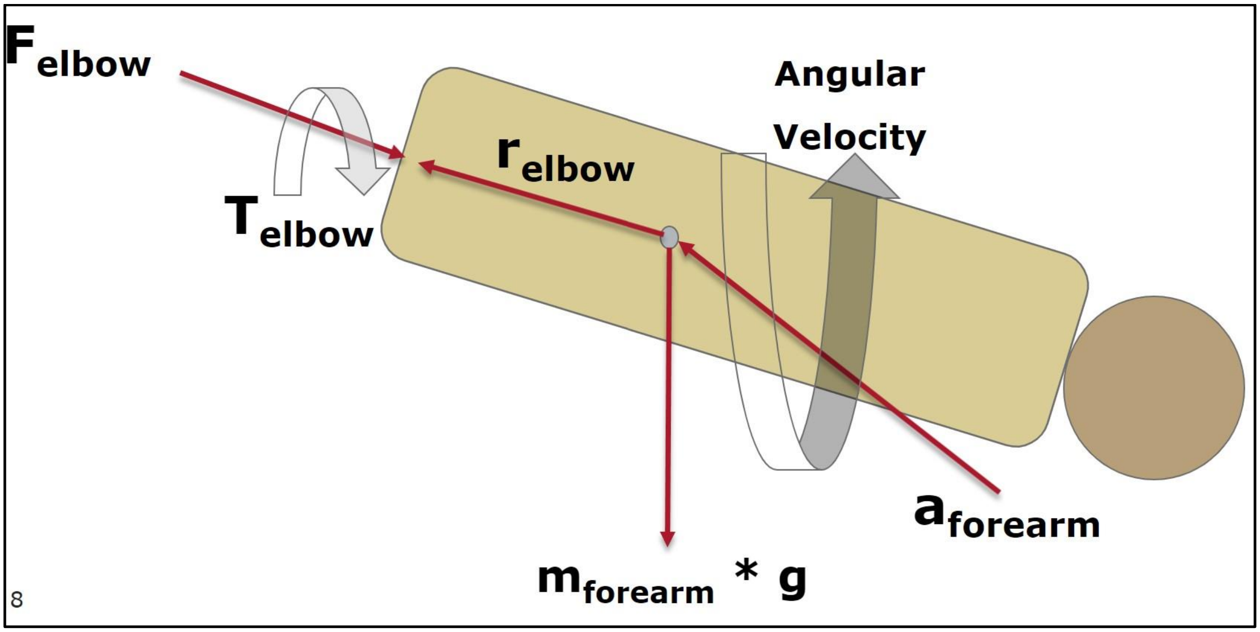


Figure 13: Free Body Diagram of the Forearm Showing the Forces Applied to the Arm

Figure 13 shows a zoomed-in free body diagram of the forearm segment. The model also displays the values that are measured to calculate the joint force and torque at the elbow. Shown below in Equation 1 is the derived force equation for the elbow. The variables in the equation are defined as follows: **F** = Force at the elbow measured in Newtons, **m** = Mass of the forearm measured in kilograms, **g** = Acceleration due to gravity in meters per second squared, and **a** = Calculated Acceleration of the forearm from the sensor measured in meters per second squared.

$$-F_{elbow} + m_{forearm} * g = m_{forearm} * a_{forearm}$$

Equation 1: *Equation for Force at the Elbow*

Shown in Equation 2 is the derived torque equation for the elbow. The derivations of the two equations can be located in Appendix A**.** The variables in the equation are defined as follows: **T** = Torque of the elbow measured in Newton-meters, **r** = Distance from the sensor location to the elbow measured in meters, **F** = Force applied to the elbow measured in Newtons, **I** = Moment of inertia given through the formula in Appendix A measured in kilograms per meter squared, and **α** = Calculated Angular Velocity from the sensor measured in radians per second.

$$T_{elbow} = (r_{elbow} \times F_{elbow}) - (I * \alpha)$$

Equation 2: *Equation for Torque at the Elbow*

The equations for joint force and torque are embedded into a MATLAB code. The linear acceleration and angular velocity found from the sensors are calculated through the MATLAB code to evaluate the desired force and torque.

The equations of motion developed assume the arm is bent at 90 degrees to vertical (parallel with the ground). The team made this assumption based on previous research which found the majority of injuries in a baseball pitch to occur when the arm is bent at 90 degrees. The team also assumed the weight of the sensor system to be negligible. The sensor system is light and has little to no impact on the mass of the forearm. The equations are working in 3D, as the Force and the Torque at the elbow are the calculated magnitude. The IMU sensor calculates the vector linear acceleration and angular velocity of the 3-axis. Through the software and equations of motion, the magnitude of Force and Torque at the elbow was found.

4.6: Feasibility Study and Experiments

Before testing the wearable sensor system on other subjects, the team had to validate that the sensors could perform the required tasks for the design concept. The first test of the sensor was to analyze if the Bluetooth transmission was correctly transmitting data. To test this, the team held the sensor in place on a desk, constantly sending raw data to the computer. This experiment validated that the sensor could transmit raw data through Bluetooth, as well as accurately measure linear acceleration through gravity.

To validate the sensors could properly measure angular velocity, the team attached the sensor to the center of a wheel with a radius of 16 inches. The wheel was moved forwards at a constant velocity of 5 miles per hour. Using the angular velocity equation of angular velocity is equal to linear velocity divided by radius ($\omega = v/r$), the team could calculate the expected angular velocity value. Comparing the expected angular velocity with the measured angular velocity from the sensor, validated that the sensor worked properly (data can be seen in section 4.9).

After validating the sensors properly to measure angular velocity and linear acceleration, the team then conducted initial testing on themselves. The team placed the sensor in the center of mass of the forearm, as indicated by the free body diagram below in Figure 14.

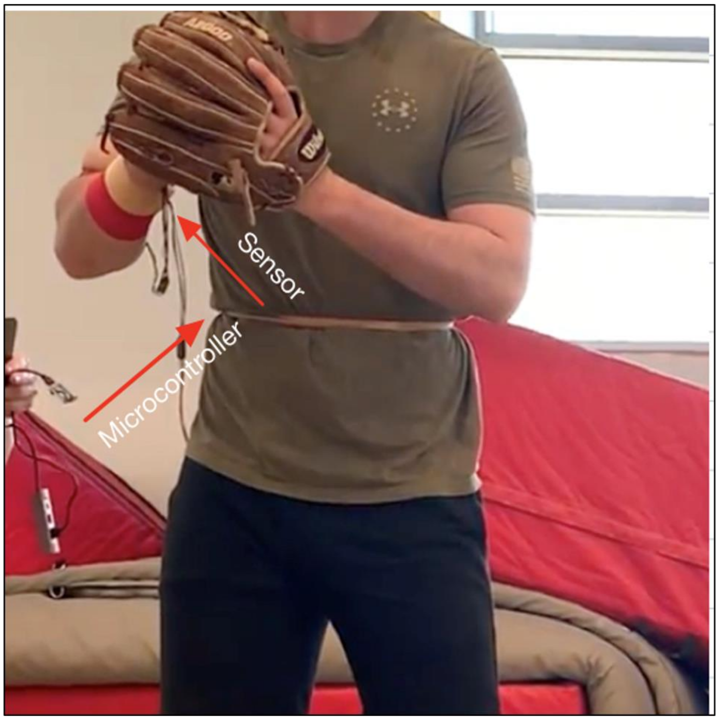


Figure 14: Sensor System Attached to a Pitching Subject

After placing the sensor on the forearm, the team member was informed to throw a ball into a net to analyze if the force and torque on the elbow would be calculated. This experiment posed to be an issue. The team realized the Bluetooth data was being interrupted when a pitch was thrown, not correctly transmitting the raw data.

These initial tests showed that the sensors properly measured linear acceleration and angular velocity. However, the experiments also showed that Bluetooth transmission became interrupted when pitches were delivered. This led to the Bluetooth transceiver placement being changed from the forearm to the back. This led to a much better Bluetooth transmission.

4.7: Final Design Concept

The structure for the final design concept was outlined by the team's research on sensor motion and pitching mechanics. The team analyzed the pitching mechanics and sensor motion calculations to develop hardware and software requirements. The final design section accounted for all the requirements of the hardware and software.

As previously stated in section 4.4, the team analyzed the four different sensor options of: Nicla Sense ME, Adafruit Feather nRF52840 Express, Arduino Nano RP2040 Connect with headers, and Adafruit ICM20649 Wide-Range 6-DoF IMU Accelerometer and Gyro. The team ultimately found the Adafruit ICM20649 microcontroller and sensor to be the most viable option for the system. This microcontroller has the ability to capture motion at 4000 degrees per second, much larger than that of the other sensors. The Adafruit ICM20649 microcontroller also meets the requirements of transmitting wirelessly through Bluetooth compatibility. Ultimately this microcontroller was found to be the best option for the team's sensor system.

The final design concept has the Adafruit ICM20649 sensor unit connected to a lithium-ion battery for power. The sensor was attached to the center of mass of the forearm, and the microcontroller attached to the center of the subject's back. The microcontroller would be attached to the subject's back to restrict its movement, allowing for less disruption with the Bluetooth connection. The final hardware for the sensor system is shown below in Figure 15.

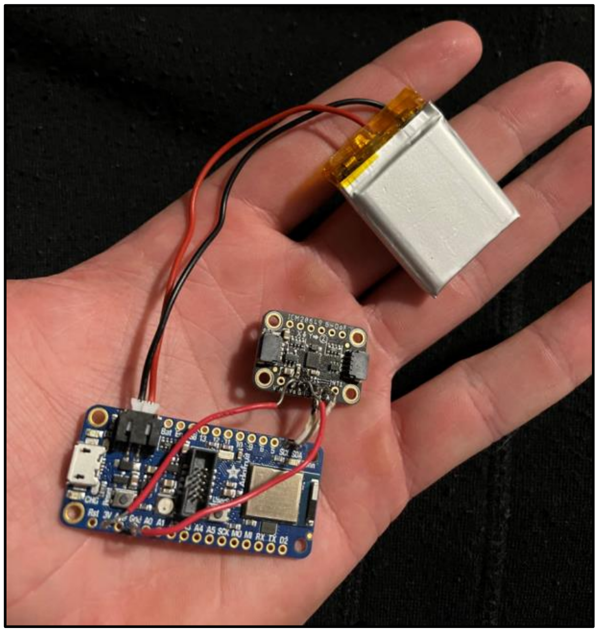


Figure 15: Final Design Hardware

The sensor measures the linear acceleration and angular velocity at the elbow and transmits this data wirelessly through Bluetooth to a laptop. The data is then processed through MATLAB code written to calculate the force and torque at the elbow for each pitch. These calculated metrics show the average of baseline data, as well as the variation in data as fatigue is induced to the subjects. The final design concept can be seen through the flow chart shown below in Figure 16.

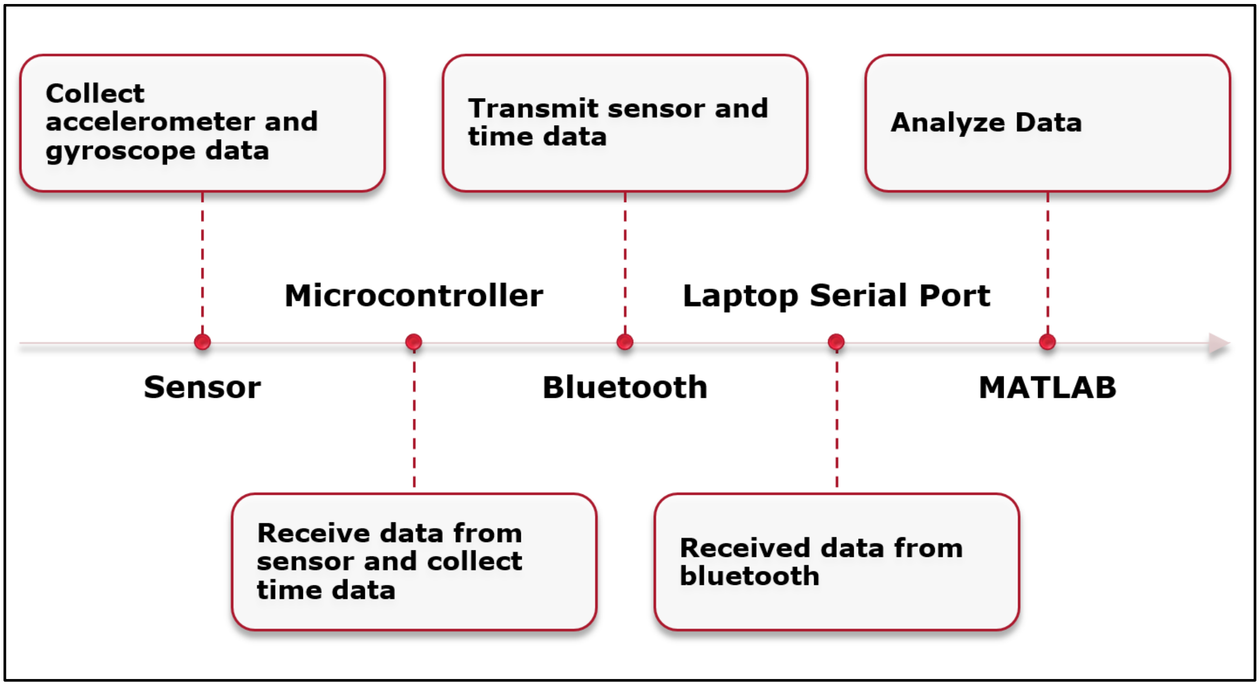


Figure 16: Flowchart of Final Design Concept of Sensor System

4.8: Optimization

All the design specifications need to be optimized to produce the best data for the system. These specifications include sensor location, method of attaching the sensors to subjects, and data analysis of each pitch.

The location of the sensor is at the center of mass of the forearm. The center of mass of the forearm is determined through the Anthropometric Data [43], the center of mass is 0.430 from the elbow of the entire forearm length. This location optimizes the data collection of the system. The center of mass of the forearm is an ideal location as the sensor is surrounding the joint of interest, rather than placing the sensor directly on the joint of interest. This allows for the sensor to not interfere with the joint as a pitch is being delivered. The location of the sensor was also decided based on the assumption the equations of motions are developed as the arm is at 90 degrees. The arm can be assumed to be 90 degrees to vertical due to the research discussed in section 2.6. The majority of injuries that occur in a baseball pitch, happen during the late cocking phase when the arm is bent at 90 degrees from vertical.

Attaching the sensor and microcontroller to the subjects in a timely manner was optimized. The current method of attaching the sensor and microcontroller to the subjects is using pre-wrap and self-adhesive tape. A layer of pre-wrap was applied to the subject's skin to prevent any discomfort. The sensor was then applied to the pre-wrap with the x-axis facing the elbow (along the long axis of the forearm), and the positive z-axis into the forearm. The IMU is then wrapped around the forearm using self-adhesive tape. The same process was applied for the microcontroller on the back. However, a small cut was made to expose the Bluetooth transceiver on the microcontroller to not block the connection. It is crucial to optimize fixing the sensor and microcontroller on the subjects as any external movement could result in false data.

Before conducting human subject testing, the team’s approved Institutional Review Board consent form (shown in Appendix B) was reviewed and signed by all participants. After signing the IRB consent form, the subjects conducted the approved data collection protocol found in Appendix C. The current method of comparing healthy pitches to those which prove to result in injuries is to create baseline data. Shown below in Figure 17 is a flowchart of the current data analysis process.

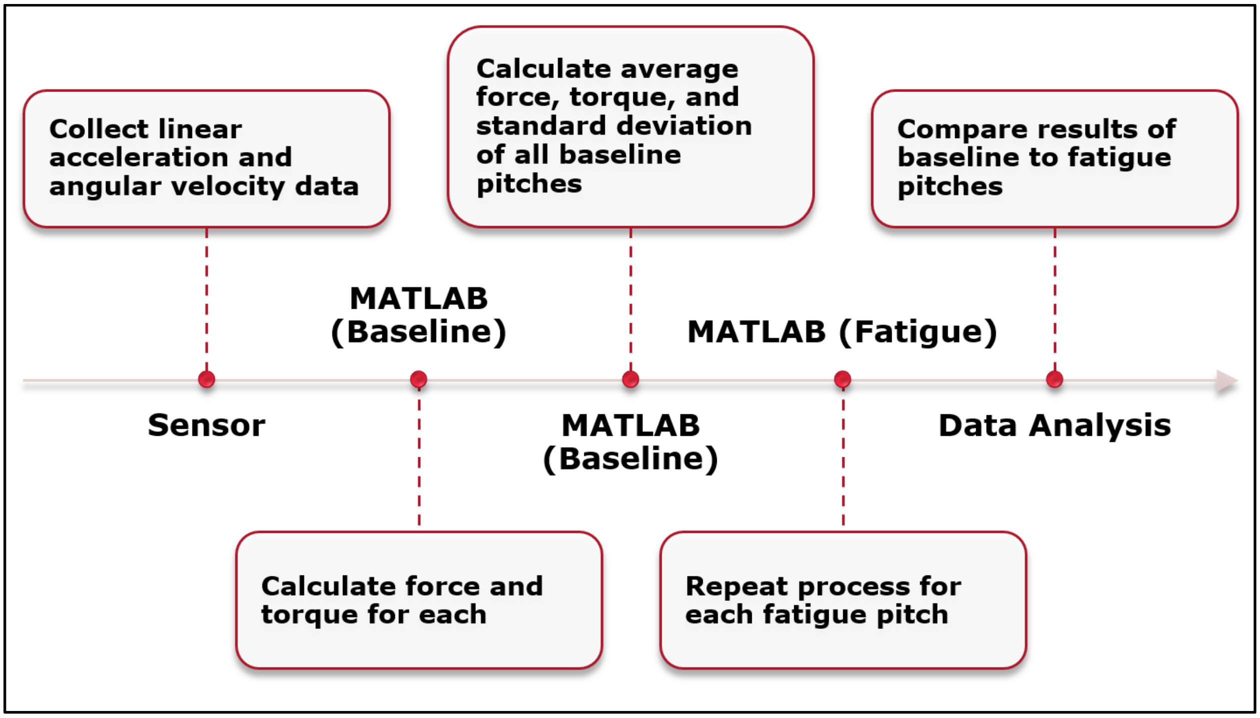


Figure 17: Flowchart of the Data Analysis Process

Developing baseline data showed the force and the torque at the elbow during a healthy pitch. The average of the baseline pitches was calculated upon completion of baseline testing. After fatigue is induced, the force and torque at the elbow is calculated for each pitch. The average of the fatigue induced pitches was calculated upon completion of the testing. The averages of the baseline and fatigue induced forces and torques were compared to show the risk of injury as fatigue is evident in pitching. It is necessary to optimize the number of pitches in the baseline and fatigue data to receive the best result. Not enough data sets could result in skewed or incorrect data.

4.9: Preliminary Data

To determine if the sensor was live and functional, the team must collect preliminary data. The experiment conducted by the team was set up by placing the sensor in the center of a wheel. The wheel was then moved forward at a specific speed to test the live feedback. In this case, the wheel was attached to a team member's vehicle that he drove at roughly 5 miles per hour, equivalent to 2.24 meters per second. Using the equation for angular velocity, angular velocity is equal to linear velocity divided by radius (ω = v/r), the team was able to compare the expected angular velocity to the calculated angular velocity from the sensor's data. The test was successful and showed the expected angular velocity, which given 16-inch tires, should result in approximately 4.68 degree/s.

Figure 18: Sensor Attached to Vehicle Wheel

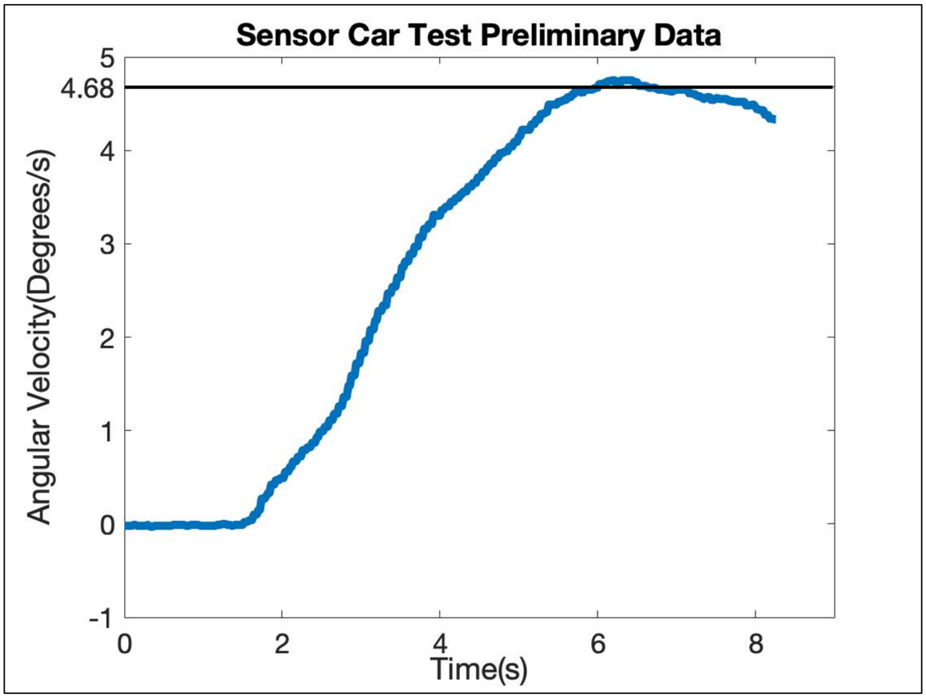


Figure 19: Angular Velocity of Mechanical Model

Figure 19 shows the real-time feedback model of angular velocity over time. The graph verifies the sensor is accurate in measuring angular velocity and linear acceleration. The graph shows the angular velocity to reach a plateau average of 4.63 degrees per second, which is within range of the expected angular velocity.

Chapter 5: Final Design Verification

5.1: Hardware Design Verification

In order to prove that the sensors worked sufficiently, tests were performed based on each of the 16 requirements. These requirements each had a specific standard that needed to be met, for them to pass the testing. A list of the 12 Hardware requirements that was tested for can be found above in Table 2.

Requirement 1: For the sensor to collect adequate data, it must be able measure up to the maximum linear acceleration of a baseball pitcher's arm during a pitch. It was found that the linear acceleration can get up to around +/- 30 G’s (294.2m/s^2). The sensor claims to measure up to +/- 32 G’s (313.8m/s^2). It was tested on one pitch, which can be seen in Figure 20.

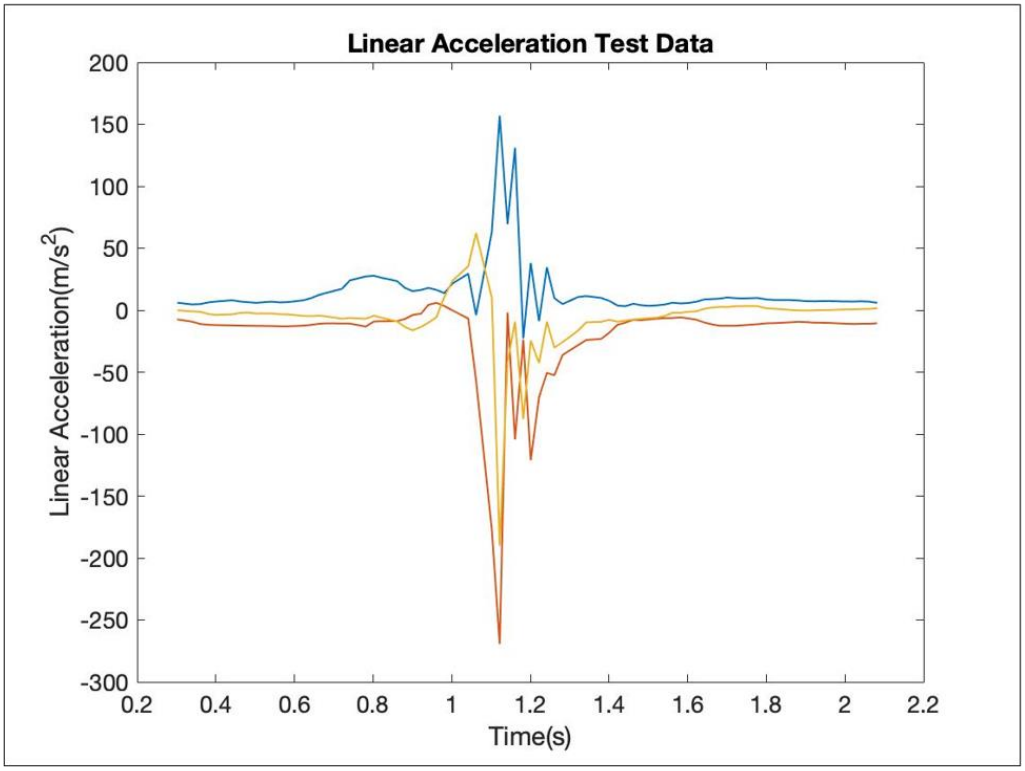


Figure 20: Accelerometer Sensor Test Graph

This graph shows that the linear acceleration reaches down to -275 m/s^2, which is a little less than -28 G’s. This shows that the accelerometer sensor is adequate for testing.

Requirement 2: The sensor needs to be able to be able to measure up to 4000 degrees per second angular velocity. Prior research suggested that the elbow can reach up to 2900 angular velocity during a pitch. The sensor claims to be able to measure up to 4000 degrees per second.

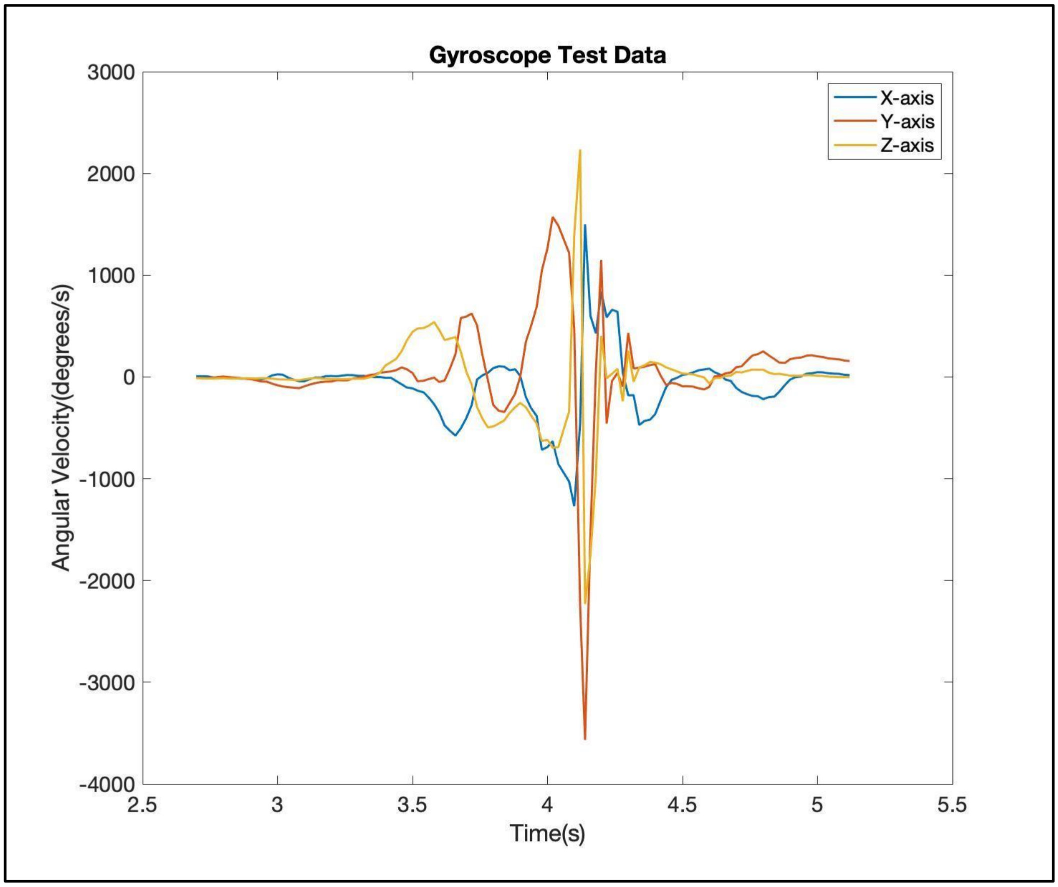


Figure 21: Gyroscope Sensor Test Graph

The gyroscope sensor was able to measure the angular velocity data of a baseball pitch with no issues. In testing, the angular velocity reached around 3500 degrees per second which shows that the sensor is adequate for measuring high angular velocities.

Requirement 3: For the sensors to collect the correct raw data, they need to be able to measure in six degrees of freedom. This consists of the x, y and z axis for the accelerometer and x, y and z for the gyroscope. This requirement passed and can be seen in the above figures for the first two requirements. Each of the figures have 3 axes with them. A photo of the sensor can be seen below with each of the axes labeled.

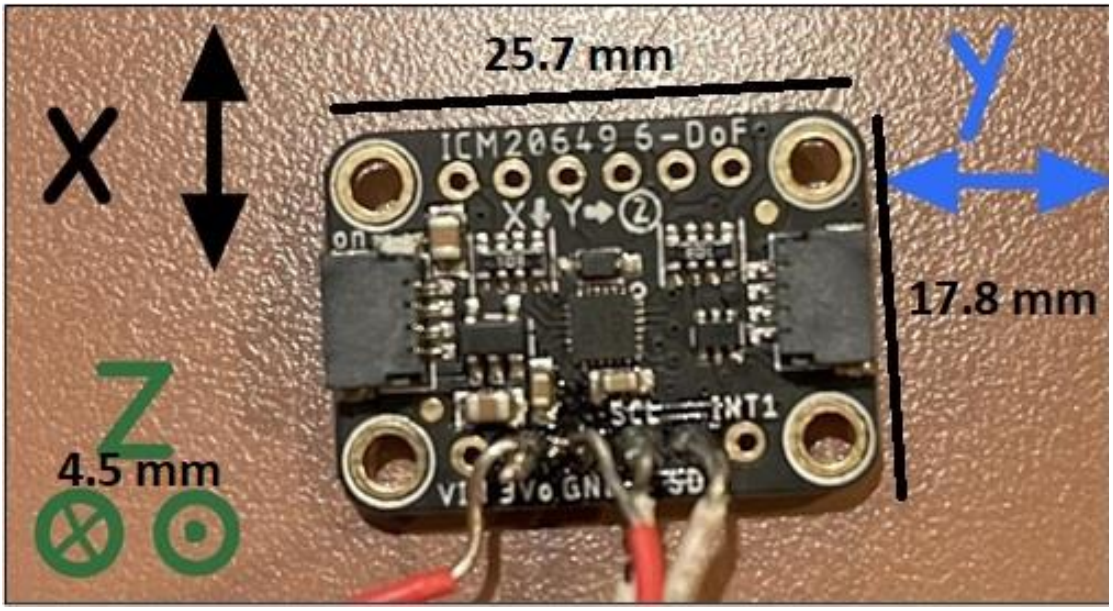


Figure 22: Sensor Axes for X, Y, Z

Requirement 4: The target sampling frequency was at 120Hz in order to get the best results. This would mean that data would be received every 8.33 ms. When tested, the data was received at only every 20 ms because of the microcontroller slowing down from the Bluetooth transmissions. This only gives us a 50 Hz sampling frequency. This fails the verification. A couple ways explored to fix this problem was to collect all the data in the microcontroller locally and then transmit the data from there. This would allow the microcontroller to collect data at a sufficient sampling rate because the transmitter does not need to send the data every time the microcontroller gets data from the sensor. There were issues with the microcontroller being able to store all the data from each pitch before it is sent. This low sampling rate can cause us to possibly miss large spikes in the data. Although the data was not perfect, data was still collected at that sampling rate.

Requirement 5: The sensor needs to be able to last a full baseball game, as well as be able to be reused. This means that the battery should last at least 4 hours and be rechargeable. In order to test this the battery was left in the sensor system transmitting for 4 hours and it was still alive.

The battery can be recharged using a micro-USB cable. This shows that the device passed the testing requirement.

Requirement 6: The sensors should not affect the pitcher's throwing motion, so it must weigh less than one pound. The system claims to be 20 g based on specifications. This along with added wiring, weighed around 27 g. This shows that the device passes this requirement testing.

Requirement 7: The sensors cannot move when they are collecting data, as it would skew the data if this happens. They were taped down on the subject's arm. After throwing pitches, the sensor was in the same spot on the arm. The tape was tight on the arm, therefore the movement of the skin during the pitch would be very minimal, not affecting the data. This shows that the sensor was secure on the arm when the pitcher was throwing, therefore the device passed the test.

Requirement 8: The sensor needs to provide the data in real-time in indoor and outdoor conditions. This way the injury risk can be assessed in game as well as during practice. The data is sent from one microcontroller to another using Bluetooth which works in both indoor and outdoor conditions. This also provides the data back right after the pitch. Therefore, this requirement passes the test.

Requirement 9: The sensor needs to be connected to a microcontroller, which are used to send the data with Bluetooth. Therefore, the data needs to be sent from the sensor to the microcontroller. In order to test this, the microcontroller that was connected to the sensor was plugged to a laptop and opened the serial port. The sensor and time data was printed in the serial port, showing that this requirement was met.

Requirement 10: The motion and time data need to be compatible with the team's MATLAB code in order for the system to work. This was tested by importing the seven data coordinates that are needed for the analysis into the MATLAB script. This passed the testing, as the data analysis was successful with the motion and time data.

Requirement 11: For the real-time feature to be successful, the data should be analyzed within a minute of the pitch. This was tested by throwing a pitch and seeing hope fast the data was analyzed. The data analysis was received within seven seconds of the pitch. Each pitch was time to when there was a spike in data on the graph and found this to be around seven seconds each time. This shows the requirement is met and the testing passed.

Requirement 12: The pitcher mound and a dugout are around 60 ft apart, so the device should be able to receive data from the sensor up 60 ft away. This was tested by seeing how far away the Bluetooth transceiver on the microcontroller could be before it was disconnected from the other transceiver. The disconnection happened at 72 ft away. This was tried multiple times and the disconnection happened around the same area each time. Therefore, this requirement passes the testing.

5.2: Software Design Verification

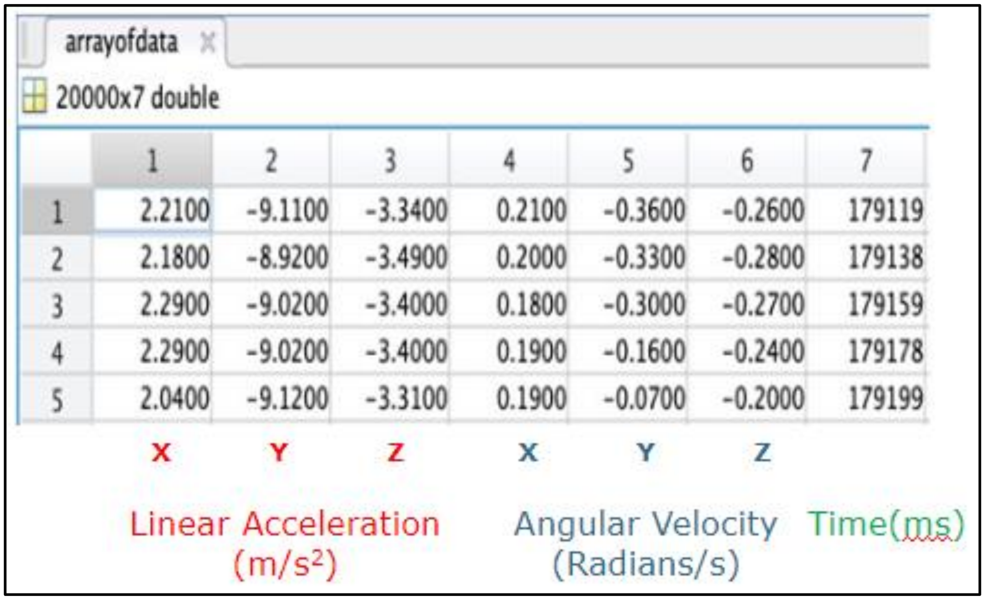
In order to verify that the software was functioning correctly, it was tested against each of the software requirements in Table 5. This tested how the sensor and software functioned together, as well as, how the code was able to analyze the raw data from the sensor.

Requirement #	Software Requirement
1	The software shall receive raw data from the serial port of the user’s laptop
2	The software should create a 7-column array for the linear acceleration and angular velocity each with 3 DOF and time.
3	The software shall calculate the force at the elbow during a baseball pitch
4	The software shall calculate the torque at the elbow during a baseball pitch

Table 4: Software Requirements for Testing

Requirement 1: For MATLAB to process the data, it must be receiving it from the microcontroller. The code was written to be able to receive the data from the array and the software was able to do this successfully. Therefore, this requirement passed the testing.

Requirement 2: The data received in a seven-column array to organize the raw data. This is made up of a three column of linear acceleration, three columns of angular velocity and one column for the time data.



	1	2	3	4	5	6	7
1	2.2100	-9.1100	-3.3400	0.2100	-0.3600	-0.2600	179119
2	2.1800	-8.9200	-3.4900	0.2000	-0.3300	-0.2800	179138
3	2.2900	-9.0200	-3.4000	0.1800	-0.3000	-0.2700	179159
4	2.2900	-9.0200	-3.4000	0.1900	-0.1600	-0.2400	179178
5	2.0400	-9.1200	-3.3100	0.1900	-0.0700	-0.2000	179199

Figure 23: Seven Column Array for Receiving Data

The raw data array from the serial port can be seen above. Each data point is received in each of the seven columns, so this passes the testing for this requirement.

Requirement 3: The force at the elbow is needed to assess the injury risk at the elbow when a pitcher is throwing. The software must be able to do this using the equations for force at the elbow. From the research, the calculated maximum force should be around 190-210 Newtons per pitch.

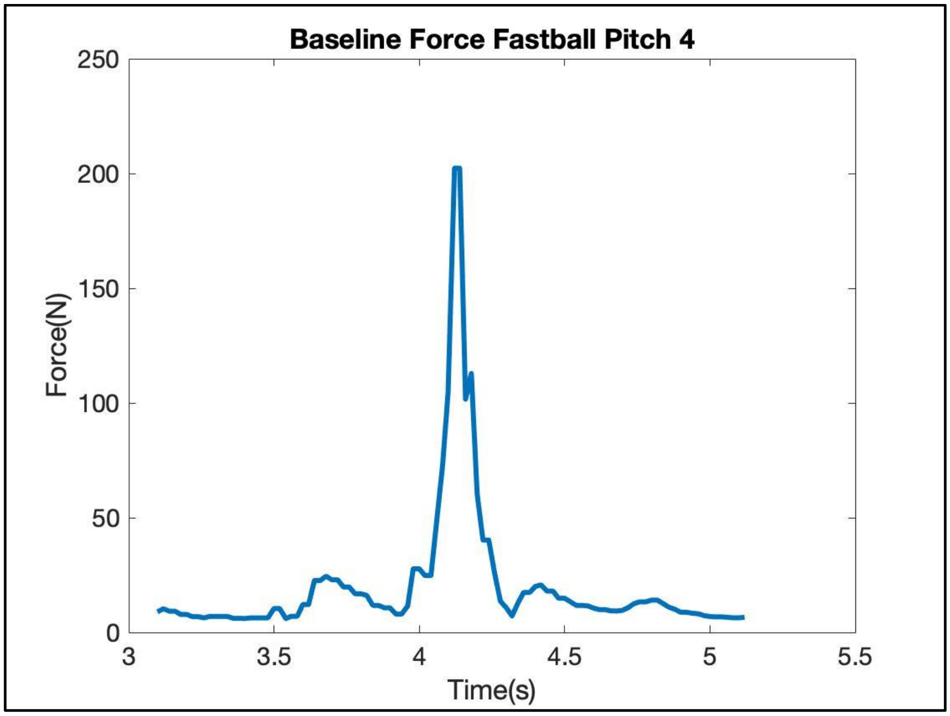


Figure 24: Force at the Elbow Array Data (in Newtons)

As seen in the graph above, the maximum force during this pitch was 205 Newtons. This is in range of what was expected and passes the testing.

Requirement 4: The torque at the elbow is also needed to assess the injury risk of a pitcher. The software must be able to use the equations to find the torque from the sensor data. The expected maximum torque per pitch was 40-60 Newton-Meters.

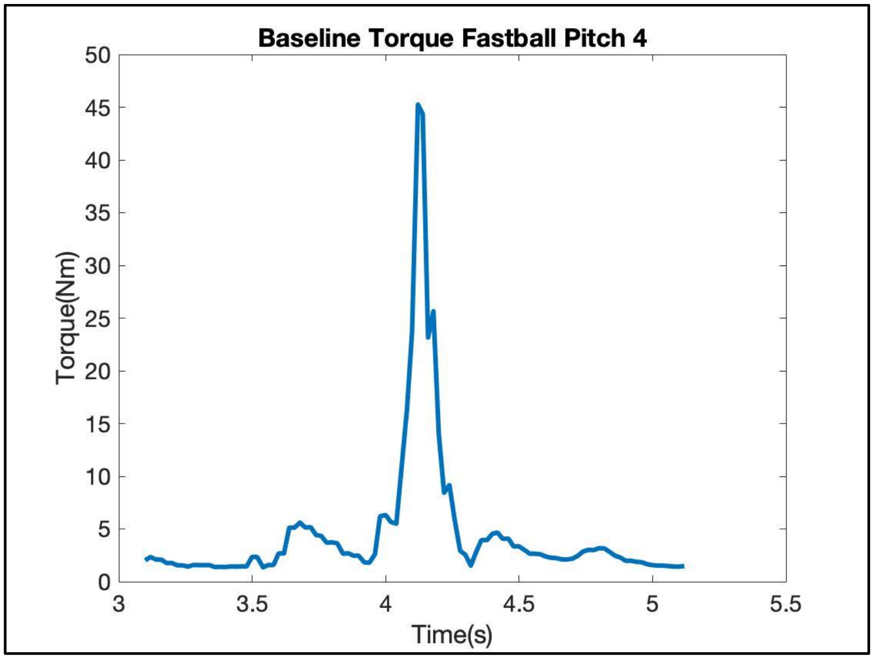


Figure 25: Elbow Torque Array Data (in Newton-meters)

The maximum torque of this pitch was around 47 which is what was expected; therefore, this requirement passed the testing.

5.3: Preliminary Testing

Preliminary subject testing was done on the project team. This was used to optimize the methods, so that subject testing was as efficient as possible. As seen in Figure 25, the sensors were attached to the forearm using athletic tape.

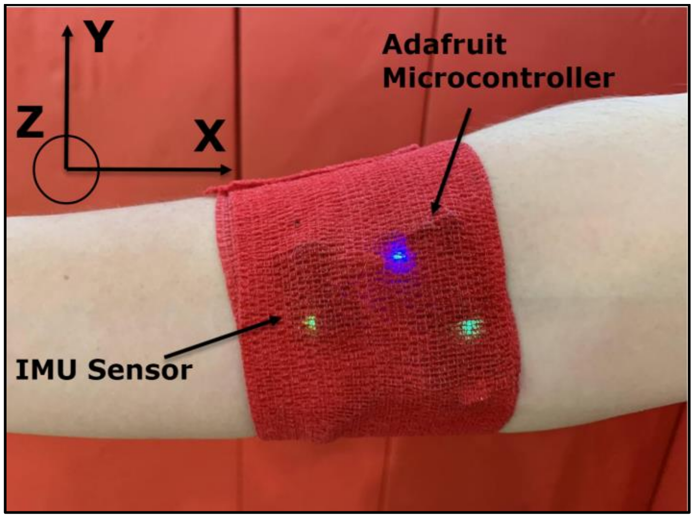


Figure 26: Sensor Attached to Forearm with Local Coordinate System

This was done by holding the sensor on to the forearm, with the palm facing up and wrapping the tape around the sensor. This kept the sensor secure for the testing. The sensor was measured out to make sure it was in the middle of the forearm, so that the equations would be correct. From this testing, it was beneficial for the Bluetooth transceiver to be exposed from the tape, as it allows for a better connection with the other microcontroller. Pitches were thrown with the sensor on to see the data that would be received. There were some issues with the Bluetooth transmissions. This was resolved by keeping the transceiver exposed and moving it to a more stable place on the body, like the back.

Figure 27: Sensor on Forearm Microcontroller on Back Placement

This setup can be seen in the figure above. The sensor was placed on the forearm and the microcontroller was wired to the back allowing for better Bluetooth transmissions. The preliminary subject testing gave the team a much better understanding of how to perform the methodology efficiently and how to have the sensor system work correctly to get adequate data.

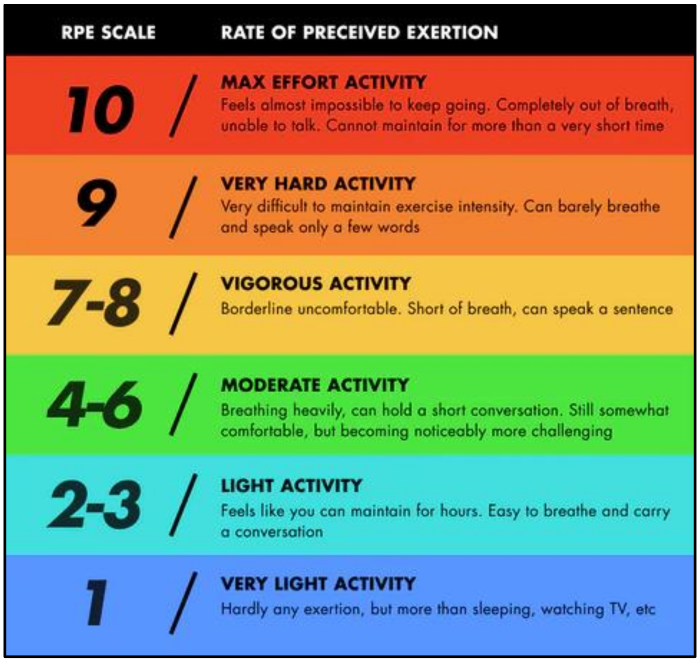
5.4: Borg Scale

The team wanted to induce fatigue through an external fatigue method. This is to ensure that the fatigue mostly comes from the controlled fatigue procedure rather than the pitches themselves.

One main issue brought up when creating a protocol for human subject testing was the repeatability of the experiment. Specifically, when it came to inducing fatigue, how would the fatigue be standardized and measured? The original protocol had the subjects performing the same amount of exercise to simulate fatigue, but different subjects may be more tired than others despite doing the same exercises, meaning there was no objective standardization. Also, there was no way to objectively measure fatigue, in terms of quantifying it. Heart rate and blood pressure measurements were considered, but those would be very time-consuming and difficult to measure during the exercise.

There was a more subjective method of measuring fatigue that has acceptance in research called the Borg Scale of Perceived Exertion [44]. The Borg Scale uses a number system for the subject to rank from no effort to max exertion. Subjects rank based on certain criteria that determine fatigue, such as ease of breathing. There is no standard on which number ranges should be used, with some using 6-20 and 1-10. However, as long as the subjects present similar fatigue criteria, the Borg Scale is useful enough to be a valid method of fatigue measurement.

The Borg Scale used is the one developed by Jonathan Holtz of Maximize Potential (Figure 27). Maximize Potential’s Borg Scale is simple to explain and understand while being detailed enough for the subject to be specific in the measurement of fatigue.



RPE SCALE	RATE OF PRECEIVED EXERTION
10	**MAX EFFORT ACTIVITY** Feels almost impossible to keep going. Completely out of breath, unable to talk. Cannot maintain for more than a very short time
9	**VERY HARD ACTIVITY** Very difficult to maintain exercise intensity. Can barely breathe and speak only a few words
7-8	**VIGOROUS ACTIVITY** Borderline uncomfortable. Short of breath, can speak a sentence
4-6	**MODERATE ACTIVITY** Breathing heavily, can hold a short conversation. Still somewhat comfortable, but becoming noticeably more challenging
2-3	**LIGHT ACTIVITY** Feels like you can maintain for hours. Easy to breathe and carry a conversation
1	**VERY LIGHT ACTIVITY** Hardly any exertion, but more than sleeping, watching TV, etc

Figure 28: Borg Scale RPE from [45]

The team estimates that a perceived fatigue level of 7-8 out of 10 is the target fatigue, where the subject is borderline uncomfortable, is short of breath, and can speak a sentence or two. The fatigue should simulate the fatigue a pitcher usually feels by the time he is pulled from the game. While pitchers are not usually out of breath during the game, the intent is not for the subject to be the same when fatigued, but to generate the effects of fatigue in a shorter time. The subject should not reach a rank of 9 or higher, in order to minimize the risk of the subject injuring himself.

Chapter 6: Final Design Validation

6.1: Methodology Summary

The group began the project by conducting background research on the initial problem statement given. The initial research was conducted on elbow anatomy, the mechanics of a baseball pitch, biomechanics of a baseball pitch, and current equipment developed to calculate the biomechanics of a baseball pitch. The research allowed the team to understand the background information on elbow injuries due to the mechanics of a baseball pitch.

After completing the literature review, the team then began to develop the sensor system. Developing the sensor system was the first step in the design section of the project. The beginning of the design section was divided into two sections: the hardware and the software. The hardware would be used to calculate the metrics of the biomechanical motions during a pitch, while the software would be able to process and interpret the data. The team found the Adafruit ICM20649 microcontroller and sensor to be the most viable option for the system based on the design requirements of the project. The microcontroller had the ability to wirelessly transmit data to a laptop to be processed through MATLAB software. The software code used the equations of motions developed through the free body diagrams to calculate the force and torque developed at the elbow during each baseball pitch. The calculations from the software code were then further analyzed to determine the cause of a dangerous level of injury in a baseball pitch.

Data were collected through human subject testing of collegiate pitchers. The overall human subject testing protocol can be seen in section 6.3. In short, the subjects were asked for some body measurements: weight, height, arm length, and then were given the IRB consent form to sign. After the subject was warmed up and ready to pitch, they delivered a set of 5-10 fastballs and curveballs to serve as baseline data. The subject was then put through a fatigue protocol developed by the team and asked to repeat the same pitches they conducted for their baseline pitches.

After the data was collected, further analysis was developed on the comparison of the baseline pitches to the fatigue induced pitches. The MATLAB code was able to determine the average force and torque at the elbow during the baseline pitches and the average force and torque at the elbow when fatigue was induced.

6.2 Human Subject Testing Protocol

The goal of the final design validation is to take the white-box functional testing done in the preliminary subject testing and turn it into black-box functional testing. This data collection should provide more insight into how the system works on the players themselves in real-world conditions. Additionally, the subjects can provide any feedback they have to improve the system. Subjects included collegiate baseball pitchers on the WPI varsity baseball team. These subjects had to have no prior injuries and the ability to perform at least 30 pitches for testing.

The protocol designed below was approved by the WPI Institutional Review Board (IRB-22-0257). Subject enrollment was scheduled to ensure that the testing did not interfere with their practice schedule and affect them minimally in terms of getting ready for practice games in the spring. Subjects had to be healthy and able to throw fastballs and curveballs. The testing was done in the WPI Sports & Recreation Center Courts.

With the hardware design concept finalized, the goal of the protocol is to create baseline data representing the pitcher as rested and warmed up and to create data representing the pitcher as fatigued. The subject is then fatigued in both his arm and his whole body. His whole body is fatigued because of the nature of the kinetic chain.

***Preparation before subject arrival*:**

Before the subject arrived, an artificial mound and catcher's net were set up. The distance between was 60.5 ft (18.44 m) and the mound was 10 inches above home plate, per NCAA standards. This is to replicate the real-world conditions of the testing.

***Preparation when subject arrives*:**

When the subject arrived, the consent form was explained, and the subject signed to show he understood. Body measurements were performed (weight, arm lengths, sensor location) to adjust for each subject's individual physical features. The subject then performs his normal warm-up routine while the device and software get prepared.

***Baseline Procedure*:**

The sensors are put on the subject's throwing arm as seen in Figure 25 and 26. The subject then throws a fastball. The subject then prepares to throw another fastball up to four more times. The steps are repeated for curveballs. In total, the pitcher should have thrown between five to ten pitches for each of the two pitch types. This should develop an initial baseline. The subject should have thrown ten to twenty pitches in total up to this point. This is to ensure that the fatigue mostly comes from the controlled fatigue procedure rather than the pitches themselves. The sensor should be on during this point to collect the data, while differentiating each pitch type.

Arm Fatigue Procedure:

Using the SCIFIT PRO1000 Seated Upper Body (Figure 28), the subject arm cycles at a speed of 50-70 RPM as the investigator increases the resistance setting to a comfortable effort for the subject to maintain his speed for sixty seconds. The recommended resistance setting is between 5 and 7, though the setting is dependent on the subject. The subject maintains the same speed while the investigator increases the resistance of the arm cycle to an effort level where the subject is at full effort, for ten seconds. The recommended resistance setting is between 7-10, though the setting is dependent on the subject. In between transitions after the full effort, the subject is asked to rank on the Borg Scale. The previous steps are repeated until the subject reports a Borg Scale rank of 7-8.

Figure 28: SCIFIT PRO1000 Seated Upper Body

Whole Body Fatigue Procedure:

The subject performs back and forth sprints across the basketball court. The subject starts from and returns to the basketball baseline, with a quarter length, the half-court length, three-quarter length, and the full court length distance. The subjects are asked to rank on the Borg Scale. The previous steps are repeated until the subject reports a Borg Scale rank of 8. This fatigue is introduced to simulate real-life in-game experience.

Induced Fatigue Procedure:

The subject was allowed to rest for one minute. This was to ensure that the subject's fatigue still remained while protecting him. The Baseline Procedure steps were repeated while again recording the sensor data for each pitch. This developed the fatigue data. The sensor should be on during this point to collect the data, while differentiating each pitch type.

Final Procedure:

The sensors were removed off the subject and he was allowed to rest and ensure he feels fine before leaving. The subject is asked to give any feedback he may have had.

6.3 Summary of Data Collection

Before conducting the human subject testing, the sensors were first verified through different tests to ensure all specifications were working properly, as stated in sections 4.9 and 5.2. The verification testing completed on the vehicle was to ensure the sensors were properly calculating linear acceleration and angular velocity. Understanding the relationship between linear and angular velocity, the team was able to determine the correct magnitude of angular velocity the sensor should read. The sensor passed the verification test, calculating the expected angular velocity induced by the car. The next verification test was to ensure the software could process the data into a 7-column array in MATLAB and calculate the force and the torque at the elbow. The sensor system passed the verification test as shown by the tables in section 5.2.

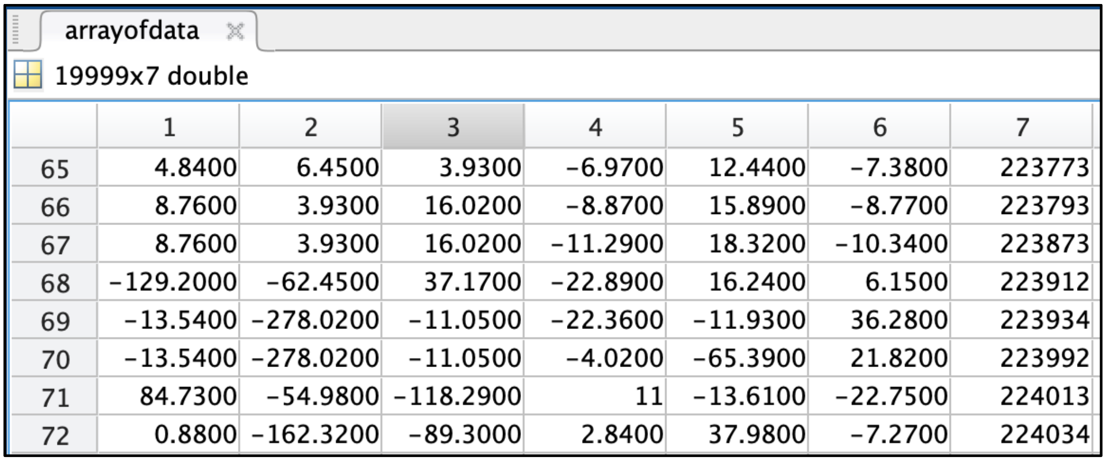
The system verification allowed the term to further move forward in testing on human subjects with the confidence the system was working properly. The next phase of the design section was to conduct the human subject testing.

6.3.1: Data Collection Results

The participation in the human subject testing consisted of three collegiate pitchers (male ages 19-21). The heights and weights of the subjects were 5ft 9in 190 lb, 5ft 10in 180lb, and 6ft 200lb. Two of these testing sets had setbacks, one with the hardware, the other with the software. These two data sets were not included in the processing of the final data from the human subject testing. Each subject was informed to continue to express their level of fatigue through the Borg Scale throughout the testing process. After the pitches were thrown to complete a given set, the testing subjects all felt the same fatigue type. During the baseline pitches the subjects identified their fatigue around a Borg level 3, and after fatigue was induced, all expressed they were at a fatigue Borg level of 7.

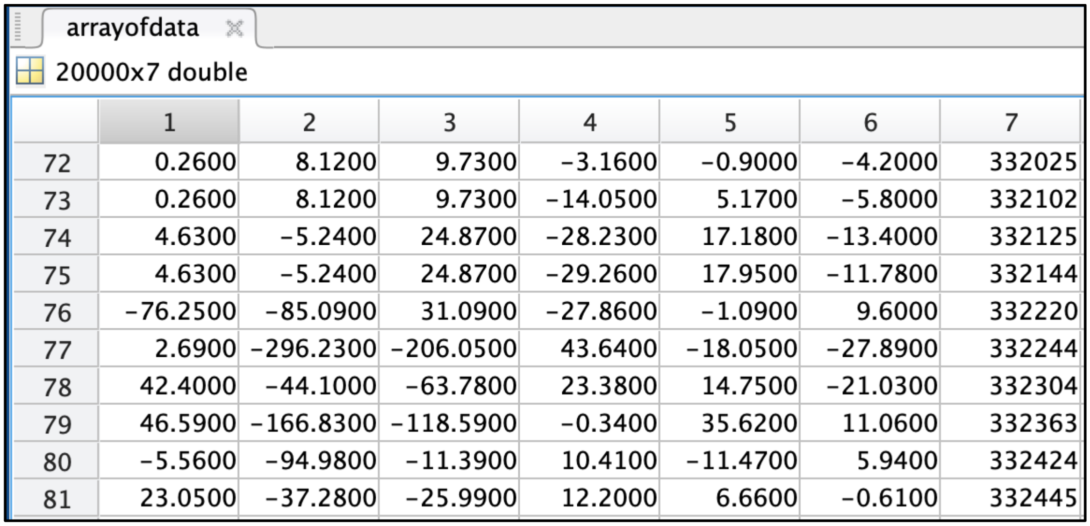
6.3.2: Data Analysis

To analyze the data collected from the human subject testing, the raw data from the sensors are wirelessly transmitted to a Bluetooth transceiver microcontroller which is connected to a laptop through the serial port. The raw data is then fed through the serial port to the MATLAB script Array_of_Raw_Data.m, found in Appendix D**.** The script collected the data as the linear acceleration in the x, y, and z-direction was placed in the first three columns. The angular velocity was placed in the next three columns and the time was placed in the seventh column. An example of these raw data arrays can be seen below. The values of the data were repeated a couple of times; this could be attributed to a lack of hardware efficiency.



	1	2	3	4	5	6	7
65	4.8400	6.4500	3.9300	-6.9700	12.4400	-7.3800	223773
66	8.7600	3.9300	16.0200	-8.8700	15.8900	-8.7700	223793
67	8.7600	3.9300	16.0200	-11.2900	18.3200	-10.3400	223873
68	-129.2000	-62.4500	37.1700	-22.8900	16.2400	6.1500	223912
69	-13.5400	-278.0200	-11.0500	-22.3600	-11.9300	36.2800	223934
70	-13.5400	-278.0200	-11.0500	-4.0200	-65.3900	21.8200	223992
71	84.7300	-54.9800	-118.2900	11	-13.6100	-22.7500	224013
72	0.8800	-162.3200	-89.3000	2.8400	37.9800	-7.2700	224034

Figure 30: Raw Data from Fastball



	1	2	3	4	5	6	7
72	0.2600	8.1200	9.7300	-3.1600	-0.9000	-4.2000	332025
73	0.2600	8.1200	9.7300	-14.0500	5.1700	-5.8000	332102
74	4.6300	-5.2400	24.8700	-28.2300	17.1800	-13.4000	332125
75	4.6300	-5.2400	24.8700	-29.2600	17.9500	-11.7800	332144
76	-76.2500	-85.0900	31.0900	-27.8600	-1.0900	9.6000	332220
77	2.6900	-296.2300	-206.0500	43.6400	-18.0500	-27.8900	332244
78	42.4000	-44.1000	-63.7800	23.3800	14.7500	-21.0300	332304
79	46.5900	-166.8300	-118.5900	-0.3400	35.6200	11.0600	332363
80	-5.5600	-94.9800	-11.3900	10.4100	-11.4700	5.9400	332424
81	23.0500	-37.2800	-25.9900	12.2000	6.6600	-0.6100	332445

Figure 31: Raw Data from Curveball

The raw data calculated from the sensor is output in angular velocity measured in radians per second and linear acceleration measured in meters per second squared. The angular velocity was then converted into degrees, as that is what the equations called for. The data collected in the Array_of_Raw_Data.m, was then applied to the equations found in ForceandTorque.m. This script uses the force and torque equations, an array, and a graph of the Forces and Torques during each pitch. ForceandTorque.m is also able to directly import the data from the serial port and get the graphs and arrays live if the input from the serial port is working correctly. This would allow the user to bypass the initial step of collecting the data in a seven-column array.

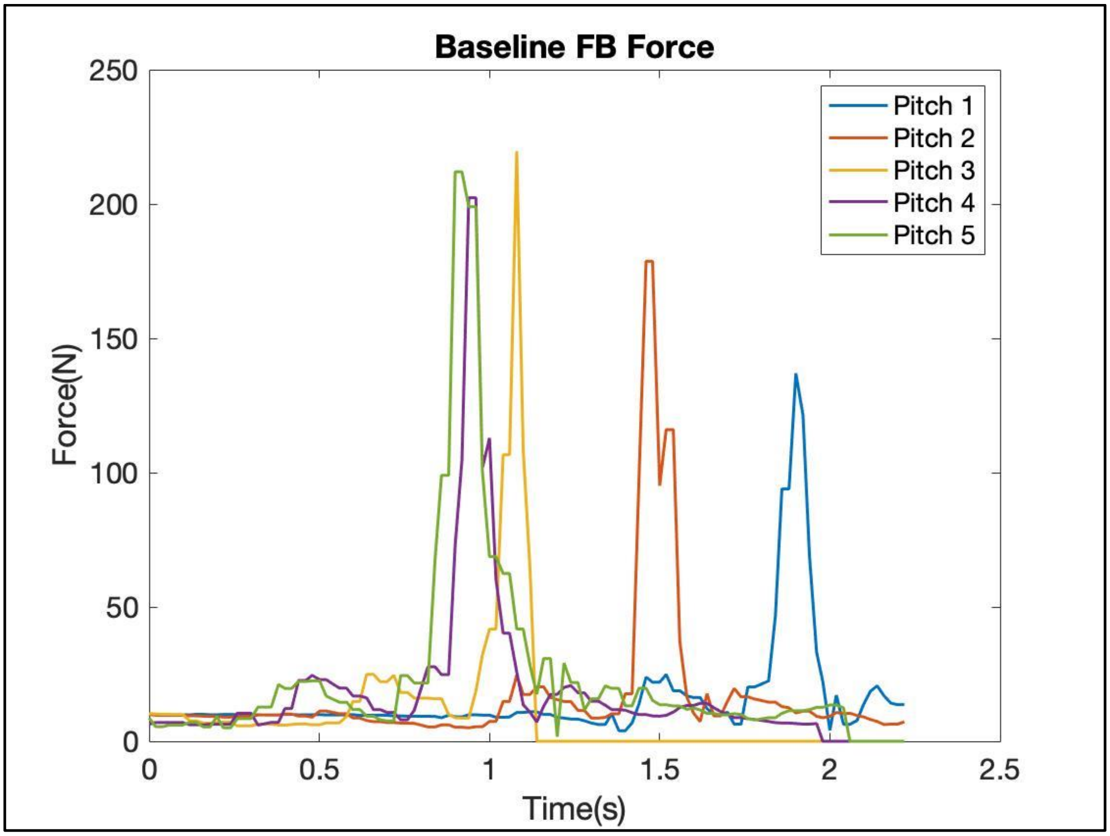


Figure 32: Baseline Fastball Force at the Elbow

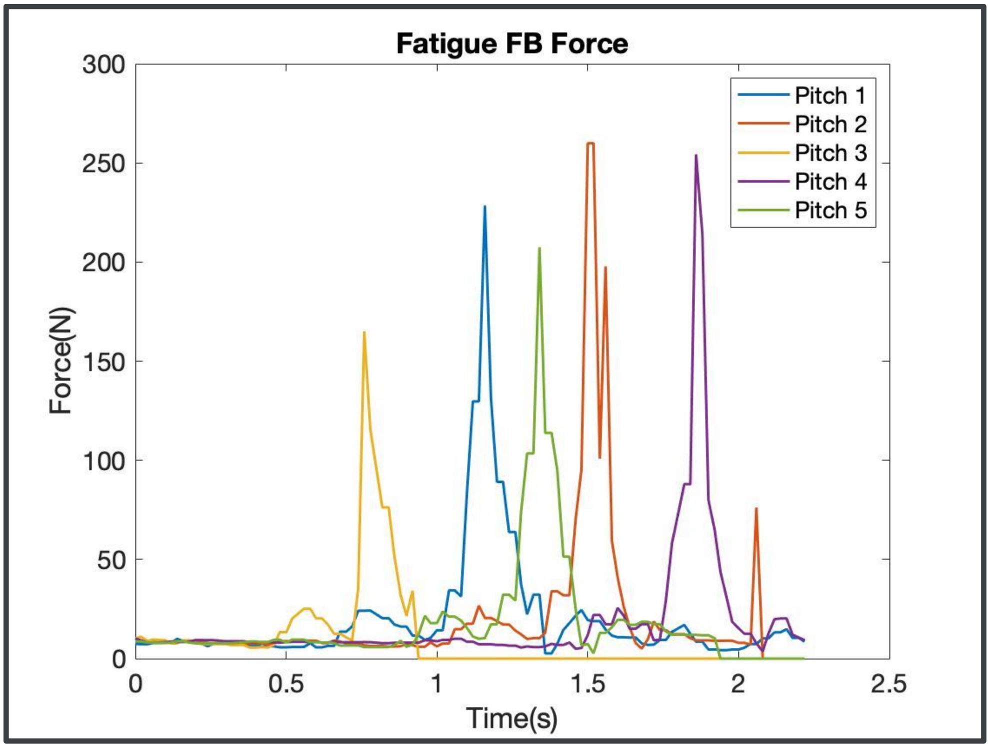


Figure 33: Fatigue Fastball Force at the Elbow

After collecting the raw data from the sensor, the MATLAB script initially calculates the force at the elbow which can be seen above. This data is based on the linear acceleration data that was collected in the seven-column array, Array_of_Raw_Data.m. As seen above in the graphs, the peak force on the elbow of the baseline data is about 220 Newtons, while the peak force on the elbow of the fatigue data is 260 Newtons. Due to the induced fatigue, the elbow is experiencing more force during each pitch than the baseline data. Using the forced data along with the angular velocity from the sensor, ForceandTorque goes on to calculate the torque at the elbow.

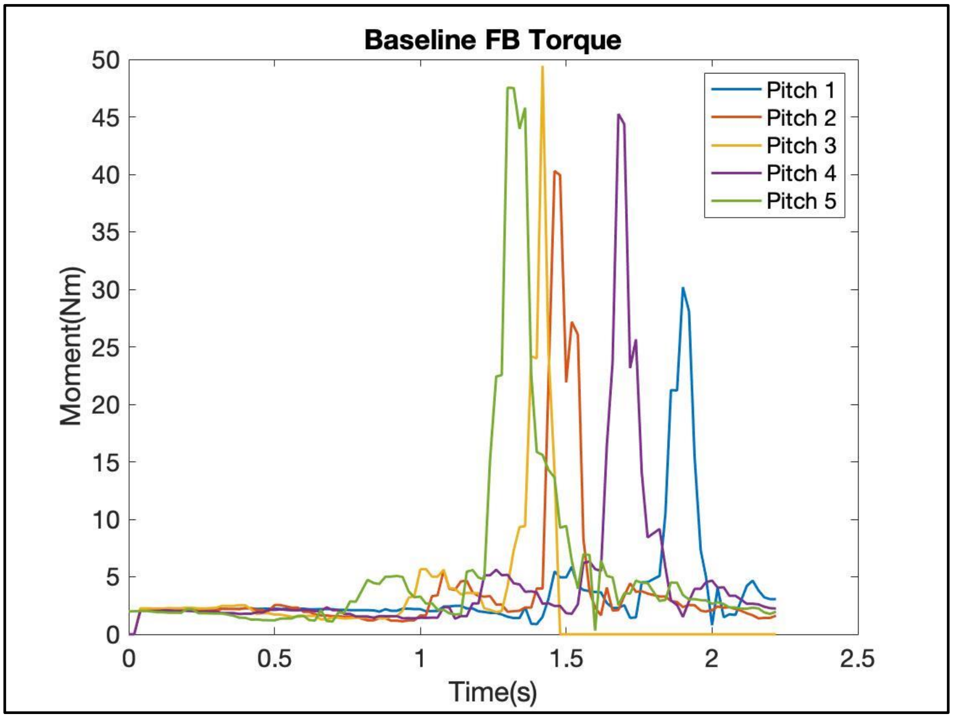


Figure 34: Baseline Fastball Torque at Elbow Data

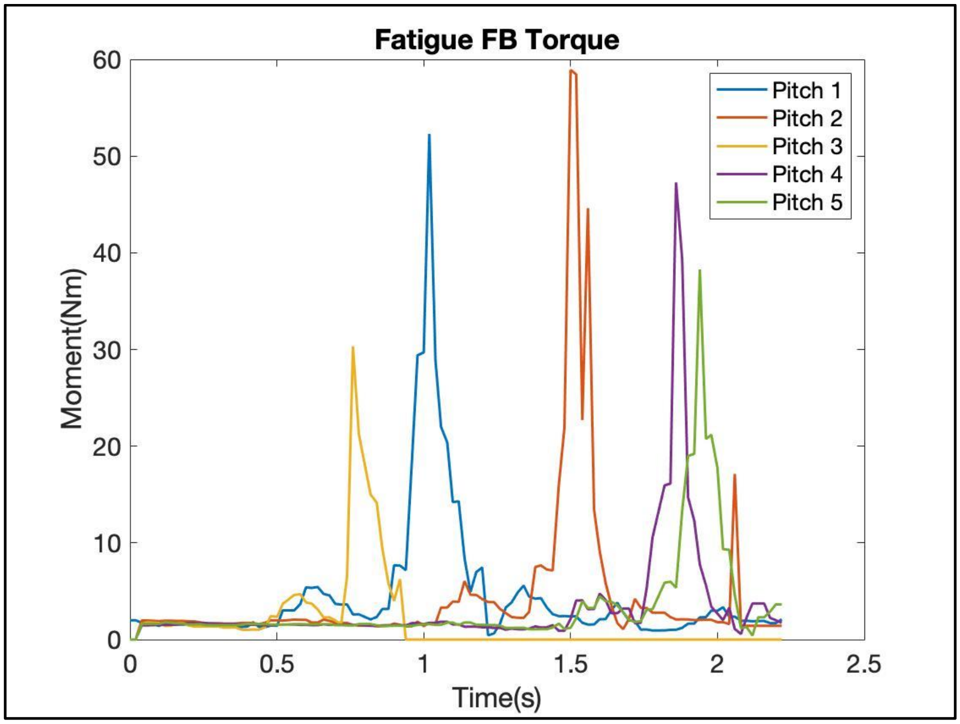


Figure 35: Fatigued Fastball Torque Data at Elbow

The resulting graphs can be seen above in Figures 31 and 32. They show the torque data for both the baseline and the fatigue data with respect to the time in seconds. This allows the user to see what the non-fatigued data looks like and then from there compare the fatigue data. This allows for the injury risk at the elbow to be tracked. From this data, it was found that the average maximum torque per pitch was 3 Newton-meters higher in the fatigue dataset compared to the baseline. The baseline was 42.505 Newton-meters, and the Fatigue was 45.354 Newton-meters. Recent research found the UCL contributes 55% of the force on the elbow during a baseball pitch [46]. Further analyzing the data shows that when fatigue is induced, the UCL is contributing roughly 25 Newton-meters of force compared to 23.7 Newton-meters of force during the baseline pitches. Although this data does not show a dangerous risk of injury level due to fatigue, it does present the change in torque when fatigue is applied. If there is more fatigue there would show a greater amount of torque, which could lead to a higher risk of injury. This was then repeated with curveballs.

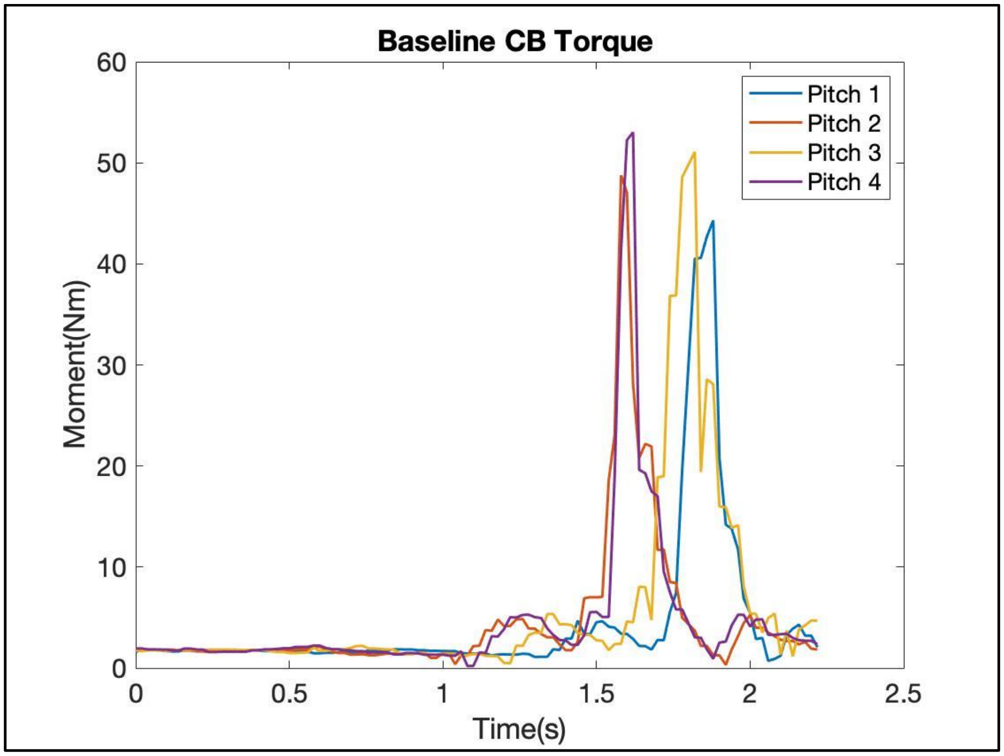


Figure 36: Baseline Curveball Torque Data at the Elbow

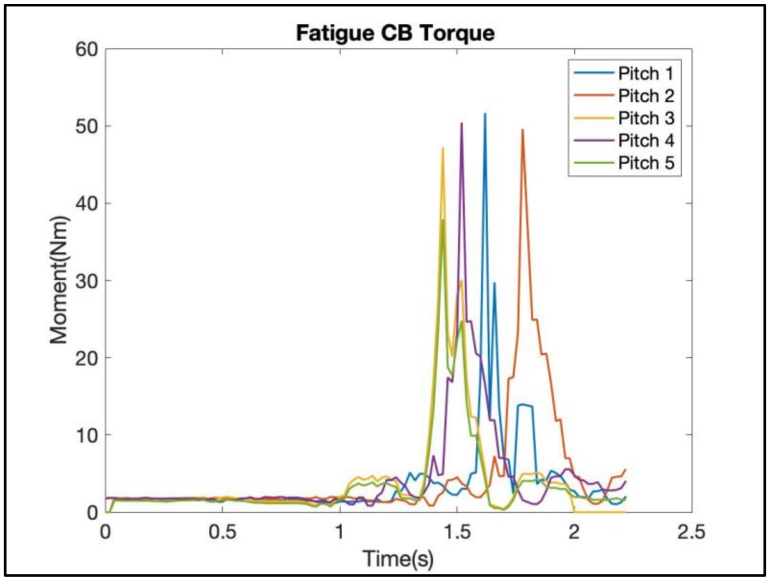


Figure 37: Fatigue Curveball Torque Data at the Elbow

In the curveball dataset, it was found that the average fatigue torque data was 2 Newton-meters less than the baseline data. The average baseline torque was 49.289 Newton-meters, while the fatigue average was 47.365 Newton-meters. This does not fully line up with what was expected. With more data, it would be expected for the results to form towards a higher risk of injury as more fatigue is induced.

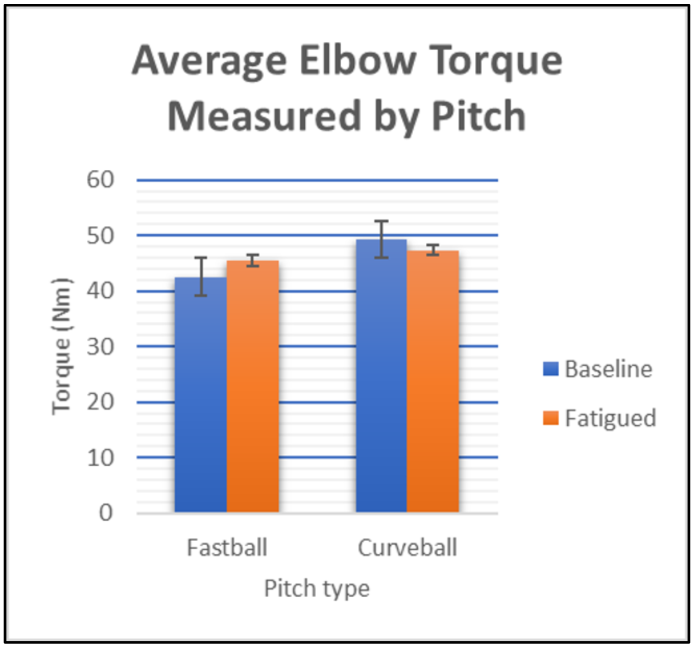


Figure 38: Average Maximum Elbow Torque for Each Pitch

As stated previously, the average torque of the fastball increased with fatigue, which was expected, while the average torque of the curveball decreased with fatigue, which is not expected.

6.4: Impacts of Final Design

6.4.1: Economic Impact

UCL reconstruction can also take a toll economically. UCL reconstruction surgery can cost more than $15,000 and that's not even including the cost of rehabilitation. When it comes to professional baseball, teams are paying pitchers millions of dollars per year to pitch and when they are injured it costs the teams a lot of money. A study was done on the cost analysis of UCL repairs for MLB teams. There were 94 pitchers that had a UCL reconstruction from 2004 to 2014 and this cost the teams $395 million, or $1.9 million per player [47]. This is only in consideration of players who play professionally. Pitchers in amateur leagues, college, or even high school intuitively experience the same amount of risk. These injuries, depending on their intentions, could affect their future ability to pitch in terms of playing for college scholarships or even professionally.

Our device is very cheap compared to those numbers. The wide-range IMU sensor in the device cost $14.95. The microcontrollers cost $24.95 each and two were used. The battery costs $7.95 each. This comes out to a total of $72.80 for the whole system. This is a very good investment to prevent injury given how expensive UCL repair can be. If the device were to prove successful at preventing UCL injuries, this could be a widely used device, including both professional baseball teams and players. At the end of the day, MLB teams are just businesses, and this could save them millions, as well as preventing career changing injuries in pitchers. For amateur pitchers, this could affect their future values should they want to pursue further baseball ambitions, let alone prevent the costs that come with treating their injuries.

6.4.2: Environmental/Sustainability Impacts

With the project at a small scale, this had very little negative environmental impact. The biggest impact would come from the manufacturing of the sensors, primarily the batteries. Should the manufacturing of these sensors increase, there could be some potential environmental impact factors, such as the single-use nature of the batteries and the energy used to power multiple sensors. The use of single-use batteries could be replaced with rechargeable batteries to prevent waste.

6.4.3: Societal Influence

The biggest societal influence would be mostly within the game of baseball. The intended goal of this device is to minimize the risk of injury pitchers experience. The success of this device depends on how useful players and teams view the sensors to be. Outside of the current limitations of the device, the biggest factor to consider is how much do players and teams value short-term and long-term success.

Every pitcher would prefer to be able to start and finish games if they could. Lasting longer in the game without giving up runs is an accomplishment because the likelihood of the pitcher making a mistake increases later in the game when fatigue becomes more of a factor. Consider a general scenario where a pitcher is successful late into a game and the sensors detect that the injury risk is high. Would the pitcher or team be willing to listen to what the device suggests in favor of long-term success? Or would the potential to get one more batter out outweigh the risk presented? If so, how much effort is the pitcher willing to put in? In a general scenario, teams and pitchers have to evaluate their own risk-reward mindsets when introduced to the device.

The overall goal the project would like to accomplish is to promote a baseball culture that emphasizes long-term health. Recently, baseball has promoted a game that emphasizes short-term, in-game success, which is a mentality that has spread down into the amateur league, and ultimately, to the youth league as well. While the two are not exactly mutually exclusive, further promoting long-term health is part of addressing the need to prevent these injuries to begin with, not just for professionals, but for amateurs and the youth leagues as well.

6.4.4: Ethical Concerns

The methodology involves the use of human subjects, which required IRB approval before any testing began. The sensors themselves did not pose any significant risk to the subject. The protocol used was meant to simulate a situation where a pitcher would experience a high level of risk of injury. However, the justification the IRB approved was based on the fact that the subjects, who are pitchers themselves, already assume the risks of pitching in practice and in-games.

6.4.5 Political Ramifications

Bringing something like this onto the market would intuitively implicate political ramifications, as it could be listed as a medical device, given they are designed for injury prevention. However, as stated before, the sensors themselves do not pose any significant risk. In fact, these sensors would probably not need to be classified as a medical device. The MotusBaseball wearable sensor is not listed on the FDA's medical device database. Given that the most similar product on the market has neither a public medical device listing, it is unclear if the use of the sensors would implicate any political ramifications.

6.4.6: Health and Safety Issues

As stated before, UCL injuries have become more prominent and take months off of a pitcher's career. UCL injuries not only have an effect on future performance but also an effect on future health pitching wise. While there are steps teams and pitchers can take to minimize the risk, this device has the capability to monitor and predict risk based on estimated measurements, instead of just the feeling of the pitcher. Teams and pitchers can get an "additional opinion" when it comes to preventing overall elbow injuries. This all depends on whether the device is accurate in its estimated measurements. If the device underestimates the risk, the potential for UCL injury increases.

6.4.7: Manufacturability

The sensor system is developed using sensors already on the market. These Adafruit ICM 20649 sensors can be purchased for $15 each off the market. The sensors meet the requirements defined by the team. However, with a larger budget, higher quality sensors could be purchased or designed. Better quality sensors could include a larger measurement in degrees per second, as well as a stronger Bluetooth connection for transmission of raw data. The data analysis processed from the sensors runs through the MATLAB software. Overall, an increased budget would allow for better quality sensors to produce more efficient data.

Chapter 7: Discussion

7.1: Final Design Architecture

The final design architecture of the sensor system addresses the requirements of the revised client statement. The revised client statement is the following:

> "The goal of the project is to develop a sensor system that is able to read raw data as the pitcher is throwing the baseball. The system consists of an Inertial Motion Sensor in the middle of the forearm of the pitcher. A microcontroller is wired to the sensor and where it receives and wirelessly sends the sensor data to another microcontroller connected to a laptop. The microcontroller transmits the data through the serial port of the laptop. The data are processed from here, allowing for the injury risk to be found in real-time."

The sensor system can be classified into two different categories: the hardware and software. The hardware of the sensor system is made up of an IMU, microcontroller, and lithium-ion battery. The IMU used in the final design is the Adafruit ICM20649 Wide-Range 6-DoF IMU Accelerometer and Gyro. The specifications of the Adafruit ICM20649 include measurements in six degrees of freedom, up to 30 Gs, and up to 4000 degrees per second. The IMU processes data through an I2C connection to the microcontroller. The data is then transmitted wirelessly through a Bluetooth connection to another microcontroller plugged into a laptop.

The process in which the sensor is attached to the user is calculated using body measurements to find the center of mass of the subject's forearm. The IMU is attached to the forearm using pre-wrap and self-adhesive tape, while the microcontroller is attached to the back of the subject using the same materials. The subject then conducts their pitching protocol. The sensor and microcontroller are continuously transmitting and processing data for each pitch. Once the subject has thrown the specified number of pitches, the pitching session ends.

The raw data that was wirelessly transmitted through Bluetooth is analyzed. The analysis of the raw data is shown through baseline average force and torque, and induced fatigue force and torque at the elbow. The raw data is processed through graphs to show the variation in each pitch from the baseline pitches to fatigued pitches. A critical analysis highlights where the critical deviation of a baseball pitch would be flagged as a dangerous risk of injury to the pitcher.

7.2: Design Validation

7.2.1: Methodology Limitations

During the initial subject testing, the soldering of the sensor fell apart and a wire snapped. Fortunately, the team was able to adjust for that by replacing the wire and resoldering it on. While Table 3 suggested that the device is both light and secure onto the subject’s body, clearly the device needed to be secure in and of itself. The design verification had the team throwing the ball far less hard than the subjects themselves, which would suggest that the individual parts of the sensor each experience the pitch differently.

The team was also only able to fully acquire data from just one subject. This not only severely limited the data collection, but it also severely limited any other adjustments that could possibly be considered.

The device was also designed with a lot more wiring than initially anticipated. However, the team prioritized the functionality of data collection, and it was unfortunately at the expense of the physical design. The design required longer wires between the Arduino and the Bluetooth transmitter on the subject’s back, which had to run along the arm in order to avoid the wires flying. This much more complex design made the device more uncomfortable than originally intended for the subject, which defeats the goal of simulating a real-life pitching experience. The design also made the set up a lot longer than expected, along with checking the security on the subject and ensuring the Bluetooth transmits data.

The method of inducing fatigue also had some limitations as well. The goal of the inducing fatigue procedure was to simulate a situation where the subject feels fatigued late in a game without having him actually go through with it. The hope was that the increased fatigue would be able to last long enough to collect the fatigued baseline data. However, due to the long setup time and the Bluetooth reset, the data presented may not exactly represent a fully fatigued pitch.

7.2.2: Data Collection Limitations

The data collection for the project had some major limitations leading to many setbacks for the group. A major limitation was the Bluetooth transmission. The main factor providing real-time feedback was that the sensor data was being transmitted through Bluetooth. An issue with Bluetooth is that when the path to the receiver is blocked, transmission can be interrupted. The testing had issues with this as it originally had the microcontroller with the transmitter on the forearm. This led to the transmissions being interrupted when the pitcher was throwing a pitch. This led to the data coming in through the serial port of the laptop being out of order which makes the data analysis software unable to analyze the data. The connection had to keep being reset in order to restart the data collection. While Table 3 suggests that the sensor and the software interface with each other, the interface is not as smooth as originally intended.

Another data collection limitation faced was a slow sampling rate for the data. The sensor was able to provide over the target frequency of 120 Hz, but when the microcontroller was also transmitting seven data points through Bluetooth it slowed it down a lot leading to the sampling frequency dropping to about 50 Hz. There are a couple ways this could be fixed. One way is to store the data locally on a micro-SD chip, this would allow for the microcontroller to collect the data at a faster rate. This would eliminate the real-time feedback aspect. Another possible way of fixing this is changing the programming of the microcontroller to collect all the data from each pitch, then transmit the results after the pitch when the connection is not interrupted. The hardware had issues when attempting to do this. Overall, the low sampling rate limits the reliability of the data, as there could be some important data missing from the pitches, but it was still able to give us some data points at each pitch.

7.2.3: Limitations Conclusion

This project ultimately completed the requirements of determining the dangerous level of injury on a baseball pitch due to fatigue. Even though the data the team collected may be true, the team does not have enough data to successfully answer the question of if the risk of injury is the same for each pitcher. Testing on subjects came with drawbacks, including the stripping of a wire on the sensor, leading to a new design of the sensor system. This new design had wires dangling down the arm of the pitcher, which could have affected the mechanics of the pitcher. Data was collected with this new design, however, a smaller sampling frequency led to less reliable data. Due to the issues with the Bluetooth transmission, the team was forced to lower the sampling rate in order to effectively transmit the data to the serial port. Overall, the sensor system was able to collect valuable data to be processed and analyzed, yet the analysis may not be authenticated due to these limitations.

Chapter 8: Conclusion

8.1: Conclusions

Due to the nature and progression of baseball pitchers throwing at increasingly high velocities, elbow injuries have become a common theme in the sport. Injuries occurring to the UCL can often result in career-ending injuries. Through recent research and study, it has been found that the lack of preventative strategies for UCL injuries is what results in necessary UCL reconstructive surgeries. Currently, the aims for preventative strategies lie with braces, stretching, and motion analysis. The overall goal of the project was to develop a worn sensor-based system to prevent elbow injury that occurs as a result of baseball pitching.

The wearable sensor system and software system worked in unison to demonstrate the dangerous risk of injuries due to fatigue on a baseball pitch. This method was developed through the analysis of forces and torques at the elbow. The sensor system was developed and tested on collegiate pitchers throwing both fastballs and curveballs. From the collected raw data, the software easily demonstrated the spike in force and torque on the elbow as fatigue was induced. Overall, the wearable sensor system and software system met the needs of estimating the force and torque on the elbow during pitching. More research needs to be conducted into the sensor system’s ability to predict fatigue and prevent UCL injuries.

The developed sensor system improved upon the limited market of preventive UCL injury approaches. Further analysis can be conducted to ultimately determine the “breaking point” of the UCL due to fatigue. Through further development, this sensor system can be incorporated into the sport of baseball to prevent UCL injuries in pitchers.

8.2: Lessons Learned/Future Recommendations

The biggest lesson the team learned throughout the project was to never underestimate how much time will go into a project. The design of the sensors took a much longer time than the group had anticipated, time that was planned to have been used on subject testing.

The sensor system designed for the project was somewhat successful in meeting the requirements outlined by the revised client statement. However, the system could be improved in certain areas to produce better data. The team recommends the following improvements to the sensor system project:

- **More Efficient Wireless Connection:** During the project testing, there were issues involving the Bluetooth transmission of the sensor data to the laptop. This was because as the pitch was being thrown, it caused the Bluetooth transmitter, which was on the forearm, to be blocked from the receiver attached to the laptop. This caused the data to be interrupted leading to issues with the data analysis. This was solved by moving the transmitter to the back, where there is less motion, but it still could have been more efficient. This could be improved by using a microcontroller able to store the data from the pitch and then transmit the data after the pitch is over, when the connection is no longer blocked.
- **More Efficient Hardware:** One of the major issues with the data received was the low sampling rate. This can be attributed to the microcontroller not being able to collect the data from the sensor quickly enough. The microcontroller sending the Bluetooth transmissions slowed it down leading to a slow sampling frequency. The sensor was able to sample at an adequate frequency, but since the microcontroller was unable to collect it fast enough, data was received only at a sampling rate of 50 Hz. This can be improved in

the future by using a more efficient microcontroller that is able to transmit Bluetooth, while also collecting the sensor data at a high rate.

- **Compact Design:** Adjustability and wearability were two of the requirements of the hardware system. The original design was tight and compact, with little to no discomfort for the subjects. However, this design was not functioning properly, and the team was forced to create a new design. The microcontroller was wired to the back, while the sensor was attached to the forearm with wires running down the subject's arm. This caused discomfort to the subjects. To combat this in the future, the team should attach their sensor using a compression sleeve or find a way to make the original compact design functional. Another solution to this limitation is to keep the original compact design, and just store the data from the pitch by turning off the Bluetooth transmitter. Turning off the Bluetooth transmitter allows the raw data from the pitch to be stored, then turning the Bluetooth transmitter back on after the pitch to send the data to the laptop serial port. This process could eliminate the issue with recording and transmitting data simultaneously, while maintaining the compact design.
- **Pitch Detection:** To be an effective sensor system for baseball pitchers to use, the software must be able to detect different pitch types. The only way for the software to differentiate was because each was specified by the team when displaying the results. The team only had the ability to test between fastballs and curveballs. Baseball pitchers throw many more pitches, software that has the ability to categorize these pitches is essential. The detection of these different pitches leads to further analysis of the risk of injury for the current pitcher.
- **More Subject Testing:** As stated in Section 6.3.1, the team was only able to test on three different collegiate pitchers. Out of those pitchers, only one of the data sets was correct

and able to be processed. One data set is not nearly enough to make an accurate assumption or conclusion on the effect of fatigue on the UCL. Also, the testing was only conducted on collegiate pitchers. The team further recommends expanding the testing from youth pitchers to professional pitchers. The data varies from skill level and may result in different conclusions.

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Appendices

Appendix A: Equations of Motion

$$-F_{elbow} + m_{forearm} * g = m_{forearm} * a_{forearm}$$

<u>Variables</u>:

F_{elbow} = force at the elbow
$g = 9.81 \text{ m/s}^2$
$m_{forearm}$ = (body weight * 0.022) + 0.142
$a_{forearm}$ = calculated through IMU

$$T_{elbow} = (r_{elbow} \text{ X } F_{elbow}) / (I * \alpha)$$

<u>Variables</u>:

T_{elbow} = torque at the elbow
r_{elbow} = forearm length * 0.430
X = cross-product
F_{elbow} = force at the elbow
I = moment of inertia = (1/12) * m * forearm length^2
α = calculated through IMU

Appendix B: Informed Consent Agreement for Participation in Research Study - As Approved by the Worcester Polytechnic Institutional Review Board

Informed Consent Agreement for Participation in a Research Study

Student Investigators
Michael Fraser (mcfraser@wpi.edu)
Martin McCormack (mmccormack@wpi.edu)
Jeffrey Mei (jmei@wpi.edu)

Faculty Advisors
Prof. Ted Clancy (ted@wpi.edu)
Prof. Karen Troy (ktroy@wpi.edu)
Dr. David Magit, MD

Title of Research Study: Baseball Pitching Biomechanics and Injury Prevention

Introduction

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks, or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation. Feel free to ask any questions at any point.

Purpose of the Study

The purpose of the project is to design a sensor device that will be used to prevent elbow injuries in baseball pitchers. The sensors will be used to estimate metrics of interest in real-time, with respect to different pitches thrown. During this study, the sensors will be used to test their function and feasibility in a more simulated manner, such as in practice or in-game.

Procedures to be followed

Duration of your participation: You will be expected to participate in this study for a single session lasting approximately one to two hours.

Preparation when you arrive:
When you arrive, these procedures will be explained to you, then you will sign if you agree to the terms. You will be asked for your weight to estimate limb mass. On the pitching mound, you will perform your normal warm-up routine while we prepare the device and software.

Baseline Procedure:
We will help you secure the sensing device to your throwing arm using athletic tape. This device is small and lightweight [no more than a couple of ounces] and designed to interfere with your pitching as little as possible. When instructed, you will throw a fastball. This process will repeat between five and ten times. After throwing fastballs, you will throw a curveball. This process will repeat between five and ten times,

as to not perform substantial fatigue on the arm during this procedure of the project. This will establish your baseline “healthy” data.

Arm Fatigue Procedure:
Using the SCIFIT PRO1000 Seated Upper Body, you will perform arm cycles at a speed of 50-70 RPM as the investigator increases the resistance setting to a comfortable effort. The recommended resistance setting is between 5 and 7, though the setting is dependent on your effort. You will cycle for one minute.

After a minute, you will maintain the same speed while the investigator increases the resistance of the arms cycle to an effort level where you feel unable to talk while cycling, for ten seconds. The recommended resistance setting is between 7-10, though the setting is dependent on your effort.

Throughout the process, you will be asked to give a ranking based on how you feel off of the Borg Scale chart explained.

Whole Body Fatigue Procedure:
You will perform back and forth sprints across the court. You will do so with a quarter length, the half-court length, three-quarter length, and the full court length distance.

Induced Fatigue Procedure:
You will be allowed to rest for one minute.
The Baseline Procedure of fastball and curveball pitches will be repeated, while you will still throw more than five fastballs and curveballs, you will throw less than what you threw previously in the Baseline Procedure.

Final Procedure
The sensor will be removed from your arm. You will be allowed to rest and the investigators will ensure you feel fine before leaving.

Risks to study participants
Given this is a study based on injury prevention, there is always a risk for pain, discomfort, or injury. You will be assigned to throw pitches that may cause fatigue in the arm. However, because you already assume that risk during your regular practice and play, there should be no more than the minimal risk involved. You should discontinue any study pitching or exercising if you feel that continuing would risk injury.

Benefits to research participants and others
There is no immediate, direct benefit, but your data will be used in a project that is part of the greater interest of injury prevention in the sport.

Pay
You will receive a $10 Dunkin’ gift card as a thank you for your participation.

Record keeping and confidentiality
All data collected will be maintained and kept in a private folder among the research team. All interviews will be documented using general information about the interviewee (including age, role, and experience

with the subject matter). Your identity will be kept confidential in future publications as a result of this study. Your data may be used by other projects who wish to use this project as a source, but any identifying information will not be made available. All records will be kept by the faculty advisor of this project for three years following the completion of the project. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

Compensation or treatment in the event of an injury: Because we do not ask that you assume more than the minimal risk when pitching, there is no compensation or treatment being offered in the case of an injury. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:
WPI IRB Manager: Ruth McKeogh, irb@wpi.edu
WPI Human Protection Administrator: Gabriel Johnson, gjohnson@wpi.edu

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. By signing, you acknowledge that there is no feeling of coercion involving teammates, coaches, faculty, etc. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered before signing. You are entitled to retain a copy of this consent agreement.

___________________________ Date: ___________________
Study Participant Signature

____
Study Participant Name (Please print)

____________________________________ Date: ___________________
Signature of Person who explained this study

Appendix C: Data Collection Protocol

Title

Baseball Pitching Biomechanics and Injury Prevention

Investigators

Student Investigators: Michael Fraser, Martin McCormack, Jeffrey Mei
Faculty Advisors: Prof. Ted Clancy, Prof. Karen Troy
Faculty Consultant: Dr. David Magit, MD (UMass Medical School-Worcester)

Locations

WPI Sports & Recreation Center (Basketball Courts and Baseball Cages)

Anticipated Dates of Research

Jan 12 - May 3, 2022

Purpose

The purpose of the project is to design a sensor device that will be used to prevent elbow injuries in baseball pitchers. The sensors will be used to estimate metrics of interest in real-time, with respect to different pitches thrown. The sensors will be on a subject's pitching arm in order to test sensor function and feasibility in a controlled (non-competitive game) pitching task.

Funding

Funded by WPI (MQP funds)

Subjects

College baseball pitchers who throw both fastballs and curveballs

Potential Risks

The subjects will not be asked to pitch beyond normal training limits consistent with their conditioning at the time of the experiment. College pitchers routinely track their pitch count during their training, either formally or informally. And, each pitcher will be given ample time for normal warm-up activities. However, there is always a risk for pain, discomfort, or injury whenever a college pitcher is throwing. Subjects will be assigned to throw pitches that may cause some fatigue in the arm. However, because they already assume that risk during their regular practice and play, there should be no more than the minimal risk involved. Subjects will be advised to discontinue any pitching or exercising that they feel would risk injury, and will be asked from time to time during the procedure if they can continue.

The sensors include electronics, which could present the risk of electrocution. The sensors will be placed onto the arm. The sensors are no larger than the size of a quarter and weigh roughly 20-30 g. The size of the battery is 3 V, 500 mA hours capacity. The sensors will be enclosed, thus there will be no electrical connections to the body and little risk of damaging electrical currents.

Potential Benefits

There are no immediate, direct benefits subjects will earn, such as compensation, but their data will be used in a project that is part of the greater interest of injury prevention.

Study Information

Recruitment

1. Subjects will be narrowed down to the pitching roster of a college baseball team. The subjects are limited to baseball teams instead of softball teams because softball pitchers

throw overhand. Female subjects are not intentionally excluded, but it is expected that the subjects will be male, given that the subject pool is overwhelmingly male.

2. Subjects must be healthy and be able to throw fastballs and curveballs.

Materials

1. Adafruit units (2) (placed on the forearm and upper arm, no greater than a size of a quarter and no heavier than a couple of ounces)
    a. Adafruit IMU Sensor
    b. Adafruit Microcontroller Board
    c. Li-ion Polymer Battery (3V, 500 mA hrs)
2. Baseball
3. Shirt with sewn pockets

Preparation before subject arrival:

1. Before the subject arrives, set up an artificial mound and catcher's net. The distance between will be 60.5 ft (18.44 m) and the mound will be 10 inches above home plate, per NCAA standards.

Preparation when subject arrives:

1. When the subject arrives, explain the consent form and have him sign.
2. Perform body measurements (height, weight, arm lengths, sensor location)
3. Have the pitcher perform a normal warm-up routine while we prepare the device and software.

Baseline Procedure:

1. The sensors will be put on the subject's throwing arm. One will be placed on the forearm and the other on the upper arm.
2. Have the subject throw a fastball.
3. Have the subject prepare to throw another fastball. Repeat step 2.
4. Repeat the process for curveballs.
5. In total, the pitcher should throw between five to ten pitches for each of the two pitch types. This should develop an initial baseline. Ten to twenty total pitches have been thrown.

Arm Fatigue Procedure:

1. Using the SCIFIT PRO1000 Seated Upper Body (Figure 1), the subject arm cycles at a speed of 50-70 RPM as the investigator increases the resistance setting to a comfortable effort for the subject to maintain his speed for sixty seconds. The recommended resistance setting is between 5 and 7, though the setting is dependent on the subject.
2. The subject maintains the same speed while the investigator increases the resistance of the arm cycle to an effort level where the subject is at full effort, for ten seconds. There will be a transition time until that setting is found. The recommended resistance setting is between 7-10, though the setting is dependent on the subject.
3. Repeat steps 1-2 four additional times. The whole procedure should take roughly ten minutes.

SCIFIT PRO1000 Seated Upper Body

Whole Body Fatigue Procedure:

1. Have the subject perform back and forth sprints across the basketball court. The subject will do so starting from and returning to the basketball baseline, with a quarter length, the half-court length, three-quarter length, and the full court length distance.

Induced Fatigue Procedure:

1. Allow the subject to rest for one minute.
2. Repeat Baseline Procedure steps (throwing 5–10 fastballs and 5–10 curveballs). This should develop a fatigued baseline.

Final Procedure

1. Remove the sensors off the subject.
2. Allow the subject to rest and ensure he feels fine before leaving.

Data Collection, Storage, and Confidentiality

<u>Inputs</u>

Sensors will measure:

- Linear Acceleration (+/-x, y, and z axes) in m/s^2
- Angular Velocity (+/- azimuth, elevation, and roll) in degrees/s
- Corresponding time values in milliseconds for all measurements
- Subject Specifications (Height, weight, arm lengths, sensor location)

<u>Source</u>

The raw data from the sensor system will be sent wirelessly to a base station and stored in a comma-separated values (.csv) file that is uploaded into the MATLAB code

<u>Outputs</u>

- A cell array for each sensor at every time point containing the recorded linear acceleration and angular velocity values
- Append cell arrays where missing data points from each array have been eliminated from all arrays to ensure continuity between the data sets
- Force at the elbow and shoulder
- Torque at the elbow and shoulder

- Range of Torque
- Standard deviations of torque over time in a window with a width of 10 pitches and height of the range of torque value
- Pass/fail indication of dangerous injury risk (pass indicates healthy variation, fail indicates the dangerous variation of varus torque)

<u>Destination</u>

- A wireless database in the form of a .csv file

<u>Pre-condition</u>

- The MATLAB script must be open and displayed on the user’s screen

<u>Post-condition/Storage</u>

- The raw data .csv file is unchanged, and new .csv file of calculated values is stored locally on the user’s computer

<u>Confidentiality</u>

- The subject will be given a number as a marker, but only student investigators will know the number (explained in conflicts of interest)

Incidental Findings/Deception

There is no anticipation of incidental findings. There are no intentional deception tactics involved.

Conflicts of Interest

Subjects are also students, which might suggest a hierarchical status to the faculty advisors, Prof. Clancy and Prof. Troy. In order to address the conflict of interest, the identities of the subjects will not be explicitly stated to either Prof. Clancy or Prof. Troy.

Compensation

As a reward, subjects will be given $10 DD gift cards.

Appendix D: MATLAB Code Array of Raw Data

Array_of_Raw_Data.m

```
close all; clear all;
%receive serial port data
s = serialport("/dev/cu.usbmodem1412101", 115200 ...);
num_values = 20000;
arrayofdata = zeros(num_values,7);
i = 1;
%Receive data in a 7 column array, for each data point
for i = 1:num_values

data1 = readline(s);
arrayofdata(i,1) = str2double(data1);
data2 = readline(s);
arrayofdata(i,2) = str2double(data2);
data3 = readline(s);
arrayofdata(i,3) = str2double(data3);

data4 = readline(s);
arrayofdata(i,4) = str2double(data4);
data5 = readline(s);
arrayofdata(i,5) = str2double(data5);

data6 = readline(s);
arrayofdata(i,6) = str2double(data6);

data7 = readline(s);
arrayofdata(i,7) = str2double(data7);
 i = i + 1;
end
```

Appendix E: MATLAB Code Force and Torque Equations

ForceandTorque.m

```
close all; clear all;

s = serialport("/dev/cu.usbmodem1412301", 115200); %connect to serial port

   num_values = 1000;
   %Array of zeros for gyroscope
   gyroData_x = zeros(1,num_values);
   gyroData_y = zeros(1,num_values);
   gyroData_z = zeros(1,num_values);
   %Array of zeros for accelerometer
   accelData_x = zeros(1,num_values);
   accelData_y = zeros(1,num_values);
   accelData_z = zeros(1,num_values);
   %Array of zeros for gyroscope
   gyroData_xdeg = zeros(1,num_values);
   gyroData_ydeg = zeros(1,num_values);
   gyroData_zdeg = zeros(1,num_values);
   %Array of zeros for Force
   elbowForce_x = zeros(1,num_values);
   elbowForce_y = zeros(1,num_values);
   elbowForce_z = zeros(1,num_values);
   %Array of Zeros for time
   rawTime = zeros(1,num_values);
   realTimer = zeros(1,num_values);
   % Array of zeros for each alpha value
   alpha_x = zeros(1,num_values);
   alpha_y = zeros(1,num_values);
   alpha_z = zeros(1,num_values);
   %Array of zeros for torque and force magnitudes
   elbowForce_mag = zeros(1,num_values);
   elbowTorque_mag = zeros(1,num_values);
   ballW = .141748; %Ballwieght in Kg
   bodyW = 88.4505; %Bodywieght in Kg(185 lbs)
   forearmLength = .26; %Length of the forearm(m)
   forearmMass = bodyW * 0.022; %Mass of the forearm
   I_forearm = (.0833333) * forearmMass * (forearmLength)^2; % I for the forearm
   equation
   r_elbow = .13; %Center of mass of forearm
   % Counter
   i = 1;
   %While loop to continuously plot new data
   for i = 1:num_values
   %Get the accelerometer x data
   data1 = readline(s);
   accelData_x(i) = str2double(data1);
   %Get the accelerometer y data
   data2 = readline(s);
   accelData_y(i) = str2double(data2);
   %Get the accelerometer z data
```

```
data3 = readline(s);
accelData_z(i) = str2double(data3);
%Get the gyroscope x data
data4 = readline(s);
gyroData_x(i) = str2double(data4) * (57.2958);
%Get the gyroscope y data
data5 = readline(s);
gyroData_y(i) = str2double(data5) * (57.2958);
%Get the gyroscope z data
data6 = readline(s);
gyroData_z(i) = str2double(data6) * (57.2958);
%Get the timer(ms) data and convert to seconds
data7 = readline(s);
rawTime(i) = str2double(data7);
realTimer(i) = (rawTime(i) - rawTime(1))/1000;
if i > 500 %Wait one value in order to calculate alpha
%get elbow force in each direction
elbowForce_x = -(forearmMass * accelData_x);
elbowForce_y = -(forearmMass * accelData_y);
elbowForce_z = -(forearmMass * accelData_z) + (forearmMass * -9.81);
%magnitude of the elbow force vector
elbowForce_mag = sqrt((elbowForce_x).^2 + (elbowForce_y).^2 +(elbowForce_z).^2);
% Alpha for each direction
alpha_x = (gyroData_x(i) - gyroData_xdeg(i-1))/(realTimer(i)-realTimer(i-1));
alpha_y = (gyroData_y(i) - gyroData_ydeg(i-1))/(realTimer(i)-realTimer(i-1));
alpha_z = (gyroData_z(i) - gyroData_zdeg(i-1))/(realTimer(i)-realTimer(i-1));
%elbow Torque in each direction
elbowTorque_x = (alpha_x * I_forearm)+(r_elbow * elbowForce_x);
elbowTorque_y = (alpha_y * I_forearm)+(r_elbow * elbowForce_y);
elbowTorque_z = (alpha_z * I_forearm)+(r_elbow * elbowForce_z);
%magnitude of the elbow Torque vector
elbowTorque_mag = sqrt((elbowTorque_x).^2 + (elbowTorque_y).^2 +
(elbowTorque_z).^2);
%assign force and torque to an axis to plot
y1 = elbowForce_mag;
y2 = elbowTorque_mag;
%assign time(s) to x axis
x = realTimer;
%plot each torque and force
figure(1)
plot(x,y1);
title("Force at Elbow")
xlabel("Time(s)")
ylabel("Force(N)")
figure(2)
plot(x,y2);
title("Torque at Elbow")
xlabel("Time(s)")
ylabel("Moment(Nm)")
 end
%Add one to the counter
     i = i + 1;

 end
```