COLLEGE OF ENGINEERING
MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

Robotic Baseball Throwing Arm

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ME 450 Section 4 Team 9
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Executive Summary

Injuries occur in every sport, therefore injury prevention and treatment is an important field of study to improve the lives of athletes of all ages. A myriad of potentially dangerous things can happen while someone is kicking, catching, or throwing a ball, so injury will never be off the table. For our ME450 course project, we partnered with our sponsor, Dr. Stephen Cain, to help understand these injuries.

To be able to analyze injuries, we have to be able to understand the movements that happen within significant joints or muscles in the body. Today, motion capture is used to understand the movements of a person while performing an action. The downfalls of this technology are that it can be inaccurate due to the movement of skin or clothing not always matching up with the person's action. In his lab, Dr. Stephen Cain has been trying to analyze the injuries that occur in baseball pitchers when they are throwing a ball. He currently uses motion capture technology to understand the movements that occur. Recently, he has come to understand the flaws in this measurement process and wants to move toward IMUs (Inertial Measurement Unit). He believes that this can provide more accurate measurement and that being able to compare this to motion capture technology can give us a better understanding of what exactly is happening.

Our job is to create a baseline measurement for both of these technologies to be compared to. To do this, we were tasked with creating a baseball throwing arm that is capable of similar movements to an elite baseball player. As a result, we were able to establish all of our requirements and specifications for this project. These involve the weight and length of each link so that it fully represents an actual human arm. We set our ranges of rotation by discovering the maximum and minimum angles the shoulder and elbow joints move during a throwing motion. By doing this, we figured out the best method for mimicking the kinematics of a human pitcher. We also determined the overall weight of the design, which allowed us to select the correct motor to match the torque that is needed to carry out a throwing motion. As a mechanism that will be used for multiple measurements, we established the durability of the baseball throwing arm should exceed at least 100 trials. All of these requirements and specifications can be seen in Table 1.

After completing the concept exploration, we decided that our 2-DOF mechanism would be the best for our needs. It was a design our sponsor wanted us to use, and it provided what we felt was the best possible outcome given the circumstances. We were able to determine the angular velocities and accelerations our machine should reach based on research and data provided by our sponsor. Based on these, we were able to determine the torques required using ADAMS software and verified the results through manual calculations. Achieving these values required a motor that far exceeded our budget, so we scaled the design down to reach 55% of the original angular velocities. However, we feel the design still fulfills requirements.

As a result of the many challenges faced during the course of the project from project-specific problems to other outside sources, there were a couple of things we would have done differently. There are some design changes such as reducing the length of our steel rod and fully designing our releasing mechanism for the forearm that we would have made to improve our project. Additionally, by dividing more work into different subsystems for each person to work on, we may have been able to get through more work. Overall our design met our requirements and is close to operational.

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Problem Description and Background

Injuries occur in every sport. In most cases, solutions are developed to mitigate these injuries. For example, in professional football rules have been developed to make it illegal to tackle and hit players in certain ways. The improving technology of the equipment is also aimed to make playing safer for players. The same applies to the game of baseball. Rules have been added to improve player safety. However, the part of baseball that experiences the highest rates of injuries no rule change can improve-- the throwing motion. 67% of baseball injuries occur in the shoulder or elbow joint during the throwing motion[4]. Additionally, the pitchers experience 34% higher injury rates compared to other position players[4]. This can be attributed to the fact that pitchers are the players that have to throw the hardest the most consistent amount of the time.

There have been a few attempts at making a robotic arm for the purpose of studying baseball pitchers, for example, Alexander[1] made a model including making a 2 bar linkage where the first linkage is meant to represent the upper arm, while the second linkage is meant to represent the lower arm. The pitching mechanism then went through motion capture technology to try and understand the torque levels that the arm goes through during its normal pitching motion. Currently, the throwing motion and the movement that occurs in the shoulder and elbow joints have mainly been studied using motion capture technology. Motion capture is the method of attaching markers on a subject and placed near a camera system. This camera system typically takes about 30-2000 frames per second[15]. These images can then be used to build a model of the subject for further analysis. However, motion capture technology is expensive and may have errors due to inaccurate measurements, marker occlusion, or skin motion[3]. Our sponsor, Dr. Stephen Cain suggests moving towards using Inertial Measurement Units (IMUs) to more accurately measure the movements throughout these joints. IMUs have an accelerometer, gyroscope, and magnetometer built into them. The accelerometer measures linear acceleration in three dimensions. It can detect the force of gravity, so in turn, can determine the orientation of the sensor. Additionally, IMUs have a built in gyroscope which can measure twisting and rotational motion. This is important for measuring angular velocities. Lastly, IMUs have a magnetometer that can measure magnetic fields. This can be used to determine magnetic north, which can also be used to help orientate the sensor. IMUs provide 6 degrees of freedom[16].

To assess the accuracy of motion tracking systems(IMUs, Motion Capture, etc), we need to create a mechanism that will act as the “ground truth” model. The mechanism will mimic the kinematics and kinetics experienced by a human arm throughout a baseball pitching movement. By building a robotic arm that is able to simulate a baseball throwing motion, we can compare different motion tracking systems to determine which system more accurately measures the torques and angular velocities that the elbow and shoulder undergo during a normal pitch. With this information, medical experts can determine how much torque the joints can handle and ultimately use this information to further research into ways that could allow for lower injury risk to pitchers.

Literature Search and Benchmarking

Our team conducted research that helped us in the design process. The literature sources were found through various sources, including recommendations from our sponsor, the ME 450 online library, and scholarly articles. The research is focused on the pitching motion itself, along with the study of various measuring devices for the recording of torques.

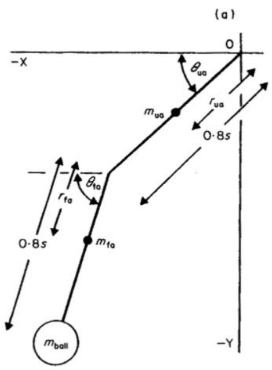
The primary objective of the project was to build an arm similar to one of an elite baseball pitcher, as a result, a large amount of our research was intended to research models of the pitching motion. “Optimum Timing of Muscle Activation for Simple Models of Throwing” by R. McN. Alexander was a good beginning in understanding the timing of the pitching motion and allows us to understand when we want our motors to activate given a basic design representation of an arm. The timing of our throwing arm will likely be calculated using this article.

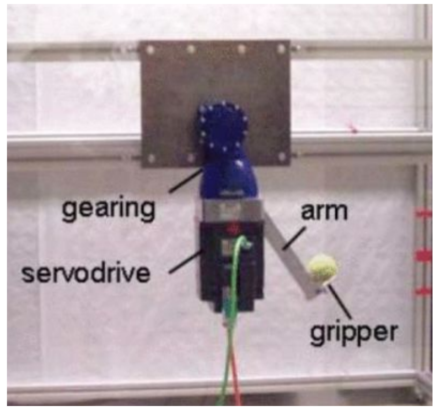
“Dynamics of the Shoulder and Elbow Joints of the Throwing Arm During a Baseball Pitch” by Michael Feltner and Jesús Dapena, was very helpful in understanding the level of force the joints are under during the pitching motion. We can use the information in this article to understand the approximate level of torque we will need in order to determine the power of the motor needed.

“Anatomical data for analyzing human motion,” will help us understand the way torques can be calculated, and decide on a possible way we want to measure the torque, as our sponsor mentioned that using IMUs or Motion Capture would be far too expensive based on our budgetary constraints. This article mentions different ways to measure the torque, and as a result, can assist us in determining how we want to physically measure the torque in our design.

In order to better inform ourselves in the design process, we benchmarked several previously used designs in an attempt to model the same thing. We were able to determine that the primary ways they differed were in degrees of freedom (DOF), number of linkages, the ability to throw a baseball, and the accuracy of the pitching motion.

We found many different designs that had been previously used, however, we did not feel these were good enough for our application. For example, the 1-DOF Throwing Robot, as pictured in Figure 2, does not accurately represent the pitching motion nor have the preferred DOF. Meanwhile, the 2-DOF Throwing Robot, pictured in Figure 3, also does not accurately represent the pitching motion. The 2-DOF Underhand Throwing Motion, as shown in Figure 1, does mimic a throwing arm, however, we want to study the overhand throwing technique, so none of these designs would accurately fulfill the purpose of the design.





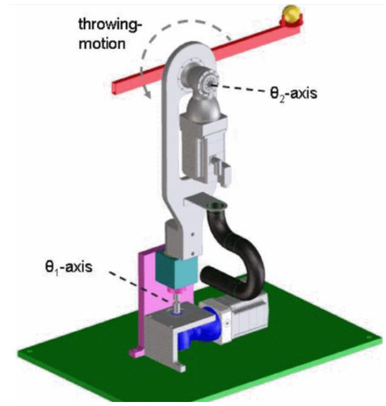
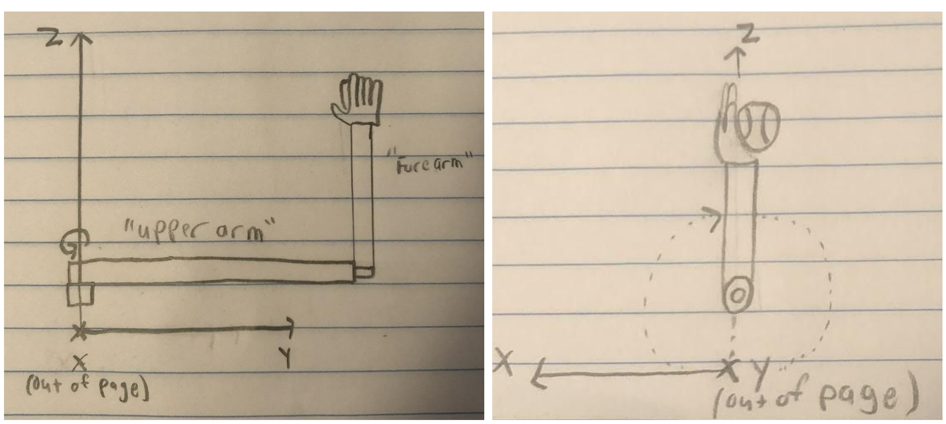


Figure 1: 2-DOF Underhand Throwing Motion [1]

Figure 2: 1-DOF Throwing Robot [12]

Figure 3: 2-DOF Throwing Robot [11]

Since we would like to study the torques on a pitcher using an overhand delivery, we need to design a robot that throws in an overhand motion. The 2-DOF Overhead Throwing Motion, as pictured below in Figure 5, provides a more accurate representation of the type of design we would like to use, however, it is far from perfect, and the final design will likely need a few modifications, though we do plan on using this design concept in the design of our product. We feel this provides a fairly accurate measurement of the data we wish to achieve, however, we acknowledge that the actual arm during a pitch is much more complicated than the design concept, as the fingers and wrist can also play a role in the pitch. However, the primary torques are in the elbow and shoulder joint, which is reasonably represented in the design concept below. The comparisons are shown in Table 3 below.



[4.A] [4.B]

Figure 4: Diagram of 2-DOF Overhead Throwing Motion. This mechanism has 2 DOF. Firstly the entire mechanism rotates around the z-axis as seen in 4.A. The forearm linkage also rotates around the y-axis as shown in 4.B.

Table 3: Benchmarking Comparisons: This table shows the comparisons between the design concepts previously used in the attempt to make a similar device.

	[1] 2-DOF Underhand Throwing Motion	[12] 1-DOF Throwing Robot	[11] 2-DOF Throwing Robot	[1] 2-DOF Overhead Throwing Motion
DOF	• Two, Planar	• One, Planar	• Two	• Two
Linkages	• Two	• One	• Two	• Two
Ability to throw a baseball	• Yes	• Yes	• Yes	• Yes
Accurate of overhead throwing motion	• No, Softball throwing motion	• No, Catapult Motion	• No, Catapult Motion	• Yes, simplified version of motion

Requirements and Specifications

In order to develop a possible solution, we first needed our requirements and specifications. We worked closely with Dr. Stephen Cain, and were able to define the requirements that our solution needed to meet. From there, we were able to determine through our research what the engineering specifications needed to be. The requirements and specifications are shown in Table 1 below and are subject to change if any new information is learned.

Table 1. Requirements and Specifications: Requirements and Specifications that our mechanism needs to fulfill. The requirements were given to us by Dr. Stephen Cain. Our team derived the quantifiable specifications by reviewing relevant literature.

Requirements	Specifications
Mechanism must accurately represent a human arm	Weight of Upper Arm ~ 7 lbs Weight of Forearm ~ 4 lbs Length of Upper Arm ~ 13 inches Length of Forearm ~ 11.5 inches [7][13]
Mechanism must mimic an overhead throwing motion	2 DOF Throwing Mechanism with 2 Links Mechanism needs to be able to achieve angles of: • External Shoulder Rotation ~ -90°/-50°

	• Internal Shoulder Rotation ~ 90° • Horizontal Abduction ~ -40/-30° • Horizontal Adduction ~ 90° [1], [2], [6]
Mechanism must have similar kinematics to an actual human pitcher	• Forearm Max Speed >= 550 rpm • Upper Arm Max Speed >= 520 rpm
Durable	Mechanism capable of lasting >100 trials

Represent a Human Arm

In order to develop a linkage system that accurately represents a human arm, we needed to establish a good estimate for a pitcher's arm dimensions. To generate these dimensions, we found literature that broke down a human's body part dimensions as a percentage of their body weight and body height[7]. Below in Table 2, is a breakdown of the arm dimensions as a percent of body weight and height.

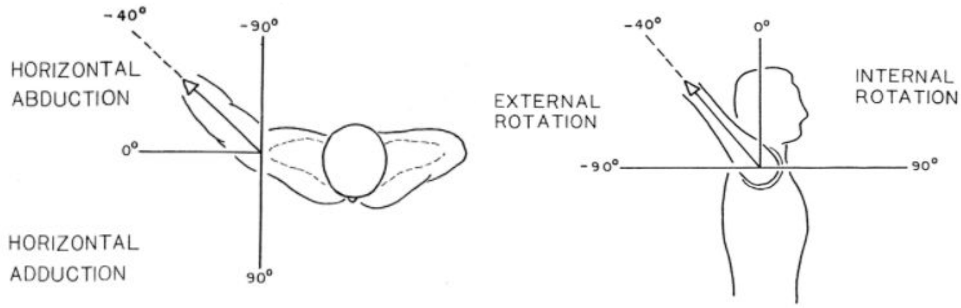
Table 2. Breakdown of Body Parts as Percentages: Weight as % of total body weight and length as % of the total height of a male[7]

	Weights as % of Total Body Weight-Male	Length as % of Total Height - Male
Upper Arm	3.25	17.2
Forearm	1.87	15.2

We found that the average weight of a major league pitcher was 210 lbs and their average height was 6' 2.5"[13]. We could then easily calculate the average length and weight of a professional major league pitcher arm, by multiplying these by the quantities in Table 2. These dimensions for the forearm and upper arm(which includes shoulder down to elbow), will be the basis of our linkage system.

Simulate an Overhead Throwing Motion

Our second main requirement is to ensure our mechanism mimics an overhead throwing motion. As the throwing motion is highly complex with multiple degrees of freedom, it was recommended by our sponsor that we develop a simplified throwing motion that has two linkages and only two degrees of freedom. For this reason, we are only focused on the upper arm and forearm as our two linkage system. However, one challenging aspect of analyzing the throwing motion lies in the fact that all pitchers have different motions and generate different angles throughout their motion. After reviewing the literature we developed a good range of motion that an average major league baseball pitcher might replicate. Below in Figure 1, is a description of terminology to better understand which angle we are referring to.



[A.1] **[B.1]**

Figure 5. Terminology of the Throwing Motion: This figure is a reference for the terminology used in describing the arm motion [2].

From literature, it was determined that our upper arm linkage must have a horizontal abduction in the range of -30° to -40°, and have horizontal adduction in the range of 40° to 60°. Our forearm linkage must be able to achieve a minimum external rotation of -50° and a max external rotation of -90°. Similarly, it was determined that the mechanism must achieve an internal rotation of 90°[1][2][6].

Not only does our mechanism need to be able to move through these degrees of rotation, but in order to simulate the overhead baseball motion, it is important that our mechanism needs to achieve certain degrees of rotation at specific times. The three instances that we are most interested in are the cocking phase, max external rotation, and release. The cocking phase occurs when the pitcher brings the ball back and achieves max horizontal abduction[14]. It is at this instance when the upper arm begins to rotate forward making the forearm externally rotate back. The maximum external rotation phase occurs when the forearm is at max external rotation[14]. It is at this moment that the elbow experiences the highest torque because it is at max rotation. Lastly, we need to analyze the instance the ball leaves the hand. The cocking phase takes place when the upper arm is horizontally abducted -30° to -40°, while the forearm is in a neutral to internally rotated 40° position[2][6]. For the max external rotation phase, the forearm is externally rotated from a range of -50° to -90°, while the upper arm is horizontally adducted 0° to 10°[2]. Lastly, at the release phase, the upper arm is horizontally adducted 40°to 60°, while the forearm is internally rotated 0° to 40°[1][2][6]. After the release phase, the upper arm continues to rotate internally, that is why in Table 1 there is maximum horizontal adduction of 90°.

Mechanism Must-Have Similar Kinematics to Actual Pitcher

We also want our mechanism to have similar kinematics to an actual pitcher. After speaking with Dr. Cain, he explained that an actual pitcher pitches at approximately 583 rpm in the forearm and approximately 540 rpm in the upper arm. We hope that we will be able to mimic this by getting at least 550 rpm in the forearm and at least 520 rpm in the upper arm.

Durability

Our final requirement is that our mechanism must be durable. The mechanism needs to be able to go through its throwing motion many times to account for the many trials that it will undergo for testing purposes. After speaking with Dr. Cain, we have decided that our mechanism must be able to last at least

100 trials. In order to do this, we will use durable material and ensure that our mechanism can withstand the forces that will be acting on it.

Concept Generation

In order to adequately explore the design space for possible solutions for our problem statement, we used tools such as brainstorming and design heuristics to generate ideas.

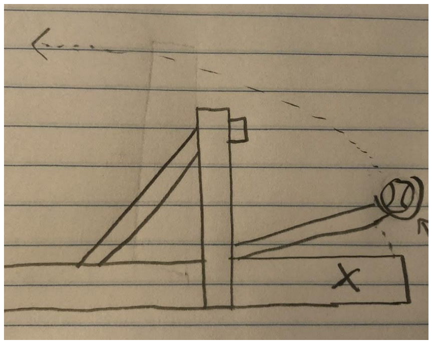
For our brainstorming session, we broke down our robot baseball arm into subsystems. This way, we can allocate time to come up with different ideas for each subsystem and focus on one function at a time before combining them into our robot arm. We divided our system into the following categories: Throwing Motions, Motion Generation, Stopping, and Measurement. While brainstorming we knew it was important to avoid fixation. Dr. Cain originally gave us a design that he believed would work well for our project. In order to fully explore the design space, we made sure not to focus our ideas around this one design. We developed creative and unique solutions to our problem statement.

We used Design Heuristics to generate new ideas and iterate through existing ideas. Below are several examples of Design Heuristics we implemented to further expand our solution space and explore different possible design combinations. For instance #52 -Redefine Joint, lead to thinking about making the elbow a fixed 90-degree joint. Additionally, #46-Mimic Natural Mechanisms lead to including springs/elastic material to mimic the muscles in the arm for motion generation and stopping the mechanism. Lastly, #57-Rotate, lead us to allow the arms spin freely at end of motion rather than forcing it to stop.

We also used many design best practices that helped us in the design process. For example, we used divergent thinking to consider many different ways that our design and its subsystems could function, then used convergent thinking to only use the best aspects of our different designs to go into the final design concept.

Designs to Throw a Baseball

The first subsection we focused on were basic designs that could actually throw a baseball. We tried to come up with pre-existing designs along with new unique designs. The first idea we came up with was a simple catapult model, as seen in Figure 6. A catapult is a basic design that achieves our goal of throwing a baseball. Secondly, we came up with a spring launcher design, as seen in Figure 7. This also achieves the requirement of launching a baseball. Next, we thought about incorporating a simple throwing device like a sling and adding it to a linkage. As seen in Figure 8, when the linkage would move the sling would whip around and launch the ball. Another unique design is seen in Figure 9, with our slingshot on a stick. It would work similarly to the sling, but instead a loaded slingshot would be at the end of the stick. Figure 4 above shows the next design of a two-bar linkage with two degrees of freedom. The mechanism would be made up of two linkages. The first linkage would simulate the upper arm and rotate around the z-axis in the x-y plane. The second linkage would operate independently on the end of the upper arm linkage and rotate around the y-axis. Our final design is similar to Figure 4, and the two-bar linkage, except instead of having an independent second linkage it would be fixed at the elbow. It would be one solid “L” piece. The upper arm would still rotate around the z-axis, but the upper arm would also rotate around the y-axis at the same time.



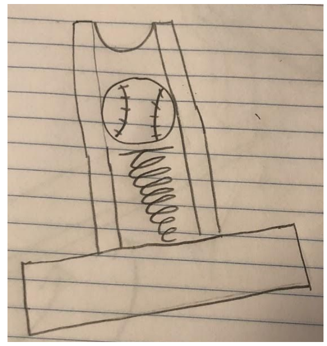
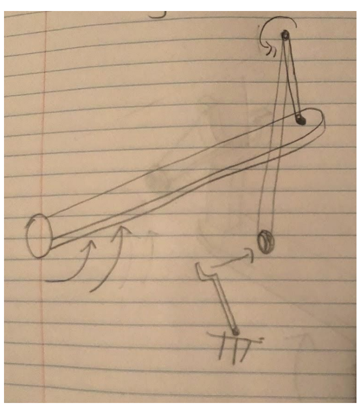


Figure 6: Catapult Design   Figure 7: Spring Launcher Design



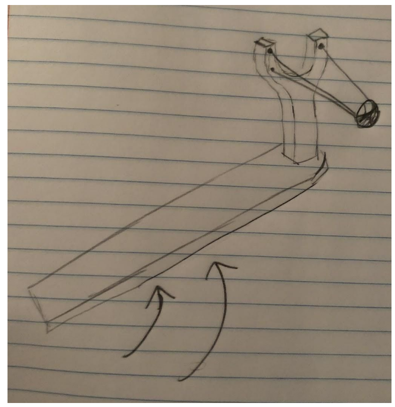


Figure 8: Sling throwing Design   Figure 9: Slingshot on a stick design

Motion Generation

Our next subsystem focused on how to generate the motion needed in our robot arm, in order to throw a baseball. Our first idea was to use some sort of elastic force. By using big rubber bands or another elastic material we could “load/cock” our robot arm, and release it at the beginning of the test to produce the motion. Similarly, our second idea revolved around using torsion or linear springs. By attaching torsion springs at the end of our linkage, we could “load” the system at the beginning of each trial and release it when needed. Our next idea was to create a mechanism that we could load some sort of thruster(i.e. CO2 cartridge, etc) onto our robot arm to create the necessary motion. Before each test, we ignite the thruster and have this power move the arm. Lastly, we thought about creating a motor system. This motor system would include some sort of drive train to increase the torque provided by the motor. The drive train could include spur gears and/or a chain drive.

Motion Control / Stopping

We then explored different ways of stopping our arm’s motion. As a professional baseball pitch involves high torques and speeds, it is likely that our robot arm will need a stopping mechanism to prevent it from breaking and last multiple trials. Our first idea was to create a counter-balance for our arm and then allow our arm to spin freely along its axis, using gravity and friction to stop the mechanism. The second idea was to use a spring to cushion the impact. The spring will be placed at the end of the arm’s motion and will compress to spring to bring it to a stop. Next, we thought about using a PID controller in order to get the motor to stop. We could calibrate the PID controller to know once the arm gets to a certain position, the motor would begin to slow down and stop. We also thought about using some sort of rubber band tensioner to stop the arm's motion. This rubber band tensioner could be placed at the end of the motion similar to the spring cushion to slow the impact, or it could be attached in a certain position that allows the rubber band to stretch pulling the arm back to a neutral position. Lastly, we came up with the idea to use some sort of e-brake system. It would act similarly to a car's braking system. At the joint stack location, there would be a disk we add to act as a disk brake to slow down the linkage.

Measurement

Finally, we thought of different ways of measuring the angles of our shoulder and elbow joints throughout the baseball pitching motion. The first idea we came up with was to use an encoder to measure the angular position of our linkages. One simple measurement idea was to just use a protractor to measure the angles achieved in the linkages. This would have to be used in a design that would have a loading phase before launching in order to measure the angles. Next, we came up with the idea to have a slow-motion camera to capture the motion of our linkages. We would then have some sort of background that would act as a linear encoder. We could see how fast the linkage moved through each specific measured segment. We could then calculate velocities from this. Lastly, we found though using a Goniometer would allow us to directly measure the angles acting within our linkage system.

Concept Evaluation / Selection

To evaluate our concepts, we identified the critical requirements for our subsystems and compared our ideas with a Pugh chart and engineering analysis.

Linkage Design

We started with an evaluation of our overall arm design. The requirements and weighted values are the following:

- **Cost -** The cost of materials needed to manufacture our robot arm is an important factor in weighing our different design choices as we have a limited budget to spend on our project. However, we think that our budget of $400 is sufficient for us to afford any chosen design, and therefore we assign a weight of 2 for our cost requirement.
- **Represents Human Arm -** One of our engineering requirements is for our robot arm to represent a real human arm, and it is important that our results are comparable to the research of a real human throwing a baseball. Therefore, we assigned this requirement a weight of 4.
- **Baseball Throwing Motion -** Our arm needs to be able to throw a baseball, and this is the motion involved in Dr. Cain's investigation on comparing motion capture technology with IMUs. We considered this requirement as one of our most important ones and assigned it a weight of 5.
- **Durability -** Another of our engineering requirements is our linkage has to be durable (capable of lasting >100 trials). We assigned this requirement a weight of 3 as it is necessary to obtain multiple data points in order to reach significant conclusions.
- **Manufacturability -** Our arm has to be manufacturable with our available resources. Nevertheless, we assigned this requirement a weight of 2 as it is also crucial to have a feasible design to fulfill the needs of Dr. Cain and not simply going with a design that is easy to manufacture.

The pugh chart is listed below.

Table 3: Pugh Chart for Linkage Design

		Fixed Elbow Design	Two Bar Linkage Design	Sling Design	Spring Launcher Design
Requirement	Weight				
Cost	2	0	-1	+1	+1
Represents Human Arm	4	0	+1	-1	-1
Baseball Throwing Motion	5	0	+1	-1	-1
Durability	3	0	-1	+1	+1
Manufacturability	2	0	-1	+1	-1
Total		0	+2	-2	-4

We decided to use the fixed elbow joint as our base design for this pugh chart, and we compared the others to it. We found that the two bar linkage design better represents a human arm, and is a better representation of the baseball throwing motion. These were our most important requirements that Dr. Cain had laid out for us, and as a result, we found the 2 bar linkage to be the best possible design given the requirements.

Stopping Mechanism

We also evaluated our designs for our stopping mechanism, as it is one of our most important subsystems. The requirements for the stopping mechanism and their weights are as follows:

- **Cost -** Cost is once again a requirement for our stopping mechanism, however, we believe that the cost of our stopping mechanism designs is well under our provided budget of $400. Therefore, we assigned a weight of 1 for cost.
- **Manufacturability -** Our stopping mechanism must also be manufacturable with our available resources. However, being able to stop our arm effectively is crucial to meeting our durability requirement, therefore we decided to focus on and prioritize maximizing its performance, and assign a weight of 2 for our manufacturability requirement.
- **Stopping Capability -** The purpose of having a stopping mechanism is to enable smooth stopping of our robot arm, and this safety measure is necessary to prevent oscillations that might occur within the system and cause harm to the mechanism, reducing its durability. As this is our main motivation for deciding to have a stopping mechanism, we assign this requirement a weight

of 4.

- **Durability -** One of our engineering specifications is for the mechanism to last over 100 trials, and this also applies to our stopping mechanism. It is important that our stopping mechanism is also durable to protect the arm, therefore we chose a weight of 3 for durability.

Table 4: Pugh chart for various Stopping mechanisms

Requirement	Weight	Hard Stop	Spin Freely	Spring Cushion	PID Controller	Rubber Band Tensioner	High Torque, Low Speed	E-Brake System
Cost	1	0	0	-1	-1	-1	0	-1
Manufacturability	2	0	+1	0	-1	0	-1	-1
Stopping Capability	4	0	0	0	+1	0	0	0
Durability	3	0	-1	+1	+1	+1	0	+1
Total		0	-1	$\boxed{+2}$	$\boxed{+4}$	$\boxed{+2}$	-2	+1

We decided to use the hard stop as our basis for design, and attempted to give scores in relation to the hard stop, we decided that a PID controller would allow for better and safer stopping in the shoulder joint while letting it spin freely would not stop as well, nor hold up in the long run. Since we considered stopping capability and durability as our primary needs for the design, it led to those designs scoring better. As a result, we plan on using a PID controller and adding in a spring cushion or rubber band tensioner to assist in slowing the mechanism down.

Solution Development

Shortly after beginning our model's analysis and the virtual model development of our design, we quickly realized that we did not have the budget necessary to complete the scale model that we had envisioned. As a result, we decided to scale the speeds down to approximately 55% of the original design. In addition, we decided that we were going to scale down the link lengths to be approximately 9 inches each. We were able to do this by using Alexander's model [1] of a throwing motion. We felt that 9 inches provided the best balance between sizing the mechanism down to save budget while remaining a reasonable model of a throwing arm.

Adjusted Analysis

We are able to get proper moments of inertia numbers in Solidworks to compare to the calculated estimation given our parts. We also had talked to our sponsor about what he wanted our critical values to be, and he mentioned that he wanted us to set out to use a specific angular velocity in the shoulder. As a result, we decided to set our base rotational speed to be approximately 300 rpm in the upper arm.

Base Speeds and Accelerations

Based on approximate calculations, we decided to set our critical value of the angular velocity at the shoulder to be 300 rpm. By doing this, and using a constant acceleration model, we were able to determine what our angular accelerations should be. 300 rpm in the shoulder as compared to a full-scale model is about 55.4%, so we will be using 55.4% of the full-scale model's elbow speed. We also know that the elbow moves through about 50 degrees of motion before it's meant to reach its top speed, while the shoulder moves through 40 degrees. We can convert that to be .873 radians for the elbow, and .698 for the shoulder.

Elbow:

$\omega_{e,f} = .554 * 583\ rpm = 0.554 * 61.05\ rad/s = 33.93\ rad/s$

$\omega_{e,f}^2 = \omega_{e,i}^2 + 2\alpha_e * \Delta\Theta_e\ ;\ \alpha_e = \frac{\omega_{e,f}^2}{2*0.873} = 659.6\ rad/s^2$

Shoulder:

$\omega = 300\ rpm\ =\ 31.42\ rad/s$

$\omega_{s,f}^2 = \omega_{s,i}^2 + 2\alpha_s * \Delta\Theta_s\ ;\ \alpha_s = \frac{\omega_{s,f}^2}{2*0.698} = 707.2\ rad/s^2$

Base Rotational Torque

We know that torque is equal to the product of the moment of inertia and angular acceleration, given a constant acceleration. We assume for our project that the acceleration is constant, given that we plan to set the acceleration to be constant in order to reduce the total amount of torque needed to actuate the linkage. These are the primary torques applied to the joints.

Elbow:

$\tau_{e,r} = I_e * \alpha_e\ =\ 0.004919\ kg/m^2 *\ 659.6\ rad/s^2\ =\ 3.244\ Nm$

Shoulder:

$\tau_{s,r} = I_s * \alpha_s = 0.0166(kg \cdot m^2)\ \cdot\ 707.2(rad/s^2)\ = 11.74\ Nm$

Additional Torques

After further investigation, the torques produced by the second moment of inertia and the angular acceleration were not the only ones at work during the full movement of our system. Instead of assuming that while the forearm is moving the upper arm is not and vice versa we took into account the movements and the opposing forces those movements produced.

For the upper arm, the centripetal force of the forearm spinning was taken into account. In order to find the maximum torque the upper arm needed to produce, we used MATLAB to calculate the force produced by centripetal acceleration, then we found the angle relative to the direction of the movement of our forearm by using angular acceleration and time to find the angles. We then found the magnitude of the centripetal force that it produced by multiplying the radius (length of the forearm) and the angular velocity squared (found by using time and angular acceleration) and the cosine of the angle so that it translated to forward direction. Out of the data points at every point in time, we then found the maximum torque produced from the centripetal force which was 6.36 NM.

For the forearm, the tangential acceleration produced by the movement of the upper arm was taken into consideration. As the upper arm was moving it would create a tangential acceleration, which the forearm had to overcome. An example of why this is an issue is because, imagine throwing a ball forward in a car going a constant speed, now imagine trying to throw a ball forward while going 4 Gs, the difficulty is much harder when you are traveling at higher accelerations, so most of our torque for our forearm is needed to overcome that tangential acceleration. To find the tangential acceleration, we multiplied the angular acceleration of the upper arm by the length of the upper arm. Then to translate that into torque the forearm has to overcome, we multiplied that acceleration by the mass of the forearm and half of its full length which was its center of mass. After doing so, we found the torque produced by tangential acceleration was 4.9117 Nm.

Total Torques

The total torques should be equal to all of the torques added together.

Elbow:

$\tau_e = \tau_{e,r} + \tau_{e,c} = 3.244 + 4.9117 = 8.1557$ Nm

Shoulder:

$\tau_s = \tau_{s,r} + \tau_{s,c} = 11.74 + 6.36 = 18.09$ Nm

Torsional Springs for Elbow Actuation

In order to reduce the cost of the project, we decided to use torsional springs to actuate the elbow. By doing this, we are able to reach the desired torques by using 2 torsional springs in parallel with each other as is shown in Figure 14, as it adds the spring constants together. We decided to use the torsional springs shown in Figure 15 below for this application.

Figure 15: Torsional Springs for Elbow Actuation

We can use the spec sheet from this spring to determine the spring constant, and given that we know we want to wind it back 230 degrees, we can also find the total outputted torque of the springs.

Spring Constant of 1 Spring:

$$K_1 = \frac{Ed^4}{64nD} = \frac{30*10^6(0.135)^4}{64(9.75)1.66} = 9.59\ lb\ in$$

Total Spring Constant:

$$K_{total} = 2 * K_1 = 19.17\ lb\ in$$

Torque Calculation:

$$\tau_{spring} = K_{total} * \Theta = 19.17 * \frac{230*}{180} = 76.95\ lb\ in = 8.69\ Nm$$

Motor Selection for Shoulder Actuation

Based on exploring the prices of motors as well as our needed torques, we decided that a motor in the range of 1-2 HP would be able to reach the required torques for our project. We decided to use the motor shown in Figure 16 below. It should be able to supply 46 Nm at 300 rpm, which should be more than enough given our needs. Using a 1 HP motor would give us enough torque to use it based on our calculations, but the price of a 1 HP motor is not significantly cheaper than a 2 HP motor, and we would like to be able to possibly increase the speed of the upper arm if the torsional springs actuate the elbow faster than expected.

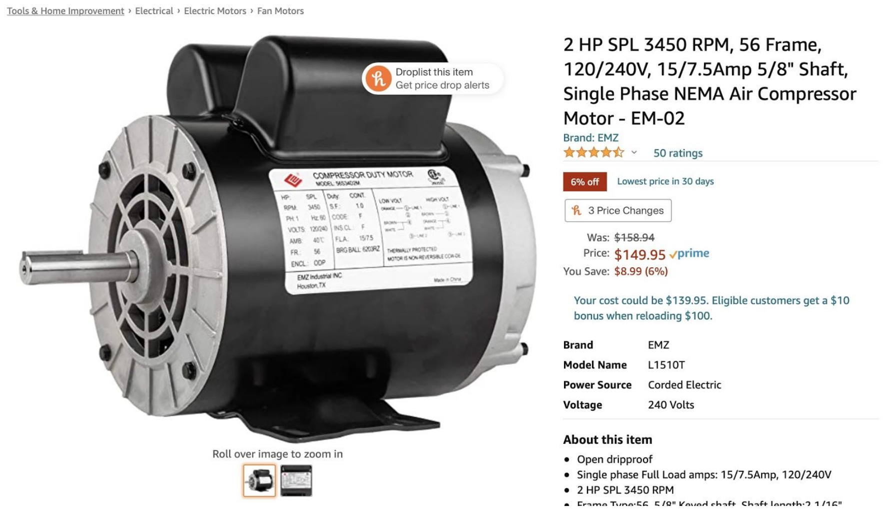


Figure 16: Selected Motor for Shoulder Actuation

Notes about Calculations

By doing the calculations shown above, we are able to determine the torque needs of our project. We are fairly confident that the torque required for actuation is within the range of the calculated values and the values found from our ADAMS model. Both methods of obtaining numbers have their own flaws, such as the calculations not factoring in gravity, or the ADAMS model being a rougher model than our full CAD design. We were not able to go into extreme detail, however, we feel like the numbers we are able to find should be enough to guide us into finding methods of actuation that generate enough torque for the needs of the project.

CAD Model

We wanted to make our CAD design before doing most of our analysis because we figured it would be easier to use the moment of inertia values that Inventor supplied for us instead of us trying to approximate the values. By doing this, we were able to find how large of a motor we need for this application. We also knew the basis for our final design, so we wanted to get a visual representation, and be able to use it to help determine the design decisions that we needed to make in order to have a functioning design.

Overall Design

The CAD model for our design is shown in Figure 9 below.

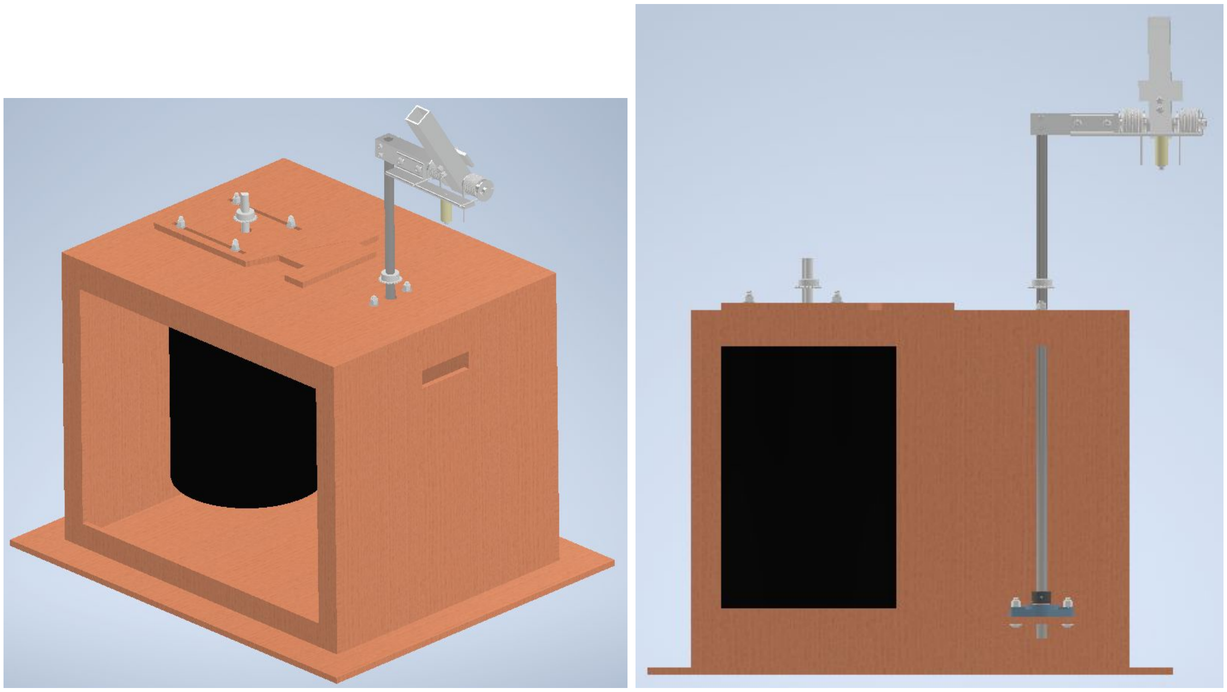


Figure 9: CAD Model of Entire Mechanical Arm and Base

Base

The base for our arm linkage, as well as the motor and its mount, are shown in Figure 10 below. We did not focus on this a lot, as this was primarily a way for us to hold together the linkage, and provide a strong enough base for our linkage to mount to. However, we decided to make the box out of wood, and by doing this, we figured that we could add more weight to the box to make sure that the design remained stable during testing. On the box, there are two flange bearings that the steel shaft is attached to. These will secure the steel shaft into place. Additionally, they will be placed at the top and bottom of the wooden box to add stability to the shaft.

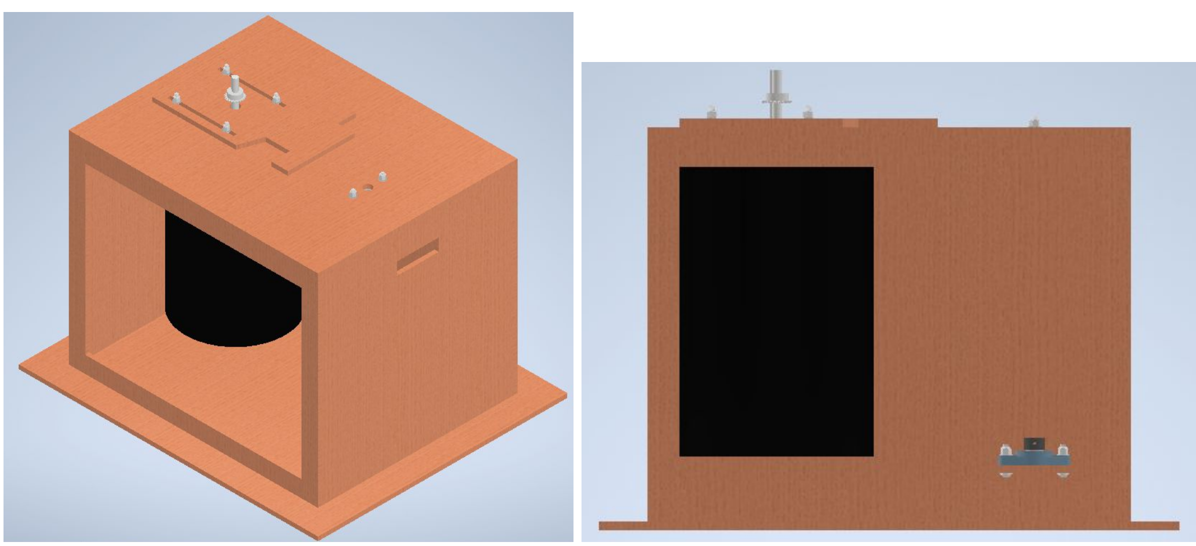


Figure 10: Wooden Base and Motor

Drive Train

This shows how the shoulder is driven for our mechanism. The gear output from the motor will be attached via chain to the motor on the steel rod supporting the linkage. This represents a 1:1 gear ratio, as we did not want to have any additional torque or speeds outputted that our motor could not already attain. This can be seen in Figure 11 below.

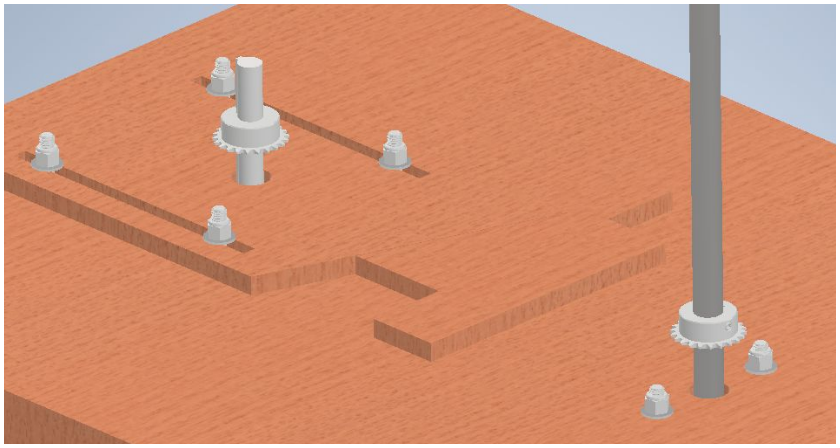


Figure 11: Mechanical Sprocket Drivetrain

Linkage

This shows the overall linkage, where we have a forearm and upper arm with a torque applied on both joints in order to actuate both the upper arm and lower arm. This is shown in Figure 12 below.

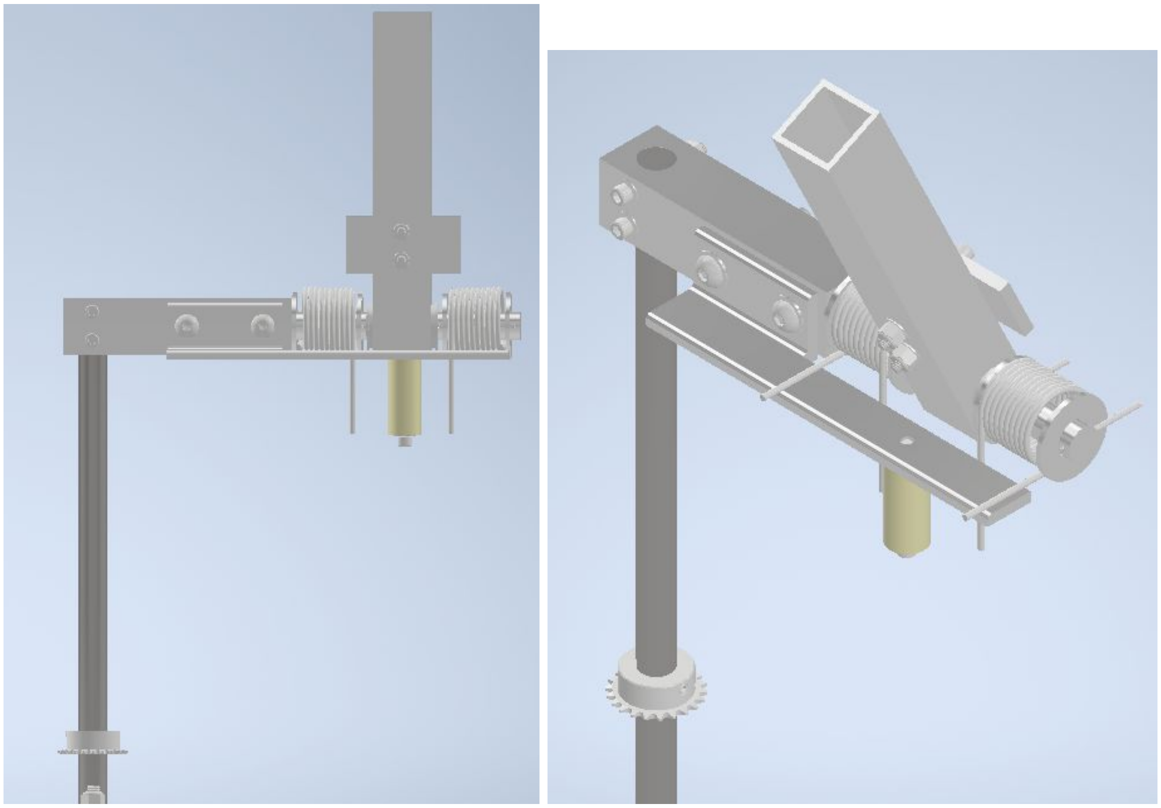


Figure 12: Arm Linkage Mechanism

Shoulder Joint

This shows how the shoulder is attached. The steel rod will spin from the motor, and the whole linkage will spin with it as a result, and this is how we are able to gain motion at the shoulder. This is shown in Figure 13 below.

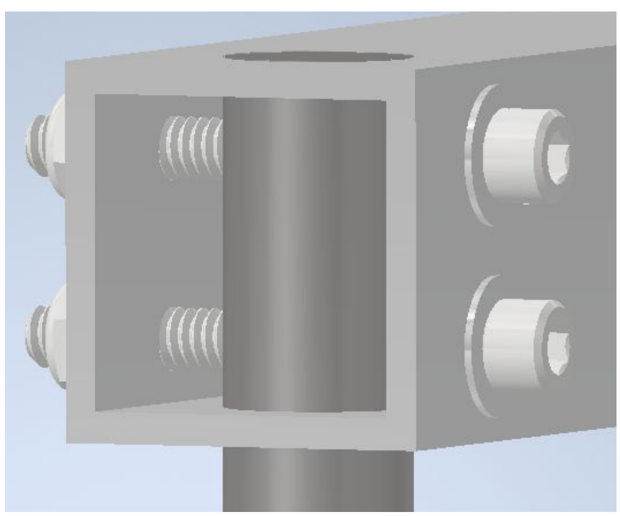


Figure 13: Shoulder Joint of Linkage

Elbow Joint

This shows the elbow joint, along with the torsional springs meant to actuate the elbow. This functions by pulling back the torsional springs to the 230-degree angle from the base of the torsional spring, and using the torque generated from that to actuate the forearm. The pulled back version of the elbow joint does not allow for spring mesh, and the legs of the spring would be behind the extruded part of the elbow. The SolidWorks file obtained from McMaster-Carr does not allow for movement of the spring.

In order to stop the forearm, we have obtained a rubber hard stop from McMaster-Carr and will rely on blunt force to stop the arm, in addition to any back pull that the springs provide. This is shown in Figure 14 below.

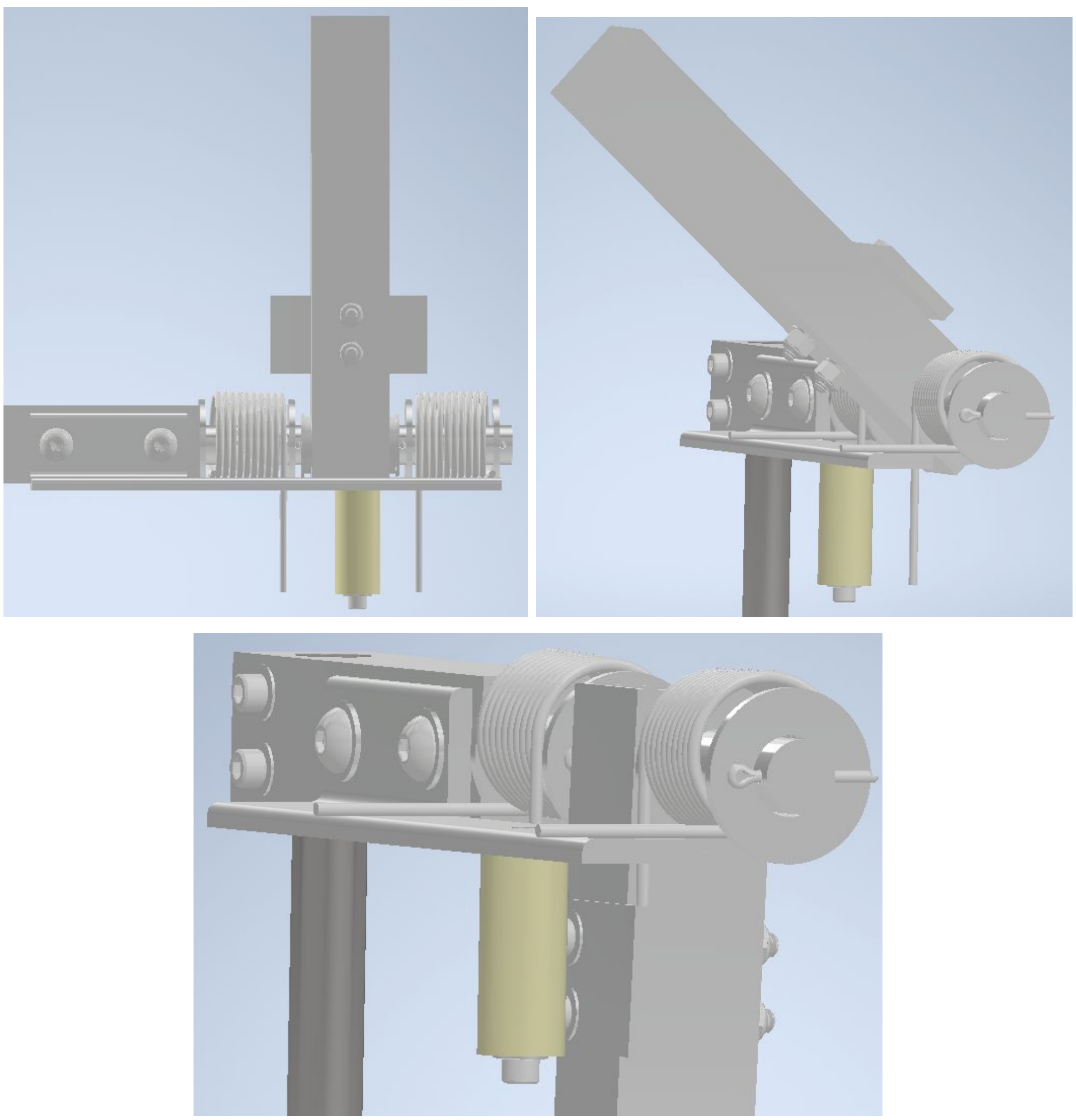


Figure 14: Elbow Joint of Linkage

Design Outcomes

As a result of using this design, we have a few consequences that result from it. For example, in the elbow, we use torsional springs to get the torque for the motion which saves money, however, this gives us a variable torque through the motion, so it may not be able to reach full speed in time, and it gives us less precision control that a motor would provide. Lastly, we also knew that we would be unable to mount a motor at the elbow, and be either forced into a highly complex system to actuate the elbow given a box mounted elbow motor, likely driving up the cost of the project, or be forced to use torsional springs, as a result of the design of the shoulder joint.

Overall, we feel like our design will function as intended, and while it might be a little slow relative to a full-scale professional baseball pitcher, it should provide a reasonable representation of the throwing motion that our sponsor wants to measure.

ADAMS Model

We also built an ADAMS model to further verify our design through a simulation of its baseball throwing motion. The ADAMS model was built while focusing on the most critical parts of our arm (upper arm, forearm, linkage connector, and steel rod).

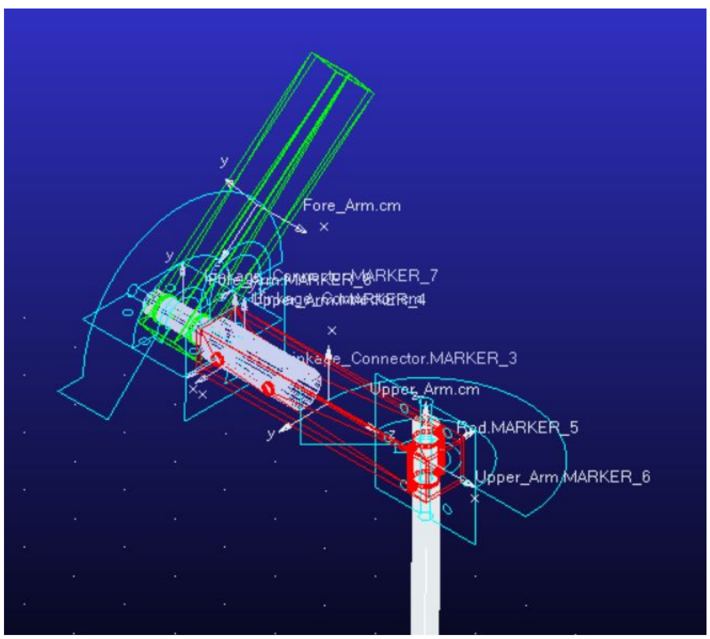


Figure 17: Isometric view of arm design in ADAMS with attached joints and motions

From the simulation, we were able to obtain an estimate of the torques required in the elbow and shoulder joints throughout its range of motion, which is shown in Figure 18 below.

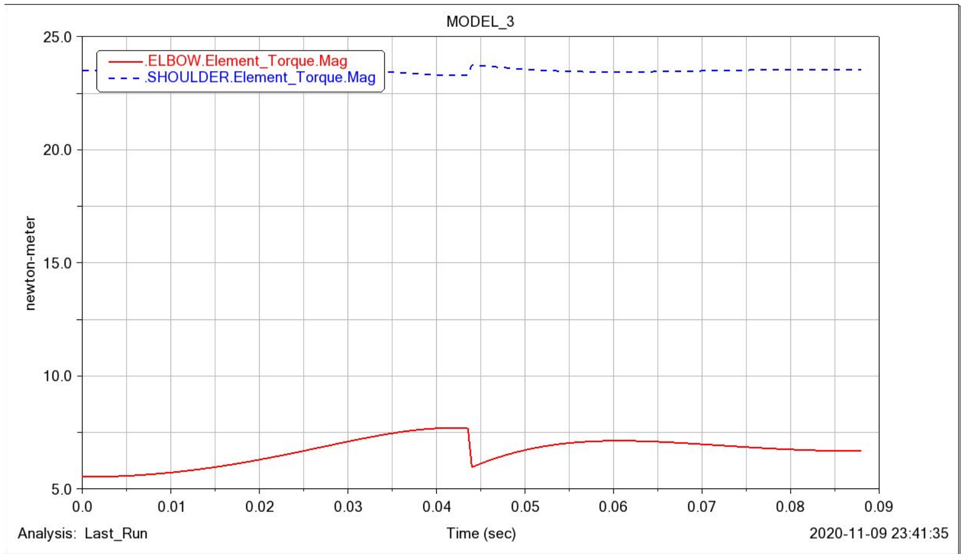


Figure 18: Shoulder and elbow torques obtained from throwing simulation

We observed that the values we obtained from our ADAMS simulation were close enough to our calculated values. There are slight differences between our calculations and the simulation due to gravitational effects, changes in the moment of inertia throughout the throwing motion, as well as other forces involved in the joints that were unaccounted for in our calculations. However, we are confident that the motor we selected will be able to provide the required torque to achieve our desired ball velocity.

Physical Prototype

Our project required a large amount of machining and assembling. Unfortunately, due to the many challenges faced during this semester, we were unable to get into the machine shop and assemble rooms as much as we would have liked. With that said, we were able to build a great majority of our project. Thankfully, we designed our parts with manufacturability in mind, because, due to some unforeseen circumstances, we were only able to have one day to be able to work in the machine shop. Below in Figure 19 is our final built mechanism.

Figure 19: Our final assembled mechanism (left) and the detailed view of the upper arm and forearm linkage (right)

Our joint stack remained the same from our CAD to our final built mechanism. As the box was not a critical design feature, we were able to slightly change the box design after the linkages were built. The overall dimensions of the box were reduced to 25” x 17” x 19”. As seen in Fig. 19 the motor mounting plate changed slightly to improve stability of the heavy motor. Below in Figure 20 a top down view of our mechanism is shown.

Figure 20: A top view of the mechanism with view of the drivetrain.

The shaft of the motor sticks through the top of the box and the sprocket is secured to the motor. The second sprocket is attached to the shaft of the steel rod and a chain is attached to both. The is a large slot in the top of the box to allow the motor to move slightly and tension the chain.

Risk Assessment

During the initial phase of our final design solution, we discussed what we believed to be our biggest failure points. These concepts became the centerpiece of our final design and how we could mitigate these failure points. Our main concern was trying to stop or slow down our linkages after testing. The linkages would be moving at such high torques and speeds that the probability was high of breaking upon a hard stop or violently shaking itself apart. There were two design choices we implemented in order to reduce these risks. The first was instead of having a physical hard stop we would allow the linkage system to spin freely. This would reduce the stress involved with repeated collisions during multiple uses. Secondly, in order to reduce the vibrations caused in the system by having both the upper arm and forearm spinning freely, we decided to include a hard stop for just the forearm. In doing so the forearm would come to rest in a vertical position. This would reduce the vibrations induced by the forearm spinning around the upper arm. The second failure point we determined was the moment at the shoulder joint created by having a secondary motor at the elbow joint. In our initial design, we had a second motor generating the motion in the elbow joint. The motor needed to generate the motion of the elbow linkage would have been a significant weight. We came up with multiple solutions to work around this problem, including adding support that would roll a track below the linkages. However, the design we settled on was removing the motor entirely and using torsion springs as the form of actuation. This greatly reduced the weight, eliminating the need to add support. Due to the reduced time allotted in the machine and assembly room, we were unable to actually get our linkage operational. Therefore it is hard to assess how well our design changes reduced the risk factor, but we believe these changes would make a significant difference in the safety of our mechanism.

Verification

Due to our limited capabilities for in-person activities this semester, we had few options for verifying our physical prototype. Nevertheless, we were able to verify some of the requirements of our prototype through our CAD and ADAMS model, as well as testing linkage motion following the assembly of our prototype. Our verification stage ensures that our most important requirements and specifications are met.

Our CAD model and simulation helped us verify that our prototype is capable of exhibiting the throwing motion we desire. We mainly utilized simulation-based methods during our early solution development phase due to a lack of in-person resources this semester to create a preliminary prototype. An advantage to using simulation-based methods is their efficiency and calculation capabilities when experimenting with different design options, which would take much longer if we had solely relied on analytical or empirical methods. However, a limitation to simulation-based methods would be the absence of real-life obstacles that may hinder our mechanism performance, such as the absence of friction in joints in simplified simulation models. To overcome this limitation, we ensured a safety factor when selecting our components with respect to our requirements, such as the power of our motor. When designing our model, we revised our link mass and length specifications based on justifications made by Alexander[1] to maximize our linkage performance while staying within our budget. We ensured that our upper arm and forearm matches the requirement by analyzing measurements and material properties in our CAD design. After completing our CAD design, we were able to utilize Autodesk Inventor and Solidworks to simulate physical contact between our parts and ensure that there were no conflicting mates and each part interacts smoothly with respective joints. Our CAD analysis ultimately ensures that our mechanism mimics an overhead throwing motion as was modeled by Alexander [1] with rotation angles of the upper arm and forearm links reflecting our research findings of human pitchers. We also conducted an ADAMS simulation to ensure that our motor and torsion springs are able to provide sufficient torques, and as a result accelerations that allow for us to reach our downsized speeds for our upper arm and forearm to reach our target speeds, thus verifying that the kinematics specification of our linkage is achievable.

After assembling the main components of our physical prototype, we verified that our linkages move smoothly. We also observed that our rubber stop was able to quickly stop our forearm while absorbing the force that would be transferred to the upper arm, thus fulfilling the role of our stopping mechanism and increasing our confidence in its durability. However, we were unable to attach the motor to the linkage, and as a result, we are unable to determine if the entire linkage is durable enough to reach our specification while at full load. While we are aware that experimental testing of our built prototype would require further steps to yield more reliable results, we used our available resources to verify that the results we obtained from our calculations and simulations are reasonable. A more thorough testing process of our physical prototype can be found in the subsequent Discussion and Recommendations section.

Although we were unable to conduct further testing with our physical prototype due to time constraints and lack of in-person activities, we verified our prototype with available resources based on our main engineering requirements, namely the mechanism accurately representing a human arm, capable of mimicking an overhead throwing motion and having similar kinematics to a human pitcher. We also verified the performance of our critical subsystems, such as the stopping capability and durability of our stopping mechanism.

Through these methods, we were able to learn that our mechanism should be able to meet the requirements set forth by our sponsor. While it will not reach the original speeds or size that an actual pitcher would be able to reach, as we had hoped to reach in our specifications, we know that our model would work as a sized down model of an actual throwing arm.

Discussion and Recommendations

There are a few things that we feel like we could have improved in our design. We think that we should have gotten help from either our sponsor or our professor earlier on in the design process when we got stuck on our engineering analysis. Additionally, we could've divided work more effectively. For the most part, we all worked on the project together and we might have been able to get through more work if we broke different projects into subsections for each person to do.

Another thing that we would have done to improve our design is to reduce the length of the steel rod. Our design called for a three-foot steel rod when it actually could've been reduced by a foot. This would have decreased the amount of torque needed to rotate the linkage. Additionally, to improve the design we would've added pieces to the linkage to firmly secure the springs in place. While the linkage was in tension the spring would not move anywhere, however, when the linkage is at rest the springs move around too easily. By adding a set screw or some sort of locking mechanism for the springs it would've helped improve the quality of our final design.

We feel like our design has many strengths, such as it reaching the speeds in the forearm that our adjusted analysis had decided that we needed to reach. We also think that our linkage remains stable, and while we were unable to verify this, we have full confidence that our design would successfully be able to handle the durability specification. We also have a chain tensioning system, so that when the chain starts to stretch out, it will be easy to add more tension to the chain.

However, our design did not feature fine control of the system, a feature that likely would have been very useful in testing our design. A recommendation would be to add a control system, like an Arduino microcontroller, to the design to allow for better control of the system. This was originally a feature that we wanted to add to our original design, however, we were unable to accomplish this in our time frame. By adding in a control system, it would allow for the mechanism to have a set motion, and having a button or simple code to run to allow for more simplistic use of the design.

Another recommendation to improve our overall design would be to add a release mechanism for the forearm. We were in the beginning stages of designing a release mechanism when unforeseen machine shop closures prevented us from fully fleshing out this design. By adding a release mechanism, there would be more consistent arm actuation. Our initial design was to have some sort of set pin that would release the forearm as the upper arm began its motion. This would allow for both linkages to be set into their known starting positions and to more accurately know the torques in the forearm.

Lastly, our design did not account for actually being able to throw a baseball. We originally had intended to have our design to throw a ball, however, our sponsor had informed us that this was not as important as some other aspects that we wanted to achieve. As a result, our mechanism can not throw a ball. If desired, a mechanism that can grip and let go of a ball at a proper timing could be designed and attached to the end of the forearm. Given that it seemed of little importance in the entire project, it ended up not being designed.

Conclusion

In baseball, injuries occur at much higher rates in pitchers compared to all other position players. Current research regarding the forces and torques a human arm experience is all done through the use of motion capture. Some research indicates that motion capture may have large amounts of error. Our sponsor Dr. Cain proposes using IMUs instead of motion capture. In order to compare motion capture technology to IMU's, our sponsor wants to create a ground truth mechanism to attach both sensors too. Our problem was to design a simplified mechanism of an overhead throwing motion to accurately compare IMUs and motion capture. Through completing this project, we were able to create a physical model for the project. This model should allow for our sponsor to attach both IMU's and Motion Capture technology to our model, and should allow him to determine if his hypothesis regarding the differences between IMU's and Motion Capture is correct. The solution that we made has decent quality, however, we were unable to complete every aspect of the design that we wanted to. We are lacking certain aspects of the design, such as fine control of the motor through Arduino, as well as a release mechanism for the forearm's spring actuation design. However, our model does compare well to the design concept that our sponsor laid out for us, and if we had a little more time and budget, we feel as if we could've created a higher quality solution.

Authors

Ethan Baker is a senior studying Mechanical Engineering at the University of Michigan and will be graduating with his bachelor's degree in December of 2020. He grew up in Cadillac, Michigan, a small town in northern Michigan. Being surrounded by lakes and the outdoors, he loves exploring the wilderness. In his spare time, he lives an active life playing sports, mountaineering and competing in triathlons. He has always been curious about how things work and has a passion for problem-solving, which led him to pursue a degree in engineering. He hopes to pursue a career in the medical sector to help bring creative solutions to medical problems.

Noah Davis is a senior studying Mechanical Engineering at the University of Michigan and is graduating in April 2021 with a BSE in Mechanical Engineering. He grew up in Canton, Michigan. In his spare time, Noah likes to play sports like soccer, football, and baseball in addition to working with his hands, and to physically build, which is why he has a passion for Engineering. He has designed a small bridge and built a functioning go-kart. Noah has always had a passion for large machinery and hopes to find a career in the manufacturing sector.

Matthew Fowler is a senior studying Mechanical Engineering at the University of Michigan in Ann Arbor. He will graduate with a bachelor's degree in December 2020. He grew up in Jackson, Michigan, and still lives there today. In his spare time, Matt enjoys playing video games with friends, as well as playing tennis. Matt has always been a critical thinker and approached problem-solving from a logical and meticulous perspective. Matt is interested in working with renewable energy and other sustainable technologies to help meet the many challenges the engineering world faces today.

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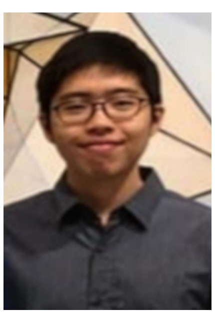

Steven Teguhlaksana is a senior studying Mechanical Engineering at the University of Michigan in Ann Arbor and is graduating in April 2021. He grew up in Indonesia. In his spare time, Steven enjoys playing video games, listening to and playing music, or reading an interesting book. Steven has always been an analytical thinker and likes to learn new things. Throughout his time at Michigan, he has gained valuable experiences in research and looks forward to more opportunities. Steven hopes to pursue a career in the manufacturing and/or robotics industry

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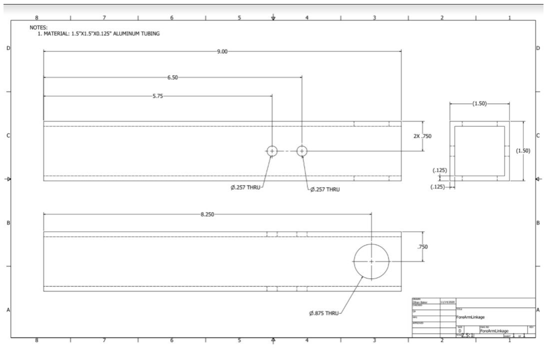
Appendix:

A.1 Bill of Materials

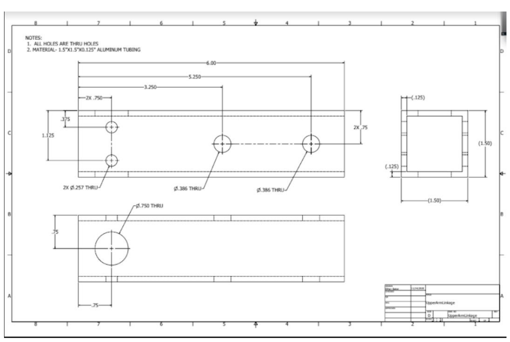
Name	Description	Price, $	Quantity	Total Price
Linkage connector-shaft	Dia- 1.25" 12" long	13.23	1	13.23
Linkages	1.5" x1.5" 2ft long	13.66	1	13.66
Flange Bushing	0.75" ID	2.21	2	4.42
Thrust Bearing	0.75" ID	1.51	2	3.02
Cotter Pin	0.125"	1.57	1	1.57
Torsion Spring	Left 270 Degree	6.89	1	6.89
Torsion Spring	Right 270 Degree	6.89	1	6.89
Steel Rod	0.75" OD 3ft long	11.35	1	11.35
2 Bolt Flange Bearing	0.75" ID	13.02	2	26.04
Sprocket	5/8" ID	13.77	1	13.77
Sprocket	3/4" ID	13.77	1	13.77
Angle Stock	1.5x1.5x 0.25	10.35	1	7.39
Cap Head Screw	1/4-20 3" long	0.89	2	1.78
Cap Head Screw	1/4-20 2.5" long	0.9	2	1.8
Lock Nut	1/4-20 Nut	2	4	8
Washers -1/4	1/4 Washers	0.15	8	1.2
Cap Head Screw	3/8" 2.5 long	0.89	4	3.56
Cap Head Screw	3/8" 2 long	0.87	2	1.74
Lock Nut	3/8"-16 Nut	0.75	6	4.5
Washers -3/8	3/8 Washers	0.15	12	1.8
Cap Head Screw	5/16 3" long	0.86	4	3.44
Washers	5/16 Washers	0.15	8	1.2
Anti-Turn Washer	Lock Washer	0.67	4	2.68
Chain	1/4" pitch	15.42	1	15.42
Motor	2hp	154.95	1	154.95
				Total
				324.07

A.2 Engineering Drawings and Manufacturing Plans



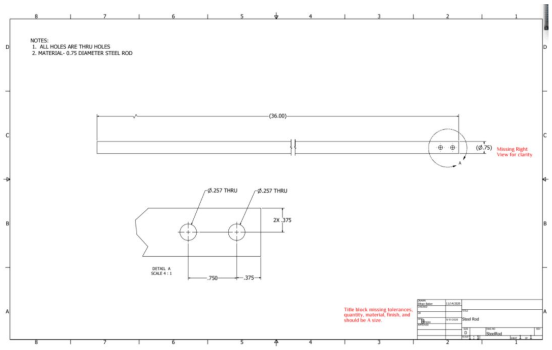
Manufacturing Plan - Forearm Linkage					
Part Number	2				
Part Title	Forearm Linkage				
	Team 9				
Raw Material Stock	Aluminum Tube - 1.5" x 1.5", 1/8" thick				
Step #	**Process Description**	**Machine**	**Fixture(s)**	**Tool(s)**	**Speed (RPM)**
1	Cut 9.125" of Stock	Horizontal Bandsaw	Vise		300
2	Clamp stock in mill on parallels so that the face just cut is exposed. Place a vise stop on the vise	Mill	Vise, vise stop, parallels		
3	Install drill chuck and edge finder	Mill	Vise, vise stop, parallels	drill chuck, edge finder	
4	Zero Y to the back face of the vice	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
5	Zero X to the left face of the part	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
6	Insert 3/4" end mill and collet into mill	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
7	Cut in .003" increments until cut to spec	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
8	Locate the position of one of the 0.257" holes	Mill	Vise, vise stop, parallels		
9	Drill a center hole for one of the 0.257" holes using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
10	Drill in the 0.257" hole using the F drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, F drill bit	1000
11	Repeat steps 8-10 for the other 0.257" hole	Mill	Vise, vise stop, parallels		
16	Flip the part so that the right face of the part is exposed. Align part to vise stop and reclamp part	Mill	Vise, vise stop, parallels		
17	Locate the position of the 0.875" hole	Mill	Vise, vise stop, parallels		
18	Drill a center hole for the 0.875" hole using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
19	Drill in the 0.875" hole using 7/8" drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, 7/8" drill bit	350
20	Remove part from vise, deburr holes			Deburring tool	

Figure A.2.1: Engineering Drawings and Manufacturing Plans for Forearm Link



Manufacturing Plan - Upper Arm Linkage					
Part Number	1				
Part Title	Upper Arm Linkage				
	Team 9				
Raw Material Stock	Aluminum Tube - 1.5" x 1.5", 1/8" thick				
Step #	**Process Description**	**Machine**	**Fixture(s)**	**Tool(s)**	**Speed (RPM)**
1	Cut 6.125" of Stock	Horizontal Bandsaw	Vise		300
2	Clamp stock in mill on parallels so that the face just cut is exposed. Place a vise stop on the vise	Mill	Vise, vise stop, parallels		
3	Install drill chuck and edge finder	Mill	Vise, vise stop, parallels	drill chuck, edge finder	
4	Zero Y to the back face of the vice	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
5	Zero X to the left face of the part	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
6	Insert 3/4" end mill and collet into mill	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
7	Cut in .003" increments until cut to spec	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
8	Locate the position of one of the 0.257" holes	Mill	Vise, vise stop, parallels		
9	Drill a center hole for one of the 0.257" holes using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
10	Drill in the 0.257" hole using the F drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, F drill bit	1000
11	Repeat steps 8-10 for the other 0.257" hole	Mill	Vise, vise stop, parallels		
12	Locate the position of one of the 0.386" holes	Mill	Vise, vise stop, parallels		
13	Drill a center hole for one of the 0.386" holes using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
14	Drill in the 0.386" hole using the W drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, W drill bit	600
15	Repeat steps 12-14 for the other 0.386" hole	Mill	Vise, vise stop, parallels		
16	Flip the part so that the right face of the part is exposed. Align part to vise stop and reclamp part	Mill	Vise, vise stop, parallels		
17	Locate the position of the 0.750" hole	Mill	Vise, vise stop, parallels		
18	Drill a center hole for the 0.750" hole using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
19	Drill in the 0.750" hole using 3/4" drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, 3/4" drill bit	350
20	Remove part from vise, deburr holes			Deburring tool	

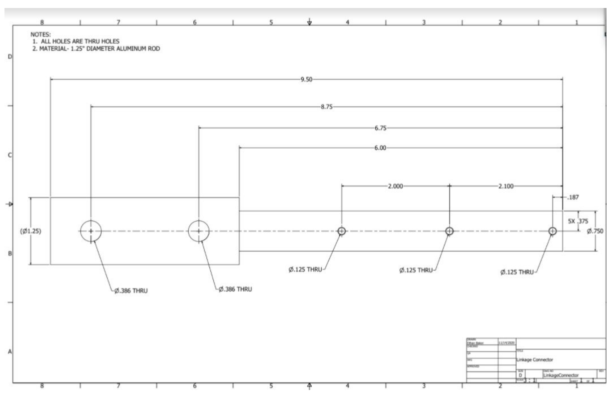
Figure A.2.2: Engineering Drawings and Manufacturing Plans for Upper Arm Link



Manufacturing Plan - Steel Rod					
Part Number	3				
Part Title	Steel Rod				
	Team 9				
Raw Material Stock	Steel Rod, 36" length, 0.75"D				
Step #	**Process Description**	**Machine**	**Fixture(s)**	**Tool(s)**	**Speed (RPM)**
1	Fasten the rod in the shaft fixture with end sticking out. Secure V-block in vise.	Mill	Shaft Fixture, Vise		
2	Use the edge finder to datum off the end of the rod (in x) and the side of the rod (in y)	Mill	Shaft Fixture, Vise	Edge Finder	1000
3	Locate the position of the hole closer to the end. Set the position as the new datum	Mill	Shaft Fixture, Vise		
4	Drill a center hole for one of the 0.257" holes using a center drill	Mill	Shaft Fixture, Vise	Center Drill	1200
5	Drill in the 0.257" hole using the F drill bit	Mill	Shaft Fixture, Vise	F Drill Bit	850
6	Repeat steps 4 & 5 for the other hole	Mill	Shaft Fixture, Vise		
7	Remove part, deburr holes	Mill	Shaft Fixture, Vise	Deburr Tool	

You should put in lathe, true up the ends and bring to length. Purchased stock will not likely be exactly 36" and have machined ends.

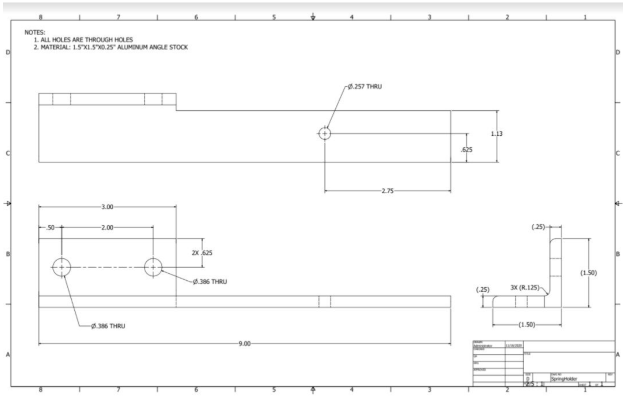
Figure A.2.3: Engineering Drawings and Manufacturing Plans for Steel Rod



Manufacturing Plan- Linkage Conncector					
Part Number:	4				
Part Title:	Linkage Connector				
Team Name:	Team 9				
Raw Material Stock:	1.25" Aluminum Rod				
Step #	***Process Description***	***Machine***	***Fixture(s)***	***Tool(s)***	***Speed (RPM)***
1	Cut 9.625" of Stock	Horizontal Bandsaw	Vise		300
2	Insert stock into collet and loosely insert collet into lathe	Lathe	Collet		
3	Secure Collet	Lathe	Collet		
4	Gently touch tool to face of part, zero DRO X	Lathe	Collet	Cutting Tool	750
5	Face part in .003" increments until entire face is cut	Lathe	Collet	Cutting Tool	750
6	Face the part 0.003" further as a finishing step	Lathe	Collet	Cutting Tool	750
7	Loosen collet, flip part, and retighten	Lathe	Collet		
8	Face part in .003" incrementsuntil entire face is cut	Lathe	Collet	Cutting Tool	750
9	Face the part 0.003" further as a finishing step	Lathe	Collet	Cutting Tool	750
10	Remove part from lathe, measure, and reinsert	Lathe	Collet	Caliper	
11	Rezero DR X	Lathe	Collet	Cutting Tool	750
12	Cut part down to size of 3/4" for a length of 6" based on drawing at 0.01" increments for every pass	Lathe	Collet	Cutting Tool	750
13	Measure with micrometer and repeat step 12	Lathe	Collet	Micrometer	
14	Cut part at 0.003" for finishing step	Lathe	Collet	Cutting Tool	750
15	Debur part and remove	Lathe	Collet	File	
16	Clamp stock in Vblock so that part is horizontal. Place Vblock in vise, and any other necessary fixtures	Mill	Vise, vise stop, parallels, Vblock		
17	Install drill chuck and edge finder	Mill	Vise, vise stop, parallels, Vblock	drill chuck, edge finder	

18	Zero Y to the back face of the vice and Zero X at end of 0.75" diameter side of part	Mill	Vise, vise stop, parallels, Vblock	drill chuck, edge finder	1000
19	Install center drill #1 and drill chuck	Mill	Vise, vise stop, parallels, Vblock	drill chuck, center drill #1	
20	Center drill the first 1/8" hole	Mill	Vise, vise stop, parallels, Vblock	drill chuck, center drill #1	1200
21	Install 1/8" drill bit and drill through	Mill	Vise, vise stop, parallels, Vblock	drill chuck, 1/8" drill bit	1600
22	Repeat steps 19-21 for the remaining 1/8" holes	Mill	Vise, vise stop, parallels, Vblock	drill chuck, #1/8" drill bit	
23	Install center drill #5 and drill chuck	Mill	Vise, vise stop, parallels, Vblock	drill chuck, center drill #5	
24	Center drill the first 0.386" hole	Mill	Vise, vise stop, parallels, Vblock	drill chuck, center drill #5	1000
25	Install W drill bit and drill through	Mill	Vise, vise stop, parallels, Vblock	drill chuck, W drill bit	600
26	Repeat steps 23-25 for the remaining 0.386" hole	Mill	Vise, vise stop, parallels, Vblock	drill chuck, W drill bit	
27	Remove part from mill, deburr			Debur Tool	

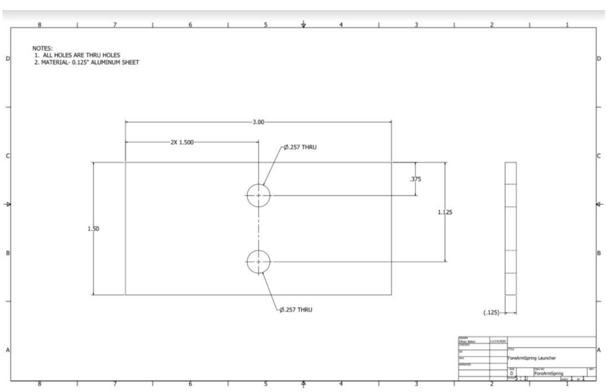
Figure A.2.4: Engineering Drawings and Manufacturing Plans for Linkage Connector



Manufacturing Plan - Spring Holder Linkage

Part Number	5				
Part Title	Spring Holder				
	Team 9				
Raw Material Stock	1/4" thick Aluminum Angle Stock				
Step #	**Process Description**	**Machine**	**Fixture(s)**	**Tool(s)**	**Speed (RPM)**
1	Cut 9.125" of Stock	Horizontal Bandsaw	Vise		300
2	Cut 5.875" off of edge with 1.125" left of flat area of angle stock and cut off top to completely detach piece according to drawing leaving 3.125"	Bandsaw	Vise		300
3	Clamp stock in mill on parallels so that the face just cut is exposed. Place a vise stop on the vise	Mill	Vise, vise stop, parallels		
4	Install drill chuck and edge finder	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
5	Zero Y to the back face of the vice	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
6	Zero X to the left face of the part	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
7	Insert 3/4" end mill and collet into mill	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
8	Cut in .003" increments until cut to spec	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
9	Locate the position of one of the 0.257" holes	Mill	Vise, vise stop, parallels		
10	Drill a center hole for one of the 0.257" holes using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
11	Drill in the 0.257" hole using the F drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, F drill bit	800
12	Flip part so smaller 3" edge is showing up	Mill	Vise, vise stop, parallels		
13	Insert 3/4" end mill and collet into mill	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
14	Touch end mill to top of 3" flat area to zero Z axis	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
15	Cut in .003" increments until cut to spec to have 3" edge piece completed and face 0.375" downward to get 1.125" edge part with 0.003" passes	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
16	Drill a center hole for one of the 0.386" holes using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
17	Drill in the 0.386" hole using the W drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, W drill bit	600
18	Repeat steps 15-16 for other hole	Mill	Vise, vise stop, parallels	Drill Chuck, W drill bit	600
19	Remove part from vise, deburr holes			Deburring tool	

Figure A.2.5: Engineering Drawings and Manufacturing Plans for Spring Holder



Manufacturing Plan - Forearm Spring

Part Number	6				
Part Title	Forearm Spring				
	Team 9				
Raw Material Stock	0.25" Aluminum Angle Stock	Note: Use excess piece from Spring Holder			
Step #	**Process Description**	**Machine**	**Fixture(s)**	**Tool(s)**	**Speed (RPM)**
1	Cut 3.125" of stock	Horizontal Bandsaw	Vise		300
2	Install drill chuck and edge finder	Mill	Vise, vise stop, parallels	drill chuck, edge finder	
3	Zero Y to the back face of the vice	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
4	Zero X to the left face of the part	Mill	Vise, vise stop, parallels	drill chuck, edge finder	1000
5	Insert 3/4" end mill and collet into mill	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
6	Cut in .003" increments until cut to spec	Mill	Vise, vise stop, parallels	Collet, 3/4" End Mill	500
7	Locate the position of one of the 0.257" holes	Mill	Vise, vise stop, parallels		
8	Drill a center hole for one of the 0.257" holes using a center drill	Mill	Vise, vise stop, parallels	Drill Chuck, Center Drill	1200
9	Drill in the 0.257" hole using the F drill bit	Mill	Vise, vise stop, parallels	Drill Chuck, F drill bit	1000
10	Repeat steps 8-10 for the other 0.257" hole	Mill	Vise, vise stop, parallels		
11	Remove part from vise, deburr holes			Deburring tool	

Figure A.2.6: Engineering Drawings and Manufacturing Plans for Forearm Spring Holder

Supplemental Appendix

Engineering Standards

We did not use any engineering standards in our design. Our project focus was very narrow in an otherwise broad field. Our sponsor had mentioned that no one had really attempted to make something of this sort, so we did not have any real standards to work off of. As a result, we had to work to make sure that our project lived up to its own standards, without having something to base it off of.

Engineering Inclusivity

The project is inclusive of overhanded pitchers. This project would not help with softball pitchers, who primarily use underhanded pitching techniques. This would also not include baseball pitchers who use an underhand or sidearm method of throwing. This is because most of the pitchers in professional baseball, the topic that our sponsor wishes to study further, pitch overhanded. They possess an invisible power by being a part of the majority, which usually leads to more studies being conducted on overhand pitchers. It is possible that we could have adjusted our design to be able to use many different methods of throwing a pitch, such as underhand or sidearm, however, our sponsor requested one with an overhand throwing motion, as that was what he wanted to study. As a result, we did not practice inclusive design and only made an overhand throwing model.

Environmental Context Analysis

We feel as if our project makes a small step in a contribution limiting injuries in baseball. Through our model, it should allow for better measurement of the position of a human in motion. Through this, speeds and accelerations can be determined resulting in a better understanding. In addition, we do not think that there is potential for our system to have undesirable consequences. If our sponsor's hypothesis is incorrect, our design should not have an effect on the measurements between the 2 methods.

Social Context Assessment

This design is not likely to be adopted nor self-sustaining in the market. It is a very specific design for a specific use that is not something the general public would often want to use. As a result, the planetary and societal systems would likely remain unaffected by our design. As a result, our design solution would be resilient in changes to business as usual as the general business would be unaffected by our design.

Ethical Decision Making

We also focused on making ethical decisions when tasked to do so. We wanted to focus on making sure our calculations were correct to make sure we had proper numbers. After we made our calculations, we found a glaring disparity between the calculated numbers and our modeled numbers as found through our ADAMS model. We were on a tight deadline with an important design review coming up, but instead of trying to fake our numbers, we set up a meeting with Dr. Cain to make sure we understood all the forces and their values and effects on the system, and we were able to pull through finding values that were very close to the values found through our ADAMS model.