Humanoid Hand

Initial Design Report Template

Noah Enlow, Project Manager

Tyler LeBeau, Logistics Manager

Joseph Maresh, CAD Engineer

David Lutz, Manufacturing Engineer

Justin Alonzo, Finacial Manager

Markus Steinebrunner, Test Engineer

Spring 2025-Fall 2025

Project Sponsors: Dr. Zach Lerner, Dr. Reza Razavian

Subject Matter Experts: Daniel Colley, Landon Coonrod

Instructor: Carson Pete

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

The goal of this project is to design a highly dexterous robotic hand which will serve as a testbed for two of NAU's research labs to dip their toes into the field of prosthetics. The sponsors of this project are Dr. Zach Lerner and Dr. Reza Razavian. The sponsors have set forth two major goals for the hand: 1) to be able to play a tune on the piano and 2) to be able to catch a ball. These requirements set forth a high bar for speed, strength, and dexterity.

The major project deliverables are the team's first and second prototype demos due on March 31st and April 28th respectively as well as the full hand prototype due on April 31st. The first prototype will be a 3D printed finger design, displaying functional tendon actuation and angle sensing in the joints. The second prototype will be a 3D printed thumb design, also displaying tendon actuation and angle sensing. The success metrics for the final design, and toward which these prototypes will be aiming are as follows. The fingers will need to be capable of exerting 1 N of force at the tip of the finger and will need to have the full or near-full range of motion of the biological hand in order to be able to play the piano. Moreover, the motors will need to be capable of between 100-300 RPM in order to meet the catching requirement.

The overall design of the hand is still largely undetermined. The work of the team so far has been directed toward establishing a solid finger design and thinking about what actuation style will be used and how. At this point, the established design consists of what follows.

Fingers will be primarily tendon driven with servos at the base of the fingers to facilitate splaying the fingers. The thumb will likely be similar, using tendons to flex and extend the thumb and two servos enabling the thumb's more complex motion. The fingers will have four tendon attachment points. One on the top side of the first and second segment of the finger each, and similarly for the bottom (palmar side) of the finger. The third segment of the finger will be mechanically linked to the motion of the second joint to cut down on how many motors are needed. There will likely be fourteen motors. Eight of them will reside in the forearm, driving the tendons. The other six will be in the hand, controlling the splaying of the fingers and the motion of the base joint of the thumb. The motors in the forearm will be BLDC motors, chosen for their speed and torque. The motors in the hand will be servos, chosen for their smaller size. Lastly, each finger will likely house 2 angle sensors. One at the base joint and one at the second joint of the finger. The angle sensors will be there to ensure accuracy and repeatability of motion. Because the last segment of the finger will be mechanically linked to the second segment of the finger, its angular position can be inferred, avoiding the need for a third angle sensor in the finger.

The results from our literature review and mathematical modelling indicate that motors will need to be wisely chosen, joints will need to be well-made, and the control scheme will need to be well-programmed. The hand is a complex machine and it is no simple task to adequately mimic its capabilities. The mathematical modelling section of this document goes into more detail regarding these requirements.

TABLE OF CONTENTS

Contents

1 BACKGROUND

This project involves creating a highly proficient robotic humanoid hand, which spans multiple fields such as biomechanics, robotics, control systems, and advanced manufacturing. Although the team had a strong background in mechanical engineering, areas like tendon-driven actuation, integration of sensors for the prediction of finger location, and high-speed dexterous motion were new areas of exploration. These subjects require focused research to inform design choices so that demanding applications, such as playing the piano or catching a ball, are possible based on the use cases defined by our sponsors. This section describes the technical context and knowledge gaps that influenced early project development.

1.1 Project Description

The goal of this project is to design a highly capable robotic hand that mimics and even matches the capabilities of the human hand. The two main goals for the hand set forth by the sponsors, Dr. Zach Lerner and Dr. Reza Razavian, are to 1) be able to play a tune on the piano and 2) be able to catch a ball. To accomplish these goals, it is clear that the hand will need to meet stringent requirements as it relates to both strength and speed.

This project has the potential to be quite valuable. The hand will be going to the research labs of the sponsors to serve as a testbed for entering into the field of prosthetics. As such, this project is in a position to have a sizeable positive impact, bolstering the capabilities of two of NAU's research labs.

The budget for this project comes to a total of $2,000. $1,500 comes from our sponsors and the other $500 was obtained through fundraising for the project. As it stands the project currently sits well within the budget. Current expected expenses come to about $900, though this will most certainly rise. The $900 factors in our largest expenses, such as motors, microcontrollers, and high-end 3D printing filament.

1.2 Deliverables

In this course, there are a lot of deliverables and deadlines to meet. Below is a table of some of the more important deliverables for this project given to us by the course instructor and our sponsor. The deliverables that were given by our sponsors were somewhat set by us in terms of the deadline as we believe the deadlines are easy enough to reach and hopefully be able to accomplish it in time.

Table 1: Major deliverables

Deliverable	**Given by**	**Deadline**
Joint Prototype	Sponsors	3/31/25
Finger Prototype	Sponsors	3/31/25
1st Prototype Demo	Instructor	3/31/25
Final CAD and Final BOM	Instructor	4/25/25
2nd Prototype Demo	Instructor	4/28/25
Whole Hand Prototype	Sponsor	4/31/25

1.3 Success Metrics

As mentioned previously, the two major success metrics for the hand are 1) to be able to play a tune on the piano and 2) to be able to catch a ball. These goals place high expectations upon the hand. Because of these high expectations, the success metrics for the hand need to be well established.

Being able to play the piano will necessitate that the fingers of the hand will need to be able to exert between 0.5N of downward force to 1N of downward force on the higher end [49]. Our goal will be 1N of downward force for each finger in the hope that even if we fall short of that goal, we still meet our base requirements. Moreover, the fingers will need to be agile and have the full (or nearly full) range of motion that the biological hand has.

Catching a ball presents a broader challenge. How fast will the ball be thrown? How large will it be? To narrow our constraints, we will say that the ball will be the size of a tennis ball (about 66mm in diameter [50]). Regarding the speed of the ball, calculations were done to determine the necessary reaction time of the hand. From these calculations which can be found in the mathematical modelling section of this report, the motors driving the tendons in the fingers will need to be able to spin between 100 [Equation 1] and 300 RPM [Equation 2].

The two requirements specified by our sponsors set high ambitions for our project and, though initially the requirements might seem nebulous, they have had the benefit of forcing the team to think in-depth about what the hand needs to do and how it will do it.

To assess the performance of the final product, the team will have the hand attempt to play a simple one-handed tune on the piano and catch a ball tossed underhanded. These two tests will be the defining factor as to whether the hand meets the requirements set forth by the sponsors.

2 REQUIREMENTS

This section describes the project's specific requirements, interpreting the expectations of sponsors and research findings to make them actionable requirements. It is critical to establish these constraints early, as they have a direct impact on essential elements of design; how big a user's hands must be, how much power is consumed, how fast an actuator is, and what material to use. Customer requirements capture high-level functional requirements, and engineering requirements define those requirements as measurable design targets. The House of Quality (HoQ) shows how these technical requirements map back to user expectations and system priorities.

2.1 Customer Requirements (CRs)

The responsibility for developing the primary customer needs was undertaken in conjunction with project sponsors Dr. Zach Lerner and Dr. Reza Razavian. The ideal robotic hand should be similar to a human hand in terms of dexterity, strength, and responsiveness while being functionally practical for research.

1. Biomimetic Dexterity – The robotic hand should be able to perform various complex manipulations, such as playing a song on the piano and catching a ball.
2. Human-like Size and Weight – To ensure realism and usability, the hand needs to mimic the size and weight of a human hand.
3. Adequate Strength – The hand must be capable of exerting a grip force slightly less than what the average person is capable of to effectively perform manipulation tasks.
4. Response Time – The actuation time from fully open to fully closed should closely resemble human reaction time enabling dynamic interactions such as catching a moving object.
5. Longevity – The design should support at least 10,000 actuation cycles per joint to ensure long-term operational use.
6. Ease of Use – The hand should be operable by researchers with minimal learning effort, featuring an intuitive user interface that requires no more than a 10-minute demonstration.
7. Cost Effectiveness – The total manufacturing cost should not exceed $1,500, despite having a combined project budget of $2,000, while maintaining high-quality materials.
8. Power Efficiency – The hand should function efficiently within standard electrical power limits (approximately 120V AC or 24V DC input).

2.2 Engineering Requirements (ERs)

The engineering requirements define the measurable technical specifications required to meet the customer requirements. These constraints ensure the robotic hand meets performance, reliability, and usability standards.

Table 2: Engineering Requirements

Requirement	Target Value	Units	Tolerance	Justification
Grip Force	25-40	kg	±5	Matches human

				grip strength
Actuation Time	150-300	ms	±50	Ensures responsive movement
Hand Size	190x85	mm	±50x25	Comparable to human hand
Weight	2.5-3	kg	±0.5	Lightweight for usability
Degrees of Freedom	~20	#	±1	Maintains human-like dexterity
Actuation Cycles	10,000+	#	±250	Ensures durability
Cost of Manufacturing	<1,500	$	±250	Maintains budget constraints
Power Consumption	~120	V	0	Compatible with standard power
Precision and Accuracy	1	mm	±0.5	Maintains accurate motion control
User Interface Time	<10	min	±2	Easy setup and usability

2.3 House of Quality (HoQ)

The House of Quality (HoQ) matrix maps the relationship between customer requirements and engineering specifications, ensuring that all customer needs are translated into measurable technical parameters.

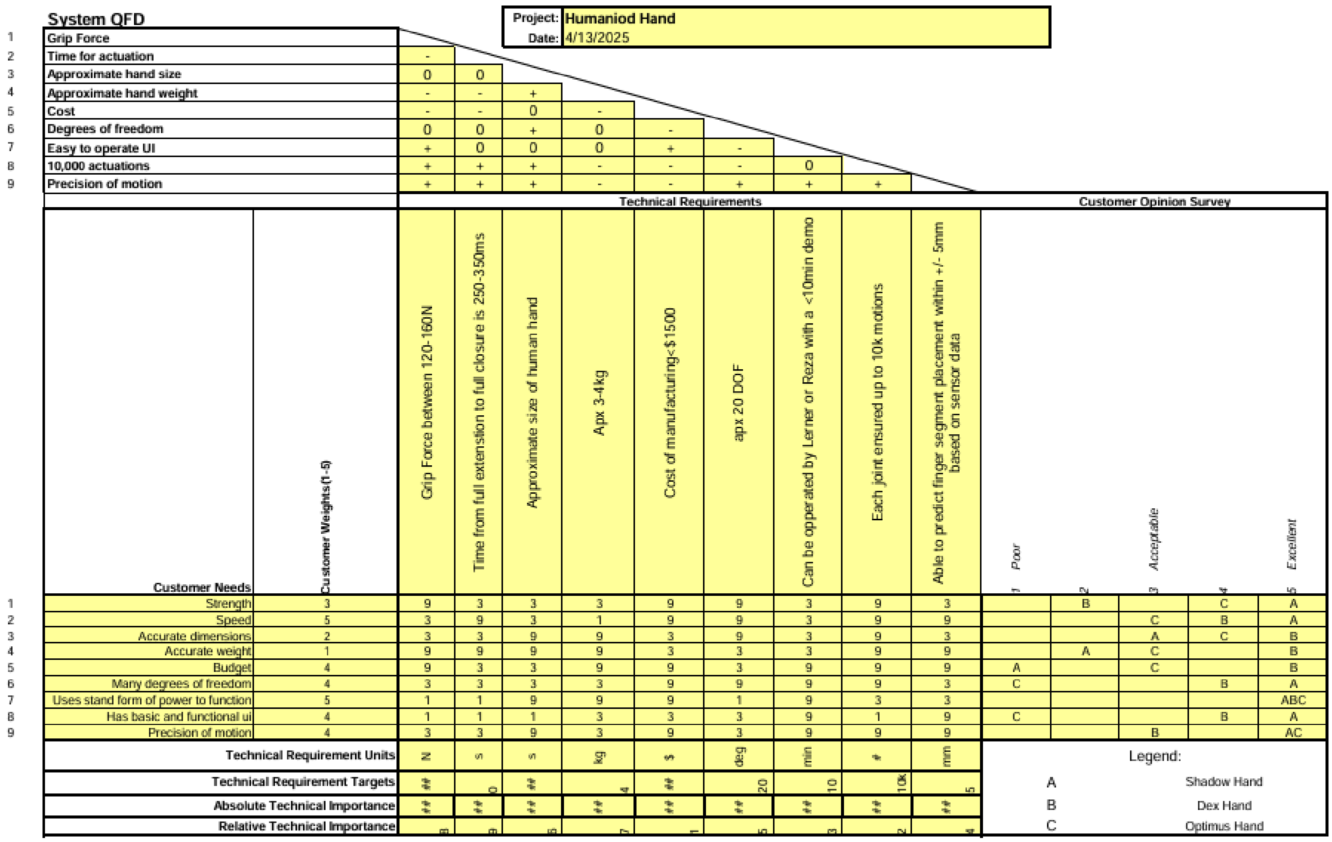


Figure 1: House of Quality

The HoQ matrix assesses how different requirements interact, helping to balance trade-offs while aligning performance metrics with project objectives. The most critical engineering factors for performance are grip force, actuation time, and degrees of freedom, as they directly impact the robotic hand's dexterity and usability. For design, the most important requirements are staying under budget, repeatability, and speed while sacrificing strength and compact size.

This requirements section serves as a structured framework to guide the design, development, and validation of the humanoid robotic hand.

3 Research Within Your Design Space

3.1 Benchmarking

To establish a benchmark for robotic hand design, three different robotic hands were assessed. The first of these hands is the Shadow Hand. The Shadow Hand, made by Shadow Robot is a highly accurate, durable, and capable robotic hand that demonstrates the state-of-the-art in the field. This hand has 24 degrees of freedom, over 100 sensors, and is capable of tactile sensing [56]. Next, the DexHand [57] is an open-source dexterous robotic hand. This hand, while still being quite technically capable, boasts an open-source and affordable design. This hand has the potential to serve as an excellent reference for the team in designing our hand, as its construction closely resembles the methods that the team will use for our hand due to budget and resource constraints. Lastly, another hand used for benchmarking was the hand of Tesla's Optimus robot. This hand boasts 22 degrees of freedom while only using 6 motors [58], demonstrating a high degree of under actuation. This hand, like the Shadow Hand, demonstrates tactile sensing, enabling delicate handling of objects.

The hands discussed set the stage for highly dexterous, capable hands. The expected outcome of this project is to create a hand that comes as close as possible to matching and, where possible, exceeding the capabilities of the hands just mentioned.

Concerning the subsystem level, several sources serve as good reference for the team's hand design. The DexHand above serves as an excellent resource for subsystem design, due to its open-source nature. Notably, the tendon-routing method and joint design may be a good reference for the team regarding those particular subsystems. Another good reference for subsystem design is Will Cogley's robotic hand design [59]. This is another open-source, affordable design. Because of its open-source nature, this hand will also serve as an excellent reference for subsytem design, particularly regarding thumb design and tendon actuation style. It has a unique design for the base joint of the thumb and may therefore be quite informative for what does and does not work for our thumb design. Moreover, this hand also has a unique pulley-style tendon actuation method, which our sponsors have shown interest in.

Together, the two above sources give ample material for inspiration and reference for our own hand design. This is the result of their open-source nature, and speaks to the importance and benefit of open-source projects. Without such resources, our project would be far more difficult and the outcome would likely be far less impressive, as we are able to learn from the successes and pitfalls of designs that others have already put ample time into.

3.2 Literature Review

3.2.1 Joseph:

1. Arduino Robotics:

   This textbook explains the application of an Arduino unit to general robotics. The book covers application starting from the basics, such as physical form and terminology, to circuitry and programming. These aspects are useful to the development of the software subsystem, as an Arduino will be necessary to design an API because of its speed and C++ compatibility. Specific examples of useful topics include the calculation of voltage, current, and resistance, how to build a PCB, and how to make simple relays.

2. Theory of Applied Robotics: Kinematics, Dynamics, and Control (3rd Edition)

   The utilization of this textbook will be highly advantageous to the team, as the book includes extensive examples and theory for the calculation and mechanical design of relevant robotic assemblies; most notably 3R planar manipulator systems, as well as error calculation and correction. These topics will aid in the development of the API subsystem as well as top-level systems, including applied forces, joint torques, forward and inverse kinematics, and position, velocity, and acceleration vectors. to calculate forces, torques, position, velocity, and acceleration vectors for varying 3R planar manipulator systems.

3. Modern Robotics: Mechanics, Planning, and Control

   The topics covered in this book are very similar to those in the previous resource. The book features chapters which explain rigid body and robotic degrees of freedom, kinematics, dynamics, link trajectory, and control methods. Every topic covered in Modern Robotics will be useful in the development of multiple top-level subsystems, most notably mechanics and software.

4. Robust Feedback Control Design of Underactuated Robotic Hands with Selectively Lockable Switches for Amputees

   This journal explains a study done on the accuracy, reliability, and practicality of underactuated robotic hands with a prosthetics application. The goal of the journal was to design a prosthetic hand as low-cost as possible. This benefits the team by offering insight to low-budget materials that the robotic hand can be made with. This resource applies to top level subsystems and directly applies to the project in the context of prosthetics, which is the intended use for our sponsors.

5. Modern C++ as a Modeling Language for Automated Driving and Human-Robot Collaboration

   This journal explains the use and method of C++ to program automated driving. This is beneficial because of the listed application in the journal which demonstrates a signal flow and how C++ handles automated actions. Used for learning how to use C++ to program the robotic hand with human inputs. The journal features state-space and Discrete-Time PID controller calculations, as well as how they are each modeled in C++. These topics apply to most top-level systems.

6. Packt Publishing: Hands On Robotics Programming with Cpp

   This book is a resource that contains information regarding setting up a Raspberry Pi to interface with a robot. Valuable information within the book includes a chapter on how to configure C++ to run a motor and a chapter on controlling using a laptop and Raspberry Pi interface. This applies solely to the API subsystem of the robotic hand but provides much information about the method to utilize a Raspberry Pi for a project such as this.

7. Raspberry Pi Settings for Robotics

   This resource is an open-source program setting site that has instructions with an attached video to set up a Raspberry Pi for any robotics project. This will provide information required to take a crucial step in the development of the robotic hand's API, as the Raspberry Pi will need to interface with both the Arduino and a laptop.

8. Robotic Anticipation Learning System for Ball Catching

   This journal details a study done on the reaction speed and learning of robots in the test of catching a ball. The journal describes the planned path a projectile taken between a human thrower and robot catcher. Data collection is used to generate a code that allows the robot to learn and anticipate the ball and catch it successfully using projectile motion equations. This information will prove useful in meeting the design challenge of catching a ball. The application falls mostly under the software subsystem, as the projectile motion equations can be coded in C++ for the robotic hand to catch a ball and provide a close estimate for its reaction time.

9. 2023 Arduino Tutorial for Beginners

This internet video course is a comprehensive lesson on the set-up and operation of Arduino hardware and software. Specifically, the lesson videos cover the software used in the Arduino IDE, programming syntax, electrical components, and circuitry. The application of this literature can be used towards the development of the API system, as the Raspberry Pi unit will need to communicate with one Arduino Teensy unit at a minimum.

10. Arduino – Bidirectional Serial Communication with Raspberry Pi

Similarly to the previous Arduino tutorial, the video tutorial details a serial connection between an Arduino and a Raspberry Pi. Each unit features its own code to communicate with the other unit to interpret readings of a temperature sensor by turning a set of LEDs on a breadboard either red or blue. This information can be applied to the software aspect of the project by connecting the Raspberry Pi and Arduino to a breadboard and writing code to control the motors that actuate the hand.

11. Forward and Reverse Kinematics for 3R Planar Manipulator

This journal details how forward and reverse kinematics can be modeled in MATLAB. The journal examples two scripts: one for forward kinematics and another for reverse kinematics. Each program takes an input to display a plotted diagram of the three links at the given distances and angles. This journal is used for validation that the finger behaves as planned, It also provides a ground for the code for the software subteam to incorporate into the control software, as the kinematic equations can be iteratively solved to calculate positional information over time.

3.2.2 Noah:

1. The C++ Programming Language [49]:

This book, written by the creator of the C++ programming language, covers the core concepts of C++. It will serve as an excellent guide in learning C++ for the programming of the hand.

2. Practical Robotics in C++ [50]:

This book is tailored to programming robotics in C++. The book gives practical examples and detailed walkthroughs for the reader. This book will also serve to inform the programming of the hand.

3. A Review of Robot Learning for Manipulation [51]:

This journal article covers the current state of machine learning as it applies to robots tasked with manipulating objects in their environment. This article will serve as a resource to refer to in considering the integration of machine learning into the hand.

4. On Dexterity and Dexterous Manipulation [52]:

This journal article outlines some of the essential postures and mechanics of robotic hands as it relates to grasping objects. This informs the joint design and actuation style of the hand. These subsystems are critical to the hand's performance.

5. Postural Hand Synergies for Tool Use [53]:

   This article is yet another source on the mechanics of robotic hands. This one, however, relates more specifically to dynamic tool use. This source provides further information on joint design and actuation style, particularly as it relates to the possibility of tool use with the hand.

6. Robotnanohand.com [54]:

   This website is dedicated to an open-source robotic hand project. It will serve as a good reference in overall hand design and construction. Both the benefits and pitfalls of their design, particularly their actuation method, will be assessed and will inform our design.

7. Control-toolbox [55]:

   This website is a GitHub repository for useful premade functions for robotics programming, written in C++. This resource will serve as reference for functions written in our code.

8. A Low-cost and Modular, 20-DOF Anthropomorphic Robotic Hand: Design, Actuation and Modeling [60]:

   This journal article outlines a low-cost cable driven robotic hand. This hand has 20DoF, similar to our goal. This journal article will serve to inform our actuation method. Their cable driven system will be analyzed for its pros and cons and thereby inform our design.

9. Integrated Linkage-Driven Dexterous Anthropomorphic Robotic Hand [61]:

   This article displays a primarily linkage-driven robotic hand and will serve to inform us of the benefits of a linkage-driven hand. While our design will be primarily tendon-driven, we may choose to incorporate linkages to couple motions within the fingers, thereby simplifiying our control and cutting down on how many motors we need to use. This in mind, this source will serve as reference as we consider such an approach.

10. Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration [62]:

    This article outlines a highly biomimetic robotic hand design. While we will not be pursuing this level of biomemesis, the design in this article will serve to highlight the areas in which biomimicry may serve to benefit the hand, particularly as it relates to the tendon-routing and tendon attachment points.

3.2.3 Tyler:

1. Kinematic Modelling of the Human Hand for Robotics [1]
   This book covers how human hands measurements can be measured, how kinematic structures can be modelled, and how kinematic structures of the hand affect the functionality. Kinematics is important for this project because we are using a lot of moving parts, and we need to know how

the human hand moves to make our robot copy those movements.

2. Human Hand Function [2]
   This book covers anatomy of the hand, along with things like how the hand functions across a lifespan, tactile sensing, and the neurophysiology of hand function. This will help the overall look of the hand. We want to see where the different joints and pieces of the hand are so we can replicate the look of the hand. Using the neurophysiology of the hand we can make the hand smart and sense the slight movement or feel of it reacting with objects and try to change angles and force based on this.

3. Functional anatomy and biomechanical concepts in the hand [3]
   In this article, the author goes over the main components and structure of the hand. This includes the neural anatomy of a hand, how the hand acts when gripping or closing your hand in a specific way, and the muscles involved in carrying weight in the hand. This will help us understand what parts of the hand react to what functions. What parts of the hand do we use to catch a ball or play a piano.

4. Biomechanics of the Human hand [4]
   This is a paper that provides information on a hand's anatomical structure with the location of the joints and the types of movement. It also shows different kinematic models that help explain the biomechanics of the hand. This will help with creating the skeleton of our hand. Using this paper, we will be able to change our design to be atomically accurate.

5. Biomechanics of the hand [5]
   In this article, the author covers topics including: the types of grasps, the joints in the hand, the mechanism of finger flexion, and how finger extension works. This will help with our tendon routing to see where we should attach our tendons to make extension and finger flexion work the best.

6. Design and Control of Robotic Hands [6]
   This book covers a lot of topics and different types of hands. The author goes over the classification of robotic hands, as well as things like the robotic grasp and manipulation of the hand, a design of a UB hand IV, and designing an underwater multi finger gripper. We can use this to compare to our prototype and make changes wherever needed. We can also see if these are needed for our project by bringing up these different upgrades to the hand and make any changes our client may want to add.

7. Tactile SoftHand-A: 3D-Printed, Tactile, Highly underactuated, Anthropomorphic Robot Hand with an Antagonistic Tendon Mechanism [7]
   On this website, there is information about a tendon driven multi fingered robotic hand. This includes information on a 3D printed hand and how it works and also the information behind making this model. We can use project as a reference for our entire project. Looking at this reference will allow us to see a working model and troubleshoot with their design.
8. What is a robot wrist and why does it matter in automation? [66]
   This website covers different actuation methods for a wrist on a robot hand. It also goes over different roles a proper wrist would play in our project. Using this website, we can plan how we will actuate our wrist and try to find out which way of actuation would be the best for our project.
9. Gear Ratios [67]
   This website goes over very simply how gears work and how the gear ratio will affect our speed, torque and any other criteria. We plan to use gears to actuate our wrist, and we want to see what

gear ratio would be best for our project.

10. Design of a Movable Palm for a 3-Fingers Robotic Hand [68]
    This report goes over the way this team designed their palm for their hand. This palm is designed to move when the fingers move. I used this document to better understand how we should make the palm of our hand. Using this I can see how they make it move and will help us consider whether or not if it is worth actuating.

3.2.4 David:

1. Design and control of robotic hands[23]
   This article was a paper that was the creation in full detail of a robotic hand that is tendon driven and has all of their technology including angle sensors and all of the listed equations that they used the we can draw inspiration from. Design choices that they made can be utilized as a reference for tendon placement as well as joint actuation.

2. Mechanical design of a biologically inspired prosthetic hand, The Touch hand 3 [24]
   This article is a project for a Master's program that is very similar to the project that we are doing right not. It has all of the kinematics and calculations from their research as well as their inspirations that they took so it will give information about a servo driven hand.

3. Put-hand-hybrid industrial and Biomimetic Gripper for Elastic Object Manipulation [25]
   This is also a robotic hand project that has different parameters and capabilities. These people went for a half tendon driven half servo driven hand that is hybrid so it can have two or three stronger fingers and two more dexterous fingers. The more dexterous fingers will be an inspiration for our designs especially tendon actuation and routing

4. Performance optimizing of pneumatic soft robotic hands using wave-shaped contour actuator [26]
   This article was about a potential finger choice, pneumatic finger actuation which would be better at fluid movement but also would make it hard for angle sensing. The pneumatic fingers are a complex geometry that doesn't have joints where an angle sensor could be placed in order to make inferences about where the finger is in space. There is also no three link kinematics that can be done to make inferences on how the finger will behave

5. *Robot Arm Kinematics*, vol. 146 [27]
   This is a book that details the kinematics of an entire robotic arm that includes the hand and finger actuation that we need in order to get proper calculations. Referencing this book will make for much easier and more accurate kinematic analysis that will be essential in the programming of the fingers motors. If we have improper kinematic analysis there will be massive uncertainty in finger position.

6. Simply Grasping Simple Shapes[28]
   This is a book that is about the coding aspect of a robotic or humanoid hand and what inputs are essential in a smooth and efficient code for running a hand. There will be a massive emphasis on the coding of the hand and if it is done improperly the project is a failure. This reference will make coding much easier because of the tips and tricks that have been compiled and mistakes that have been made so that we don't have to go through the same process of failure.

7. Highly responsive robotic prosthetic hand control considering electrodynamic delay [29]
   This is an article about a robotic hand interface that could make the hand used as a prosthetic and

goes into the ways they would send electrical impulses to the hand to make it move. It can be useful for the furute of the project down the line when interfacing with the machine is the main challenge for the project. It will also be helpful for future projects that are more focused on prosthetics.

8. Design and control of a tendon-driven robotic finger based on grasping task analysis[44]
   This is an article that goes into detail about how to actuate a pulley driven three like finger design. It will be essential in making adjustments to our current underpowered pulley design as well as finding proper ways to test the strength and validity of our pulley design. The finger featured is thicker than the one we hope to design so many adjustments need to be made.
9. Tendon Optimization for Robotic Hand [45]
   Tendon choice and analysis is an essential part of the design process and optimization of the design. Choosing the correct material and placement of the materials is very important when making sure that our design is going to be able to be strong and durable. This article highlights proper ways to make sure that tendon material and routing is done in the best way possible.
10. Anthropomorphic tendon-based hands controlled by agonist–antagonist corticospinal neural network,[46]
    This reference is an additional project of a 4-finger hand design. This one utilizes a tendon driven system but also goes into depth about thumb design and gives a new perspective of how to design fingers and thumbs as well as our three-link kinematic analysis. Not only this but the utilization of gears for actuation of joints will be important in linking out fingertips mechanically. Also, the programming of their finger will be important for our research.

3.2.5 Justin:

1. Servos Explained [8]
   This article includes quick summaries of how to power, control and use servos. It contains pictures to show the internal of servos and provides a guide video on servos. There are sub-micro and micro-sized servos, both standard and continuous rotation, as well as high-torque options. Each servo features a standard 3 pin connector for power and control, making it compatible with Arduino which is what we may use.

2. **Integrated linkage-driven dexterous anthropomorphic robotic hand [9]**
   This article talks about the anatomy of the hand, going in depth on things like the different tendons and joints in the finger, explaining how they work. Throughout the article they provide the application of this anatomy by showing their robotic hand design which utilizes a linkage-driven mechanism. Thier hand achieves 15 degrees of freedom across 20 joints, making a fingertip force of 34N while weighing only 1.1 kg.

3. Design of Tendon-Driven Robotic Fingers: Modeling and Control Issues [10]
   This is another article which goes in depth on the anatomy of the hand, showing things ranges of motion and time to move the hand. The authors analyze different configurations to optimize the dexterity and range of motion. This research provides valuable insights for developing advanced robotic systems.

4. Programming Fundamentals- A Modular Structured Approach using C++ [11]
   This book talks about all the things needed to start learning C++ and guides you through it in an organized way that makes it easier to digest. It covers topics like data types, control

structures, functions, arrays, pointers, and object-oriented programming. The book also includes practical exercises and examples to reinforce learning.

5. Fundamentals of C++ Programming [12]
   This is another book which teaches you how to learn C++. It breaks it down into chapters and explains multiple different techniques that are useful in C++. The book covers essential topics such as variables, data types, expressions, and control structures, providing clear explanations and examples.

6. Advanced Humanoid Robotic Hand Technologies [13]
   This website is made by Nasa, and it talks about what kinds of things go into one of their R2 robotic hand. It lists all the parts in the hand and discuses some of the benefits and applications of the hand. NASA's robotic hand tech mimics human movement using a tendon-driven system similar to our team. It uses smart sensors in the fingers to detect pressure, force, and even slipping.

7. Finger kinematic Durning Human Hand Grip and Release [14]
   This article talks more about the anatomy of the hand, going in depth on the different ranges of motion we have at each joint of each finger and the thumb. It analyzes 14 finger joints during gripping and releasing, highlighting that the proximal interphalangeal (PIP) joints exhibit the largest range of motion and highest peak velocities.
8. Anatomy of grip [63]
   Anatomy of Grip explains how our hand uses muscles, tendons, and joints to perform different types of grips. It covers different grips like power grips and precision grips, highlighting how key structures like the flexor retinaculum and extensor muscles play a role. The article also looks at conditions like carpal tunnel syndrome that can affect grip strength. This could be useful for designing robotic hands that mimic the human hand's abilities.
9. What is Arduino, how it works and what you can do with arduino [64]
   The article explains that Arduino platform combines hardware and software. It allows you to build microcomputers for different projects such as our robotic hands, from. Because of its flexibility Arduino is widely used for prototyping.
10. The Official Raspberry Pi Beginner's Guide [65]

This book provides foundational knowledge on interfacing hardware with the Raspberry Pi. Understanding how to connect and program sensors and actuators through the GPIO pins will be crucial in controlling the movements of our robotic hand. Additionally, the programming sections can assist in learning to write the necessary code to process inputs and control outputs.

3.2.6 Markus:

1. In brief: How do hands work? [16]

   This book provides a general overview of human hand mechanics, including tendon movement, joint articulation, and the relationship between muscle actuation and finger motion. Understanding these biological principles is essential for developing a robotic hand with human-like dexterity.

2. Clinical Mechanics of the Hand. St. Louis: Mosby Year Book [17]

   This book explores the biomechanics of hand movements, offering insights into force distribution and stress points in human hands. These concepts play a crucial role in determining the structural and material choices for designing a robotic hand.

3. TENDON DRIVEN ROBOTIC HANDS: A REVIEW[18]

   This paper examines tendon-driven robotic hands, highlighting their advantages in replicating human finger motion while minimizing actuator size.

4. Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration[19]

   This study presents a modular robotic hand with 20 degrees of freedom, emphasizing anatomical accuracy and dexterous manipulation. It serves as a key reference for designing the actuation and control system of robotic hands.

5. A low-cost and modular, 20-DOF anthropomorphic robotic hand: Design, actuation and modeling[20]

   This paper provides an in-depth analysis of actuation techniques and explores the trade-offs between cost, complexity, and dexterity in robotic hand development.

6. Excursion of the flexor digitorum profundus tendon: A kinematic study of the human and canine digits [21]

   This article investigates the movement of flexor tendons in both human and canine digits, providing essential data for modeling tendon excursions in robotic hands. These motion patterns are critical for designing a tendon-driven actuation system that achieves realistic movement.

7. Bionicsofthand[22]

   This webpage describes an advanced soft robotic hand that incorporates biomimetic principles and pneumatic actuation. The information provided influenced material selection and actuation methods for our project.

8. Design of 3D-Printed Cable Driven Humanoid Hand Based on Bidirectional Elastomeric Passive Transmission (BEPT)[69]

   The tension between cost, weight, response time, pinch strength, finger spread and dexterity in prosthetic hands have yet to be optimally approached. Here, we present a 3D-printed cable-driven humanoid hand employing BEPT with a semi-static model based on energy conservation to analyze its mechanical properties and performance results. The design offers a good trade-off between price and performance obtained for the fingertip force 33 N, in an experiment meaning of 0.6 s/180°.

9. Dual-Tendon Routing: Tendon Routing for Under-Actuated Tendon-Driven Soft Hand-Wearable Robot[70]

   This paper provides DTR which prevents tendon friction and elongation when used on under-actuated tendon-driven design. This method improves tension distribution, reliability, and efficiency of soft hand-wearable robots. It defines five performance metrics to guide tendon routing optimization: adaptability, torsional balance, reliability, efficiency, and transmission ratio.

10. Design of Hybrid Fully Actuated and Self-Adaptive Mechanism for Anthropomorphic Robotic Finger[71]

    In this paper, we propose a new design for an anthropomorphic robot finger that combines both fully actuated and self-adaptive (FASA) designs. The FASA finger is tendon-actuated and can adaptively grasp objects and reach accurate angles. The guidelines in this paper are needed to select torsion springs to satisfy the functional motions of the FASA finger and ensure optimal torsional stiffness.

3.3 Mathematical Modeling

3.3.1 Power

Noah:

One of the critical considerations that needed to be addressed for the design of our robotic hand was power consumption. To address this, a python script was written which calculates the power consumption of the hand as a whole, as well as the power consumption of the individual components and subsystems. From this script and assuming standard servos used to actuate the hand, a maximum power draw of 107W was obtained. This corresponds to the hand gripping hard enough to completely stall the servos. 107W corresponds to running 1-2 desk lamps at the same time depending on the efficiency of the lamp. One of the benefits of this Python script is that it also serves as a record book of the electrical specifications of each component which the team can refer to whenever needed. This python script represents the electrical components of the hand as objects with individual attributes. For example, the motors inherit the "motor" class and take on their own unique values for voltage, current, and efficiency. After all of the electrical components have been defined, another class representing the hand as a whole takes all of those objects in as parameters, sums their individual power consumptions, and then returns the total power consumption of the hand. The script was written so that it would be easy to add new components or change the parameters of the components currently in there, making the script quite adaptable and useful even when new components are added/components are changed out for others.

3.3.2 Motors

Noah:

An important consideration to be made in the early stages of design is that of required motor torque. The hand will be operating via a tendon-driven system, with motors in the forearm controlling the finger movements. How much torque these motors will need to provide is a question that needs to be answered early on in the design phase, as it will impact cost, weight, and size of the hand. As a result, a statics analysis of the hand was done to determine the required torque output of the motors. The assumptions of the analysis were that the hand would be holding a 40lb dumbbell in a "purse-carrying" position and that the tendons have a 50% efficiency loss in transmitting the motor torque to the fingers. From these calculations, it was found that the motors would need to output about 2Nm of torque in order to support the weight. Similarly, as with the power analysis, a Python script was written so that this calculation could be easily iterated upon in the future.

To accommodate the request of our project's sponsors, another motor torque analysis was performed. This other analysis differed from the first in that the goal was to investigate how much torque the motors would need to output in order to press a piano key. Given that it takes about 1Nm of force to press a piano key, this, along with the finger dimensions and tendon attachment points, served as the givens for a rudimentary statics problem. Similarly to the previous torque analysis, a 50% loss in efficiency through the tendons was assumed. Given the current dimensions of the fingers and a 20mm diameter pulley on the motor onto which the tendons attach and by which the motors will pull on the tendons, a minimum required torque of 0.144Nm was found. This is a pleasantly low number and serves to show that we can realistically attain the goals set forth by our sponsors

3.3.3 Tendons

David:

When making the decision of tendon material it was most important to analyze the finger that was under the most load which in our case is going to be the thumb. It was under the most load per length of the sections so based on the force we got for the thumb and the yield strength of various materials an area was calculated that could withstand the maximum force of each of the materials, Steel wire, Kevlar, and nylon could bear.

3.3.4 API
Joseph:

Projectile motion equations prove useful twofold: The first application is to calculate the flight time of an object based on initial conditions, such as a launch angle of 30 degrees and a horizontal distance of 1.5 meters, the initial velocity is 4.122 meters per second. Using the initial velocity, the total flight time is calculated to be .42 seconds. This is assuming the same initial and final height. A time of .42 seconds equates to a frequency of .42 hertz, or .42 cycles per second, which is how fast the code will need to yield an adequate reaction speed.

3.3.5 Fingers
Joseph:

To best mimic natural position and range of motion of the hand, it was important to model the joint angles with certain grips, such as full actuation and gripping a ball with a diameter of 2.5 inches. After each joint angle and splay angle was tabulated, equations were built to link the movement of the middle joint to the movement of the tip joint by using a direct ratio. These equations can now be used in multiple ways; most notably, they can be implemented into a C++ script to allow the tip joint angle to be inferred based on the reading of an angle sensor and make the design easier by removing the need for motors at certain joints.

Additionally, the forward kinematics equations were utilized for a 3-link planar manipulator system and modified to represent the end effector's position over time by taking the time derivative of the equations. Once the equations were converted to matrix form and set equal to the x and y coordinate velocity vector, the matrix was solved to produce the Jacobian transformation matrix and the end-effector's x and y velocities in vector form. The calculations were automated with a MATLAB script, allowing the calculations to be iteratively solved to find the velocities of a fingertip over time.

Justin:

Using inverse kinematics assuming a 2 joint connection, the length of each segment and the end position of the tip the angle at each joint segment could be found which could be useful when programming the finger. It will need to be able to find the angles needed to end at a specific point in a 2D plane.
Using forward kinematics to analyze a 3 joint connection with a splaying motion, we assume the length of each segment to be proportional to 1.5x human fingers (Table 3) and the angle of each segment to be whatever we want it to be as long as it is within human range of motion limits. We will use the forward kinematics equations to program the finger because we could tell it what angles to bend at, and we could then know the finger's end position in a 3D space which replicates what it will need to do.

David:

Finding a material for gripping with a proper coefficient of friction that is high enough to keep forces on fingers, joints, and tendons was essential for our design process. If we were to use rubber with a coefficient of friction on 0.8 that alone would lower our maximum allowable weight down significantly, but it would require the same amount of force on tendons and joints, so out calculated tendon sizes would be compromised much earlier than anticipated. We then factored in a safety factor of 1.5 to make sure that we would have plenty of room for error on these calculations and came to a final grip force of around half of what was initially calculated for.

Tyler:

For this calculation I used the Denavit-Hartenberg parameters which is used to assign coordinate frames and parameters to each link and joint of a finger. Using some given information like lengths of the segments of the fingers and some sample angles of the joints, we can find the location in x and y axis of where the fingertip is in relationship to the base of the finger. The equations used are below in the summary. We can use any measurements or givens to find the positioning when implimenting this into our code.

3.3.6 Overall Measurements

Tyler:

For this calculation I got the measurements of every part of the hand. We need this to be able to do any modeling and any calculations for the hand. I measured my hand and wrote down all of the measurements in Table 2 below. I also included an upper limit of each measurement.

Table 3: Overall measurements for Hand

	Length(inches)	width (inches)	Other (inches)	Length upper Limit	width upper length	other upper limit
overall length	7.6			11.4		
overall breadth		3.5			5.25	
average circumference			8.6			12.9
Index Finger	4.125			6.1875		
top segment	1.125	0.625		1.6875	0.9375	
middle segment	1.125	0.75		1.6875	1.125	
base segment	1.875	0.875		2.8125	1.3125	
Middle finger	4.75			7.125		
top segment	1.125	0.625		1.6875	0.9375	
middle segment	1.3125	0.75		1.96875	1.125	
base segment	2.3125	0.875		3.46875	1.3125	
Ring finger	4.5			6.75		
top segment	1.125	0.625		1.6875	0.9375	
middle segment	1.0625	0.75		1.59375	1.125	
base segment	2.1875	0.875		3.28125	1.3125	
Pinky Finger	3.5			5.25		
top segment	0.9375	0.5		1.40625	0.75	
middle segment	0.875	0.625		1.3125	0.9375	
base segment	1.6875	0.75		2.53125	1.125	
Thumb	2.875			4.3125		
Top segment	1.375	1		2.0625	1.5	
base segment	1.5	0.875		2.25	1.3125	
Palm	4.75	3.5		7.125	5.25	

3.3.7 Motor Speed

Markus:

To determine the required motor speed for the robotic hand's tendon-driven actuation, we performed calculations based on reaction time and finger displacement. Motor speed is critical to achieving the rapid movement needed for tasks like playing the piano and catching a ball. The following calculations establish the appropriate speed based on tendon displacement and time constraints.

Given:

- Tendon displacement range: 45-75 mm
- Total reaction time: 300 ms (assuming 25 ms for signal processing)
- Spool radius options: 5 mm and 10 mm

Using the equation:

$$\omega = \frac{d}{rt}$$

where:

- ω = angular velocity (rad/s)
- d = displacement (m)
- r = spool radius (m)
- t = time (s)

For a 5mm spool:

$$\omega = \frac{.075}{.005 \cdot .275} \approx 278RPM \quad \text{[Equation 1]}$$

For a 10mm spool:

$$\omega = \frac{.075}{.01 \cdot .275} \approx 139RPM \quad \text{[Equation 2]}$$

A larger spool reduces the required motor RPM but increases torque demand.

3.3.8 Shear Stress in Joints
Markus:

To ensure the structural integrity of the robotic hand, we calculated the shear stress experienced at each joint due to tendon force transmission. The goal is to verify that the selected materials can withstand the forces exerted during actuation without failure. These calculations help in selecting the appropriate materials for longevity and reliability.

$$V = \frac{T}{r} + F$$

And

$$\tau = \frac{F}{A}$$

where:

- $F =$ Applied force at fingertip (N)
- $T =$ applied torque at joint (Nm)
- $r =$ radius of torque(m)
- $\tau =$ shear stress at joint (Pa)
- $A =$ cross-sectional area of pin joint (m^2)

Based on the CAD model of our pin, the smallest cross section is $10.16mm^2$. This calculation is for the first joint in the thumb as this experiences the most shear force. The torque is given based on the position of the fingers within the hand and the weight the hand is holding. The calculations are done assuming an 40lb grip force.

$$V = \frac{2.225}{.01} + 44.475 = 266.975N$$

$$\tau = \frac{266.975}{10.16} = 26.28MPa$$

Carbon fiber can have shear strength up to 27MPa, further analysis needs to be done to ensure carbon fiber pins will be sufficiently strong.

Table 4: Complete List of Shear in Each Finger

Joint	Torque (T) (Nm)	Shear Force V (N)	Shear Stress τ (MPa)
Thumb 1	2.225	266.975	26.28
Thumb 2	1.335	177.975	17.52
Thumb 3	0.665	110.975	10.92
Index 1	1.6	213.37	21.00
Index 2	1.065	159.87	15.74
Index 3	0.535	106.87	10.52
Middle 1	0.8	106.685	10.50
Middle 2	0.535	80.185	7.89
Middle 3	0.265	53.185	5.23
Ring 1	0.8	106.685	10.50
Ring 2	0.535	80.185	7.89
Ring 3	0.265	53.185	5.23
Pinky 1	0.535	71.29	7.02
Pinky 2	0.355	53.29	5.25
Pinky 3	0.18	35.79	3.52

3.3.8 Torque in Joints
David:

In order to ensure the proper material choices for the robotic hand and finger components it was necessary to calculate the torque that would be applied to each one of the joints on each of the fingers. We based this on an average grip force distribution that focused more of the force on the thumb, index, and middle fingers so they were the three most important torques to calculate. We based our gripping force on the average grip force of a human which came out to be around 80lb or 36kg.

3.3.9 Wrist Actuation
Tyler:

When looking into how to actuate our wrist, we landed on the idea of using gears to actuate it. Using gear ratio equations to find the right sized gears, we found that the correct ratio should be 2:1. This will allow for higher torque, more precision, but slower movement. As this is the wrist I felt that the speed of the wrist is not overly important. The approximate number of teeth of these gears should be 40 and 20 teeth. Also using this we found an output RPM of 139.

4 Design Concepts

4.1 Functional Decomposition

Robotic hand

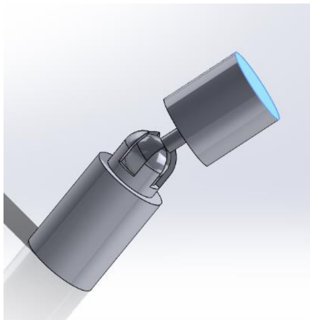
```
├── Finger
│   ├── design different finger joints
│   ├── integrate sensors into cad designs ideas
│   └── link sensors to computer program
├── Thumb
│   ├── design different thumb joints
│   ├── integrate sensors into cad designs ideas
│   └── Link sensors to computer program
└── Hand and wrist
    ├── design way to connect fingers and thumb to a wrist joint
    ├── integrate sensors into wrist
```

Our functional decomposition shows how we have 3 sub sections, the finger, thumb and wrist/hand. For each section we first have to look at how we are going to replicate the joints in the human hand. After doing this then we must plan to integrate sensors into each component. Finally, we must program it all to actuate the fingers as we intend to.

This functional decomposition enables us to look at the project in a more digestible piecewise manner, making planning and strategizing easier. It also allows us to better assess our progress by keeping track of the individual sub-components and cheking them off as we go.

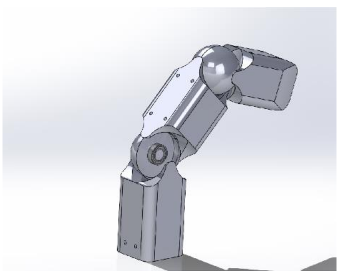
4.2 Concept Generation

4.2.1: Joint Design 1



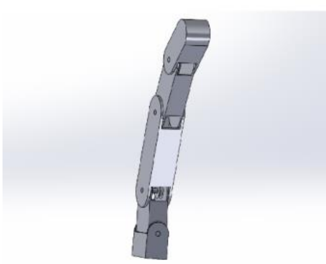
This joint design is a base joint design using a two-way ball and socket joint that is designed for maximum mobility as well as ease of printing. It may have problems with joint angle sensing

4.2.2: Joint Design 2



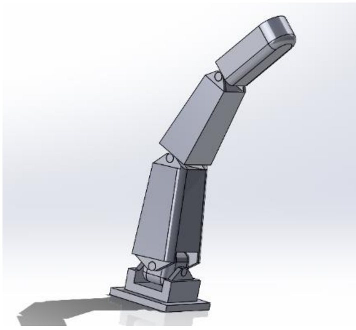
This joint design is two semispherical joint segments that fix together in the middle with a bearing. It offers maximum stability and range of motion. It is not able to easily integrate an angle sensor to the side of the joint.

4.2.3: Joint Design 3



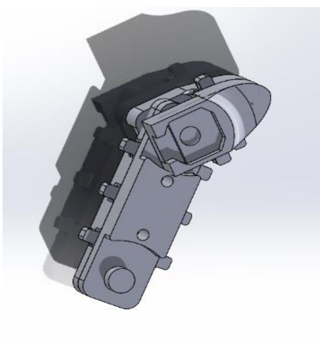
This joint design is a hollow body design for internal tendon routing as well as sensor routing, that features repeating pin hinges and a hinge at the bottom actuates in the opposite direction for the splaying motion. It may be weak to forces due to the hollow body.

4.2.4: Joint Design 4



This joint design uses clips to hold each of the joints in place which makes for easy assembly and printing. It also features a two-way ball joint with the clips at the base for the splaying motion. The joints may be weak due to the thinness of the clips.

4.2.5: Joint Design 5



This joint features a slot that allows for an angle sensor and is essential for each joint moving forward. It also has external tendon routing for finger actuation, each of which makes it bulkier but also much more functional

4.3 Selection Criteria

4.3.1 Specification Table:

Specification	Importance	Units	Target	Tol.	Comments
Grip Force	2	N	250-350	50	Average grip force of adult
Grip Speed	3	ms	200-300	50	Average reaction time of an adult
Size of Average hand	1	mm	190x85	50x25	Easy to store and more intuitive
Weight of average hand	1	kg	3.5	1	Portable and reflect biology
Cost of Manufacturing	3	$	1500	250	Budget
Many DOF	3	#	20	1	Reflects Biology
Easy to power	3	V	120	0	Operates off US electrical outlet
Easy to use interface	3	min	10	2	Time to teach sponsors interface
Precise and Accurate Motion	3	mm	1	.5	Position is known within this area
Longevity	3	#	10,000	250	Able to be actuated near infinite life

4.3.2 calculation specifications:

Grip force: Calculated by tendon analysis and joint torque analysis as well as shear stress on fingers. We Know a maximum allowable force based on our estimated parts.

Grip Speed: Calculated through motor analysis done in previous slides. Need to do more tendon analysis to get exact measurements

Hand Size: We have charts of average dimensions and once we choose materials and final designs we can calculate what dimensions of the hand will be. We will try to keep it within 1.5X the maximum dimensions of the hand.

Hand Weight: We have charts of average weights and once we choose materials and designs, we can calculate what the total weight of the hand will be. We will try to keep it within 1.5X the weight of the hand.

Manufacturing Cost: Once we finalize the design, including motors tendon material filament and all other things we will have a better idea of costs.

DOF: Once our final design for finger and thumbs is finished, we can add up the degrees of freedom we will be getting from the design.

Power: We need to still calculate the resistive network of all of the motors and then how to change from AC to DC power. Once a final motor is selected, we can complete this calculation.

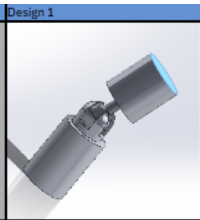
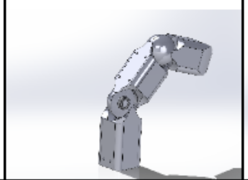
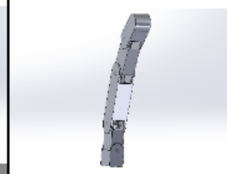
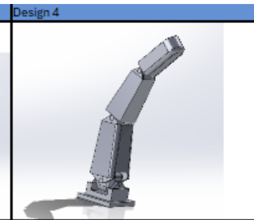
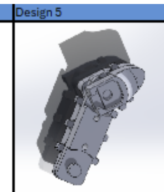
Interface: We have yet to do calculations for interface analysis. This will be done in the future once more code is generated.

Precise Motion: We used forward and reverse kinematic analyses to calculate the position of each finger segment.

Longevity: This is calculated by looking t fatigue life analysis which hasn't been done yet for tendon or joint material.

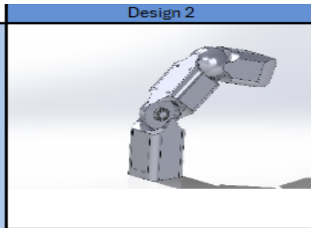
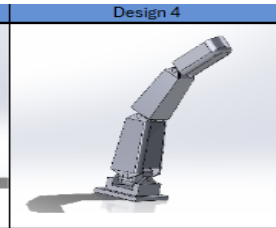
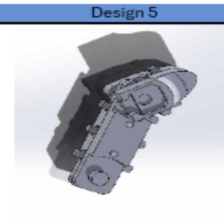
4.4 Concept Selection

4.4.1: Pugh Chart:

Concept	Design 1	Design 2	Design 3	Design 4	Design 5
Criteria					
Strength	- (thin shaft and socket reduces maximum load allowable)	+ (thick integrated joints allows for increased loading)	- (pin hinges and hollow body reduces allowable load)	Datum	+ (thick integrated joints bear loads well)
Speed	S	S	S	Datum	S
Budget	+ (less prints needed and less volume to print)	- (more material used at joints and overall increases price)	+ (hollow body reduces filament need)	Datum	+ (thinner and less total volume reduces price)
Many degrees of freedom	+ (can move 90+ degrees in either direction)	+ (can move almost 90 degrees)	+ (many joints over 90 degrees in many directions)	Datum	S
Accurate dimensions	- (smaller and thinner than human hand)	+ (More similar overall dimensioins)	- (thinner and longer than human and)	Datum	+ (accurate dimensions except extruded tendon routing)
Reliability	- (socket and shaft will wear and fail due to little material)	+ (integrated joints with bearing have high repeatability and durability)	S	Datum	+ (integrated joints with bearing have high repeatability and durability)
Positonal accuracy	- (no way to intergate angle sensors)	+ (easily integrate angle sensors into the design)	- (needs major adjustment for sngle sensors)	Datum	+ (angle sensor slot already integrated)
Accurate weight	+ (reduced material more accurate to human finger)	- (volume leads to increased excess weight)	+ (hollow body reduces weight and makes it more accurate)	Datum	- (solid body makes for potentially heavier design)
Σ+	3	4	3	n/a	5
Σ-	4	2	3	n/a	1
Σsimilar	1	1	2	n/a	2

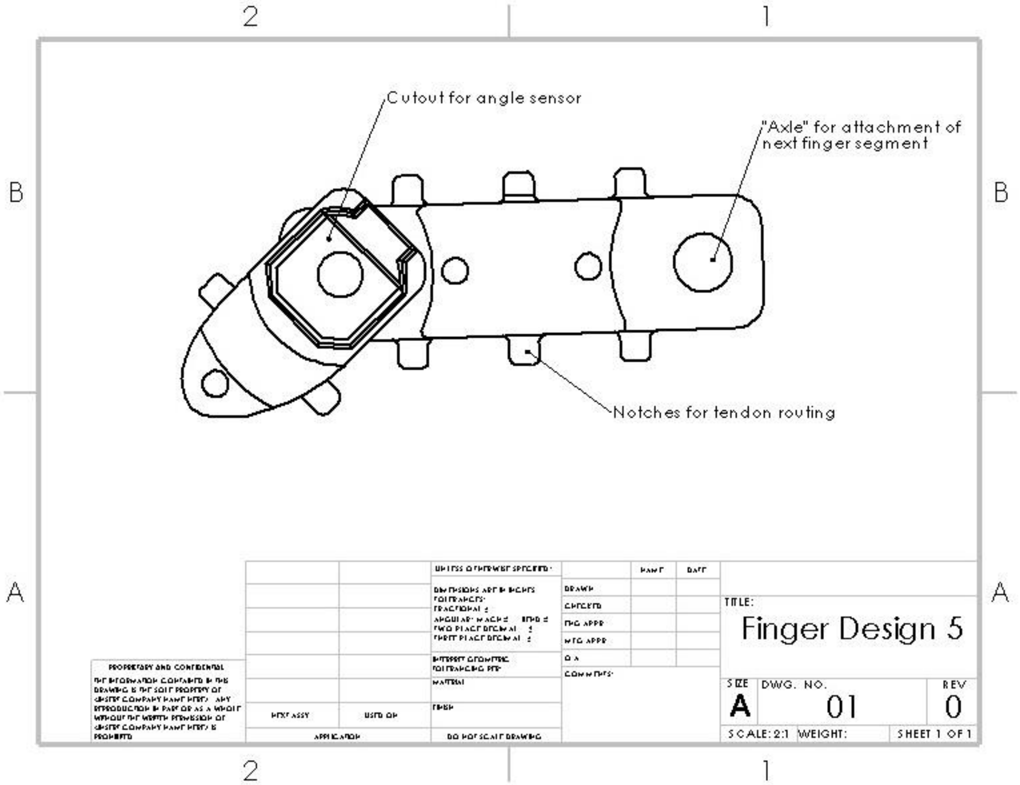
Our best five SolidWorks designs were put into a Pugh chart. We compared all of them to design 4 which was our datum, and we listed all the pros and cons of each one of the different design requirements that we came up with and outlined. Our datum was selected by the team collectively because of perceived large range of motion as well as the fact that the design included all the joints of the finger. It also had dimensions that seemed similar to that of a human finger. We gave each category a plus if we deemed it performed better in that specific category, a minus if it performed worse, and an S if it performed the same. We then added them up in order to determine the three designs that would move on in the decision process.

4.4.2: Decision Matrix:

Criteria	Weight	Design 2		Design 4		Design 5	
							
		unweighted score	weighted score	unweighted score	weighted score	unweighted score	weighted score
Strength	0.1	90	9	75	7.5	93	9.3
Speed	0.2	85	17	85	17	85	17
Positional accuracy	0.2	75	15	75	15	100	20
Budget	0.05	85	4.25	80	4	85	4.25
Many degrees of freedom	0.2	80	16	75	15	75	15
Accurate dimensions	0.05	90	4.5	85	4.25	90	4.5
Reliability	0.15	87	13.05	86	12.9	90	13.5
Accurate weight	0.05	80	4	90	4.5	80	4
Total:	1	Sum:	82.8	Sum:	80.15	Sum:	87.55

Our final three designs that made it throughout Pugh Chart were featured on the decision matrix for final design evaluation. We then added weights to each of the specific design criteria that we had listed based on the importance in the eyes of the clients but also from an engineering standpoint. Once we gave them weights, we scored each design for each criterion 1-100 and then applied the weight and added them up. We finally summed each one of the designs and came up with final scores and came up with the final design, design 5.

Below is a SolidWorks drawing of the selected finger design with annotations for the notable features.


Cutout for angle sensor
"Axle" for attachment of next finger segment
Notches for tendon routing
TITLE:
Finger Design 5
SIZE
A
DWG. NO.
01
REV
0
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1

5 SCHEDULE AND BUDGET

5.1 Schedule

Humanoid Hand Gantt Chart

TASK	ASSIGNED TO	PROGRESS	START	END	EST. HOURS	ACTUAL HOURS
Phase 1 (1st Prototype Demo)						
Work on Presentation 1	Team	100%	1/27/25	2/10/25	10.00	20.00
Establish Finger Design	Team	100%	2/4/25	2/18/25	30.00	40.00
Establish Control Scheme	Joseph, Noah	100%	2/4/25	2/18/25	10.00	20.00
Order Preliminary Parts	Justin	100%	2/18/25	2/21/25	1.00	5.00
Presentation 2	Team	100%	2/18/25	3/2/25	10.00	40.00
Joint Prototype	Team	100%	2/18/25	3/31/25	40.00	50.00
Phase 2 (Phalange Prototype)						
Report 1	Team	100%	3/1/25	3/9/25	30.00	40.00
Website Check 1	David, Markus	100%	2/25/25	3/9/25	10.00	25.00
Analysis Memo	Team	100%	3/1/25	3/21/25	20.00	30.00
Presentation 3	Team	100%	3/9/25	3/31/25	10.00	50.00
Finger Prototype	Team	100%	2/18/25	3/31/25	60.00	180.00
1st Prototype Demo	Team	100%	2/1/25	3/31/25	5.00	20.00
Phase 3 (Whole Hand)						
Report 2	Team	100%	4/1/25	4/18/25	20.00	60.00
Final CAD and Final BOM	Tyler, Noah	50%	4/1/25	4/25/25	10.00	
2nd Prototype Demo	Team	0%	4/1/25	4/28/25	5.00	
Website Check 2	David, Markus	0%	4/1/25	5/4/25	10.00	
Whole hand Prototype	Team	0%	4/1/25	4/31/25	60.00	

Phase 4 (Startup of 486C)					
Project Management for 486C	Team	0%	4/1/25	5/2/25	10.00
Project Management	Team	0%	8/28/25	8/30/25	10.00
Engineeering Calculations	Team	0%	8/28/25	9/4/25	10.00
Double check Prototype and adjust	Team	0%	8/28/25	9/31/25	30.00
Phase 5 (Building)					
Hardware Status Update - 33%	Team	0%	8/28/25	9/25/25	60.00
Hardware Status Update - 67%	Team	0%	8/28/25	10/16/25	60.00
Hardware Status Update - 100%	Team	0%	8/28/25	11/6/25	60.00
Phase 6 (Collection of Stuff)					
Website Check 3	David, Markus	0%	8/28/25	10/9/25	10.00
Finalized Testing plan	Team	0%	10/16/25	10/30/25	10.00
Final CAD Packet	Team	0%	11/1/25	11/20/25	5.00
Final Report & Final Website check	Team	0%	11/1/25	11/27/25	30.00
Phase 7 (E-Fest)					
UGrads registration	Team	0%	10/23/25	10/24/25	1.00
Draft of poster	Team	0%	10/1/25	10/30/25	15.00
Final Poster & PPT	Team	0%	11/1/25	11/13/25	20.00
Presentation	Team	0%	12/8/25	12/8/25	5.00
Conclusion					
Initial Testing Results Video	Team	0%	11/6/25	11/20/25	5.00
Product demo	Team	0%	11/6/25	11/27/25	5.00
Client Handoff	Team	0%	12/11/25	12/11/25	1.00

Total Est. Hours	Total Actual Hours
688.00	580.00

Currently our team is on schedule to complete on time. We have hit some rough spots with making our finger work while covering all of the criteria we want it to meet but we are wrapping it up and have started on the rest of our hand designs. With plans to work on the project over the summer, we feel that we are more then set to complete the project ahead of schedule.

5.2 Budget

	Budget Robotic Hand							
	Total Budget							$2,000
Item #	Item	Description	Planned Aquisiton Date	Actual Acquisiton Date	Price Per Unit	# of Units	Estimated Total Price	Actual Total Price
1	Motors	Motor with AS5048A Encoder	4/21/2025		$42.97	8	$343.76	
2	Motors	INJORA INJS035 35KG	4/21/2025		$16.99	6	$101.94	
	Breadboard	4PCS breadboard kit	4/14/2025	14-Apr	$6.78	1	$6.78	$7.40
	Wiring	22 guague Silicon wire	4/14/2025	14-Apr	$19.13	1	$19.13	$23.21
	Potentiameter	Angle sensors	4/21/2025		$1.34	20	$33.55	
3	Filament	PLA Prototyping Filament	4/21/2025		$14.99	1	$14.99	
5	Filament	Onyx Filament	4/21/2025		$209	1	$209	
6	Filament	50cc Carbon Fiber Spool	4/21/2025		$150	1	$150	
7	Computation	Arduino Mega	4/21/2025		$49.65	1	$49.65	
8	Actuation	Dyneema Cord	4/21/2025		$32.99	1	$32.99	
9	Actuation	Bearings	4/21/2025		$7.17	15	$107.55	
	Estimated Remaining Budget							$930.66
	Actual Remaining budget							$1,969

Currently our team has plenty of money to work with because members of our team had access to materials we could use to prototype, so we have not needed to buy as much as expected. However, as time goes on, we will start purchasing more things that will be used for our final design. If for some reason, we run out or don't have enough money for what we need we still can raise more money.

5.3 Bill of Materials (BoM)

Part	Quantity	Price	Total Price	Link
Motor				
iPower GM2804 Gimbal Motor w/ AS5048A Encoder	8	42.97	343.76	link
INJORA INJS035 35KG	5	16.99	84.95	link
3D Printed Parts				
PLA Prototyping Filament	1	14.99	14.99	link
Onyx Filament	1	209.00	209.00	link
50cc Carbon Fiber Spool	1	150.00	150.00	link
Hardware - Computation				
Raspberry Pi	1	0.00	0.00	link
Teensy 4.1	2	31.50	63.00	link
Hardware - Actuation				
Dyneema Cord	1	32.99	32.99	link
Bearings	15	7.17	107.55	link
Potentiometer	11	1.08	11.88	link

The above represents our current bill of materials. This list will likely continue to change as the design further evolves and solidifies. We have the benefit of being able to heavily rely upon 3D printing, dramatically reducing our cost of construction.

6 DESIGN VALIDATION AND INITIAL PROTOTYPING

6.1 Failure Modes and Effects Analysis (FMEA)

When considering the design of the robotic hand, it is important to map out the potential failure modes to incorporate failure prevention into the next iterations of the design. A project such as this possesses multiple subsystems, some of which include the frame, tendon, and control scheme. Each subsystem has a plethora of components, which increases the chance of subsystem failure. To better analyze the components and their failure modes, an FMEA document was filled out. According to the completed FMEA, the top three most at-risk components are angle sensors, motors, and servos, in descending order. To best prevent failure in those three components, a number of design changes were made to the initial prototype. To optimize the servos, high quality units are needed to minimize the possibility of failure. The risk trade-off in such a decision involves sacrificing space optimization for high quality and potentially bulky motors. The same level of quality is expected of the motors. While striving for the optimization of size and quality, it must be kept in mind that the motors are also the primary control of hand actuation. Consequently, any faulty wiring or suboptimal tendon routing will render the hand mostly inoperable. Lastly, the search of angle sensors brought up the importance of signal noise and compatible geometry. If the signal noise is too busy or the wiring is faulty, the hand will not be able to report accurate positional information. Changing the types of angle sensors used will result in altered geometry, which will be addressed in the next design iterations. Most of the risk trade-off being evaluated is the sacrifice of space to ensure high quality materials to build an impressive and dexterous hand. Pictured below is the full FMEA:

Product Name: Humanoid Hand	Development Team	Page No. 1 of
System Name		FMEA Number 1
Subsystem Name		Date 3/29/2025
Component Name		

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1 Fingers/Frame	Force-induced deformation Impact deformation	Breaking of fingers and frame	6	Overstressing, high impact loads	6	Repeated application of forces and impacts	1	36	Select strong material
2 Bearings	High-cycle Fatigue Temp-induced deformation	High friction, inaccurate actuation	6	Inadequate venting, cyclic failure	5	Repeated actuation cycles (10k)	2	60	Choose appropriate commercial bearings or explore bushing joints
3 Pulleys	High-cycle Fatigue Force-induced deformation	Moderate to severe inability of actuation	6	High impact loads, cyclic failure	6	Impact analysis, repeated cycles	1	36	Select or machine strong pulleys
4 Tendon Cord	Ductile Rupture	Inability of operation	7	Inadequate routing, high stress loads	7	Tensile strength analysis, ductile failure test	3	147	Select a strong but flexible tendon cord
5 Tendon Housing	Abrasive wear	Lack of protection for tendon cords	2	Inadequate routing, cyclic failure	5	Friction factor analysis, repeated force application	5	50	Ensure flexibility in cable housing
6 Servos	High-cycle Fatigue	Limited DoF	6	Suboptimal power supply, cyclic failure, faulty wiring	6	Multimeter verification	7	252	Select high quality servos
7 Motors	High-cycle Fatigue	Moderate to severe inability of actuation	7	Suboptimal power supply, cyclic failure, faulty wiring	6	Multimeter verification	7	294	Select high quality motors
8 Angle Sensors	Force-induced deformation	Inability to interface	8	High impact loads, faulty wiring, noisy signal	7	Impact analysis, multimeter test	6	336	Select accurate and high quality angle sensors

Figure []: Humanoid Hand Full FMEA

6.2 Initial Prototyping

6.2.1 Prototype 1:

The initial design prototype, Design 5, was optimal to iterate from because it included detailed geometric cutouts for the potentiometers and designated routings for the tendons through a pulley system for ease of control. From Design 5, prototype 1 was developed, which featured pulleys in the joints and discrete angle sensor placement to offer a sleek and compact look, all actuated by a motor to flex and extend the finger. It was helpful in answering if potentiometers were a viable choice for angle sensors and if pulley-driven tendons were optimal for control and fit into a compact design that meets size standards. After testing this design, it was discovered that potentiometers were not completely reliable in sensing angle data and had to be swapped to a different angle sensor. This resulted in a slight change in the finger geometry, as the new angle sensors required different cutouts. The motors and servos were also swapped for smaller ones to opt for a better use of space. To test this design further, the tendon material will be swapped to a material that will not stretch under tension, such as Kevlar or specialty ice fishing-line. A concern with this design is that it does not output as strong of a force as desired. One reason could be the diameter of the pulleys are too small, which creates too weak of a moment arm to apply sufficient force to meet strength goals.

6.2.2 Prototype 2:

For prototype 2, many changes are needed to improve upon the previous design iteration and minimize failure. As mentioned previously, new motors, servos, and angle sensors were selected to improve physical quality and quality of data collection. The next prototype will seek to incorporate a larger pulley diameter and stiffer tendon material to increase the force output of the finger. The next prototype will also explore the fidelity of a gear-and-belt system to drive the wrist, which will be linked to the fingers by the palm frame. The palm will also feature a mount for the thumb, which will be actuated the same way the fingers are. Prototype 2 will offer insight into the viability of thumb attachment and actuation, motor and servo reliability, and explore methods in which to capture solid movements of the finger splaying motion to integrate into future palm iterations.

6.3 Other Engineering Calculations

In this section, there is a summary of all of the calculations that we have done up to date. This will help us keep track of our numbers and make sure we have answered all of the questions that we have been faced with. In Table 5, there is all of the calculations.

Table 5: Updated Summary of Calculations

Calculation	*Equation(s)*	*Application*	*Requirement Met*	*Validation*
Projectile motion	$x_f=x_0+v_{0x}t$ $x_f=(v^2sin2theta)/g$	*Catching a ball*	*Dexterity and reaction speed*	*Dynamics* *Assumptions*
Finger tip joint inference	$theta_{Tip}$=.667$theta_{Mid}$ $theta_{Tip}$=.556$theta_{Mid}$ $theta_{Tip}$=.333$theta_{Mid}$	*Coding, ease of design, mechanical linkages*	*Biomimetic and natural motion*	*Speculation* *Grip Angles*
Motor Speed		*For Motor Selection*	*Hand actuation speed*	*Speculation* *Reaction time*
Shear Stress		*For material selection for joints*	*Number of actuations*	*Speculation* *Average Material*
Fingertip location (x,y,z)	$x_3 = x_2 + L_3\cos(\theta_1+\theta_2+\theta_3)\cos(\phi)$ $y_3 = y_2 + L_3\sin(\theta_1+\theta_2+\theta_3)\cos(\phi)$ $z_3 = z_2 + L_3\sin(\phi)$	*Finding location of fingertip in terms of the base joint*	*Control of the fingers*	*Implementing code* *Real finger lengths*
Hand Measurements	*N/A*	*Have exact measurements of joints and segments*	*Average hand size and upper limit*	*Speculation* *Average Measurements*
Power	*P = V*I*	*Power*	*Reasonable*	*Equations used agree*

		consumption	*power consumption*	*with what was learned in PHY 262, EE188* *Compare results to power consumption of real-world electrical devices*
Motor Torque	$F = ma$ $T = Fr$	*Inform motor selection*	*Establish minimum required motor torque*	*Equations and their application agree with the basic principles of static analysis* *Required motor torque agrees with reason*
Wrist Actuation	$GR = \frac{\text{Output Speed}(\omega_o)}{\text{Input Speed}(\omega_i)}$ $GR = \frac{Z_o}{Z_i}$ $\omega_o = \frac{278}{2} = 139\ \text{RPM}$	*Moving the wrist*	*Actuation process for the wrist*	*Using Machine design equations and knowledge from machine design.*
End-Effector Velocity	$\begin{bmatrix} -L_1\sin(\theta_1) - L_2\sin(\theta_1+\theta_2) - L_3\sin(\theta_1+\theta_2+\theta_3) & -L_2\sin(\theta_1+\theta_2) - L_3\sin(\theta_1+\theta_2+\theta_3) & -L_3\sin(\theta_1+\theta_2+\theta_3) \\ L_1\cos(\theta_1) + L_2\cos(\theta_1+\theta_2) + L_3\cos(\theta_1+\theta_2+\theta_3) & L_2\cos(\theta_1+\theta_2) + L_3\cos(\theta_1+\theta_2+\theta_3) & L_3\cos(\theta_1+\theta_2+\theta_3) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$	*Determining the velocity vector of a fingertip*	*Speed and dexterity*	*Previous kinematic equations and literature*

6.4 Future Testing Potential

To verify that the humanoid hand meets critical engineering requirements and functional expectations, several targeted testing procedures are planned. These tests will validate mechanical performance, operational longevity, and system usability during the next design iteration.

Weight and Size Verification
The final design will be evaluated for compliance with dimensional and mass constraints. SolidWorks will be used to estimate total volume, confirming alignment with the target of approximately 1200 cm^3 ±400 cm^3. Final assembly weight will be measured using a scale to ensure it remains within the 3.5 kg ±1 kg specification.

Static Strength Testing
To validate grip force capability, the hand will be commanded to grasp a set of dumbbells with known weights, ranging from 5 to 25 lbs. The objective is to confirm that the hand can statically hold these weights without slippage or mechanical deformation, meeting the target grip force of 120–160 N.

Durability Testing
A lifecycle test will be conducted on a single finger by repeatedly actuating it through full extension and closure until failure occurs. This procedure is intended to verify that the design meets or exceeds the minimum durability requirement of 10,000 actuation cycles.

Sensor Calibration and Accuracy Verification
Fingertip positional accuracy will be evaluated by commanding the hand to known target positions and measuring deviation. This testing will confirm compliance with the ±0.5 mm tolerance for accurate motion control based on sensor feedback.

User Interface Evaluation
Usability will be assessed by observing how quickly a user can learn to operate the system. Test participants will receive a short demonstration and will then independently run a test scenario. The goal is to ensure the system can be reliably operated within a 10-minute instruction window.

Power and Thermal Testing
The integrated system will be tested under sustained operation to monitor power draw and heat buildup in motors and electronics. This will verify compatibility with standard power sources and ensure safe thermal behavior under normal operating conditions.

Functional Performance Testing
System-level testing will include representative use cases such as piano key actuation and spatial positioning tasks. These tests will assess system response time, coordination between joints, and overall effectiveness in executing dexterous motions.

These planned tests will support design verification, guide final adjustments, and ensure the hand meets both technical specifications and sponsor-defined performance goals.

7 CONCLUSIONS

In this report we went over a lot of different subjects and progress towards the project. Our project is to make a humanoid hand that has as many degrees of freedom as possible. It needs to be able to catch a ball and play the piano as well. We went over all of the literature we have found as well as our mathematical modeling and concept generation. In the end we want to continue with Design 5 and try to build off of it to make it better.

8 REFERENCES

[1] G. Stillfried and P. Thesis, "Kinematic modelling of the human hand for robotics." Accessed: Mar. 08, 2025. [Online]. Available: https://elib.dlr.de/100591/1/Stillfried_phd_main_v1_4.pdf

[2] A. Landi, "Human Hand Function," Journal of Hand Surgery (European Volume), vol. 32, no. 4, pp. 484–485, Aug. 2007, doi: https://doi.org/10.1016/j.jhse.2007.04.015.

[3] "Functional anatomy and biomechanical concepts in the hand," Aofoundation.org, 2016. https://surgeryreference.aofoundation.org/orthopedic-trauma/adult-trauma/further-reading/hand-functional-anatomy-and-biomechanical-concepts(accessed Mar. 08, 2025).

[4] Ł. Jaworski and R. Karpiński, "BIOMECHANICS OF THE HUMAN HAND," Journal of Technology and Exploitation in Mechanical Engineering, vol. 3, no. 1, pp. 28–33, Jun. 2017, doi: https://doi.org/10.35784/jteme.536.

[5] "BIOMECHANICS OF THE HAND," Ouhsc.edu, 2025. https://ouhsc.edu/bserdac/dthompso/web/namics/hand.htm (accessed Mar. 08, 2025).

[6] *U. Scarcia, "Design and Control of Robotic Hands," Mar. 2015. https://amsdottorato.unibo.it/7085/1/Umberto_Scarcia_tesi.pdf (accessed Mar. 08, 2025).*

[7] H. Li et al., "Tactile SoftHand-A: 3D-Printed, Tactile, Highly-underactuated, Anthropomorphic Robot Hand with an Antagonistic Tendon Mechanism," arXiv.org, 2024. https://arxiv.org/abs/2406.12731?utm_source=chatgpt.com

[8] "Servos explained," Sparkfun Electronics, https://www.sparkfun.com/servos (accessed Mar. 8, 2025).

[9] U. Kim et al., "Integrated linkage-driven dexterous anthropomorphic robotic hand," Nature News, https://www.nature.com/articles/s41467-021-27261-0 (accessed Mar. 8, 2025).

[10] Design of tendon-driven robotic fingers: Modeling and ..., http://vigir.missouri.edu/~gdesouza/Research/Conference_CDs/IEEE_ICRA_2010/data/papers/1053.pdf (accessed Mar. 8, 2025).

[11] A modular structured approach using C++, https://tfetimes.com/wp-content/uploads/2015/06/Programming.pdf (accessed Mar. 8, 2025).

[12] Fundamentals of Programming | C++, https://tfetimes.com/wp-content/uploads/2015/04/progcpp.pdf (accessed Mar. 8, 2025).

[13] "Advanced humanoid robotic hand technologies," NASA, https://technology.nasa.gov/patent/MSC-TOPS-102 (accessed Mar. 8, 2025).

[14] X. Li et al., "Finger kinematics during human hand grip and release," Biomimetics (Basel, Switzerland), https://pmc.ncbi.nlm.nih.gov/articles/PMC10296280/ (accessed Mar. 8, 2025).

[15] Emo Todorov, https://roboti.us/lab/index.html (accessed Mar. 8, 2025).

[16]InformedHealth.org. Cologne, Germany: Institute for Quality and Efficiency in Health Care (IQWiG); 2006-. In brief: How do hands work? [Updated 2021 May 20] https://www.ncbi.nlm.nih.gov/books/NBK279362/

[17]P. W. Brand and A. Hollister, Clinical Mechanics of the Hand. St. Louis: Mosby Year Book, 1993.

[18]E. Nazma and S. Mohd, " TENDON DRIVEN ROBOTIC HANDS: A REVIEW," International Journal of Mechanical Engineering and robotics research. doi:10.18178/ijmerr

[19]Zhe Xu and E. Todorov, "Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration," 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 3485–3492, May 2016. doi:10.1109/icra.2016.7487528

[20]Zhe Xu, V. Kumar, and E. Todorov, "A low-cost and modular, 20-DOF anthropomorphic robotic hand: Design, actuation and modeling," 2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids), pp. 368–375, Oct. 2013. doi:10.1109/humanoids.2013.7030001

[21]S. Horibe, S. L. Woo, J. J. Spiegelman, J. P. Marcin, and R. H. Gelberman, "Excursion of the flexor digitorum profundus tendon: A kinematic study of the human and canine digits," Journal of Orthopaedic Research, vol. 8, no. 2, pp. 167–174, Mar. 1990. doi:10.1002/jor.1100080203

[22]"Bionicsofthand," BionicSoftHand | Festo USA, https://www.festo.com/us/en/e/about-festo/research-and-development/bionic-learning-network/highlights-from-2015-to-2017/bionicsofthand-id_68106/ (accessed Feb. 9, 2025).

[23] U. Scarcia, Design and control of robotic hands - Ams Dottorato, March 2021, http://amsdottorato.unibo.it/7085/1/Umberto_Scarcia_tesi.pdf (accessed Feb. 6, 2025).

[24] R. Fourie, "Mechanical design of a biologically inspired prosthetic hand, The Touch hand 3," UKZN, https://researchspace.ukzn.ac.za/server/api/core/bitstreams/eaf25fb9-f9ed-417c-a91a-7ced68cba2c4/content (accessed Feb. 6, 2025).

[25] T. Mańkowski, J. Tomczyński, K. Walas, and D. Belter, "Put-hand-hybrid industrial and Biomimetic Gripper for Elastic Object Manipulation," MDPI, https://www.mdpi.com/2079-9292/9/7/1147 (accessed Feb. 6, 2025).

[26] H. Chen and Z. Wang, "Performance optimizing of pneumatic soft robotic hands using wave-shaped contour actuator," Results in Engineering, https://www.sciencedirect.com/science/article/pii/S2590123024017080?pes=vor&utm_source=scopus&getft_integrator=scopus (accessed Feb. 6, 2025).

[27] P. Corke, in Robot Arm Kinematics, vol. 146, Brisbane: Queensland University of Technology, 2023, pp. 253–305

[28] L. C. Farrell, T. A. Dennis, and J. Badger, "Simply Grasping Simple Shapes: Commanding a Humanoid Hand with a Shape-Based Synergy," in Springer Proceedings In Advanced Robotics, vol. 10, Houston, texas: Rice University, 2020, pp. 541–553

[29] J. Won and M. Iwase, "Highly responsive robotic prosthetic hand control considering electrodynamic delay," MDPI, https://www.mdpi.com/1424-8220/25/1/113 (accessed Mar. 8, 2025).

[37]J.-D. Warren, J. Adams, and H. Molle, Arduino Robotics. Berkley: Apress, 2011.

[38]R. N. Jazar, Theory of Applied Robotics. Springer, 2023.

[39]K. M. Lynch and F. C. Park, Modern Robotics : Mechanics, Planning, and Control. Cambridge: University Press, 2017.

[40]B. M. Yousuf, A. Mehdi, A. S. Khan, A. Noor, and A. Ali, "Robust Feedback Control Design of Underactuated Robotic Hands with Selectively Lockable Switches for Amputees," Journal of Robotics, vol. 2018, p. e6835968, Jun. 2018, doi: https://doi.org/10.1155/2018/6835968.

[41]D. Tuchscherer, A. Weibert, and F. Tränkle, "Modern C++ as a modeling language for automated driving and human-robot collaboration," pp. 136–142, Sep. 2016, doi: https://doi.org/10.1145/2976767.2976772.

[42]PacktPublishing, "GitHub - PacktPublishing/Hands-On-Robotics-Programming-with-Cpp: Hands-On Robotics Programming with C++, published by Packt," GitHub, 2018. https://github.com/PacktPublishing/Hands-On-Robotics-Programming-with-Cpp?tab=readme-ov-file (accessed Feb. 09, 2025).

[43]"Ryan Logsdon / Raspberry Pi Settings for Robotics · GitLab," GitLab, 2025. https://gitlab.com/ryanlogsdon/raspberry-pi-settings-for-robotics (accessed Feb. 09, 2025).

[44] SunFounder Maker Education , "2023 Arduino Tutorial for Beginners 01 - Introduction,", SunFounder Maker Education www.youtube.com. https://www.youtube.com/watch?v=JnJIKX5J0Cc&list=PLwWF-ICTWmB7-b9bsE3UcQzz-7ipI5tbR (accessed Apr. 16, 2025).

[45] juecoreein S. • 3 years ago, "Forward and Reverse Kinematics for 3R Planar Manipulator," Hive, Dec. 21, 2020. https://hive.blog/hive-196387/@juecoree/forward-and-reverse-kinematics-for-3r-planar-manipulator (accessed Apr. 16, 2025).

[46] Eli the Computer Guy, "Arduino - Bidirectional Serial Communication with Raspberry Pi," YouTube, Dec. 12, 2020. https://www.youtube.com/watch?v=OJtpA_qTNL0 (accessed Apr. 16, 2025).
[44] X. Zhou et al., "Design and control of a tendon-driven robotic finger based on grasping task analysis," MDPI, https://www.mdpi.com/2313-7673/9/6/370 (accessed Apr. 16, 2025).
[45] H. Park, "Tendon Optimization for Robotic Hands," CMU Contributed Webserver, https://www.contrib.andrew.cmu.edu/ (accessed Apr. 16, 2025).
[46] F. García-Córdova, A. Guerrero-González, and F. Hidalgo-Castelo, "Anthropomorphic tendon-based hands controlled by agonist–antagonist corticospinal neural network," MDPI, https://www.mdpi.com/1424-8220/24/9/2924 (accessed Apr. 16, 2025).
[47] K. E. Lile and John, "Piano Finders: Touchweight," Pianofinders.com, 2024. https://www.pianofinders.com/educational/touchweight.htm

[48] Pablo, "Tennis Ball Size Guide and Dimensions," Size-Charts.com, Jan. 11, 2023. https://size-charts.com/topics/tennis-ball-size-guide-and-dimensions/

[49] Bjarne Stroustrup and Addison-Wesley (1942-1999, The C++ programming language. Upper Saddle River: Addison-Wesley, Cop, 2018.

[50] L. Brombach, Practical Robotics in C++. BPB Publications, 2021.

[51] O. Kroemer, S. Niekum, and G. Konidaris, "A Review of Robot Learning for Manipulation: Challenges, Representations, and Algorithms," Journal of Machine Learning Research, vol. 22, Jan. 2021, Accessed: Feb. 03, 2025. [Online]. Available: https://www.jmlr.org/

[52] R. Ma and A. Dollar, "On Dexterity and Dexterous Manipulation," presented at the 15th International Conference on Advanced Robotics, Yale, Jun. 2011. Accessed: Feb. 05, 2025. [Online]. Available: https://www.eng.yale.edu/grablab/pubs/Ma_ICAR2011.pdf

[53] M. Santello, M. Flanders, and J. F. Soechting, "Postural Hand Synergies for Tool Use," The Journal of Neuroscience, vol. 18, no. 23, pp. 10105–10115, Dec. 1998, doi: https://doi.org/10.1523/jneurosci.18-23-10105.1998.

[54] "Home," Robot Nano Hand - open source robot hand project. https://robotnanohand.com/

[55] "ethz-adrl/control-toolbox: The Control Toolbox - An Open-Source C++ Library for Robotics, Optimal and Model Predictive Control," GitHub, 2025. https://github.com/ethz-adrl/control-toolbox (accessed Feb. 06, 2025).

[56] "Shadow Robot Company." https://www.shadowrobot.com/

[57] "DexHand - An Open Source Dexterous Humanoid Robot Hand," DexHand - An Open Source Dexterous Humanoid Robot Hand. https://www.dexhand.org/

[58] I. Ali, "Tesla shows Optimus humanoid robot with a new hand — catching balls mid-air (video) - Tesla Oracle," Tesla Oracle, Nov. 30, 2024. https://www.teslaoracle.com/2024/11/30/tesla-tests-optimus-humanoid-robot-with-a-new-hand-catching-balls-mid-air-video/ (accessed Mar. 09, 2025).

[59] "Your connected workspace for wiki, docs & projects | Notion," Notion, 2025. https://willcogley.notion.site/ (accessed Mar. 09, 2025).

[60] Z. Xu, V. Kumar, and E. Todorov, "A low-cost and modular, 20-DOF anthropomorphic robotic hand: design, actuation and modeling," Oct. 2013, doi: https://doi.org/10.1109/humanoids.2013.7030001.

[61] U. Kim et al., "Integrated linkage-driven dexterous anthropomorphic robotic hand," Nature Communications, vol. 12, no. 1, Dec. 2021, doi: https://doi.org/10.1038/s41467-021-27261-0.

[62] Zhe Xu and E. Todorov, "Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration," 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, 2016, pp. 3485-3492, doi: 10.1109/ICRA.2016.7487528. keywords: {Joints;Robots;Bones;Biomechanics;Thumb;Ligaments},

[63]S. Shahid, "Anatomy of grip," Kenhub, Mar. 20, 2016. https://www.kenhub.com/en/library/anatomy/anatomy-of-grip
[64]"What is Arduino, how it works and what you can do with arduino," Circuit Schools. https://www.circuitschools.com/what-is-arduino-how-it-works-and-what-you-can-do-with-arduino/
[65]"The Official Raspberry Pi Beginner's Guide : Gareth Halfacree : Free Download, Borrow, and Streaming : Internet Archive," Internet Archive, Dec. 2018. https://archive.org/details/RPiBeginnersGuide (accessed Apr. 18, 2025).
[66]"What is a robot wrist and why does it matter in automation? - Standard Bots," Standardbots.com, 2025. https://standardbots.com/blog/robot-wrist?srsltid=AfmBOorPjGuavCfruP-uKBNJO0VruurV2xLnhDuz9Kec2Qf3K0j-OekQ (accessed Apr. 19, 2025).
[67]"Gear Ratios," VEX ROBOTICS COMPETITION. https://cariwilliamzvex.weebly.com/gear-ratios.html
[68]Stefano Rodinò, F. Lago, Dmitry Malyshev, and G. Carbone, "DESIGN OF A MOVABLE PALMFOR A 3-FINGERS ROBOTIC HAND," vol. 24, no. 1, Aug. 2023, Available: https://www.researchgate.net/publication/373302265_DESIGN_OF_A_MOVABLE_PALMFOR_A_3-FINGERS_ROBOTIC_HAND
[69] C.-T. Lee and J.-Y. (James) Chang, "Design of hybrid fully actuated and self-adaptive mechanism for anthropomorphic robotic finger," Journal of Mechanisms and Robotics, vol. 15, no. 4, Nov. 2022. doi:10.1115/1.4055061
[70] B. Kim, U. Jeong, and K.-J. Cho, "Dual-tendon routing: Tendon routing for under-actuated tendon-driven soft hand-wearable robot," IEEE Robotics and Automation Letters, vol. 10, no. 4, pp. 3612–3619, Apr. 2025. doi:10.1109/lra.2025.3544056

[71] T. Chen, X. Zhao, G. Ma, B. Tao, and Z. Yin, "Design of 3D-printed cable driven humanoid hand based on bidirectional elastomeric passive transmission," Chinese Journal of Mechanical Engineering, vol. 34, no. 1, Aug. 2021. doi:10.1186/s10033-021-00595-y

9 APPENDICES

9.1 Appendix A: Data for Grip Angle Positioning and Code grip angle positioning

Finger	DOF	Base Joint Max Angle (deg)	Middle Joint Max Angle (deg)	Tip Joint Max Angle (deg)	Max Total Angle (deg)	Max Splay Angle (deg)
Index	4	100	135	90	265	45
Middle	4	100	135	90	325	25
Ring	4	100	135	45	280	30
Pinky	4	100	120	90	310	45
Thumb	4	90	X	90	270	90
Thumb Hinge	1	90	X	X	90	X

Finger	DOF	Base Joint Angle (deg)	Middle Joint Angle (deg)	Tip Joint Angle (deg)	Total Angle (deg)	Splay Angle (deg)
Index	4	0	0	0	0	0
Middle	4	100	135	90	325	0
Ring	4	100	135	45	280	0
Pinky	4	100	120	90	310	0
Thumb	4	45	X	45	90	90
Thumb Hinge	1	90	X	X	90	X

Finger	DOF	Base Joint Angle (deg)	Middle Joint Angle (deg)	Tip Joint Angle (deg)	Total Angle (deg)	Splay Angle (deg)
Index	4	45	45	30	120	15
Middle	4	45	45	30	120	15
Ring	4	45	45	25	115	10
Pinky	4	45	45	15	105	25
Thumb	4	60	X	20	80	90
Thumb Hinge	1	80	X	X	80	X

Finger	Tip/Middle Ratio	Tip Joint Angle Equation
Index	.667	$\theta_{Tip} = .667\theta_{Mid}$
Middle	.667	$\theta_{Tip} = .667\theta_{Mid}$
Ring	.556	$\theta_{Tip} = .556\theta_{Mid}$
Pinky	.333	$\theta_{Tip} = .333\theta_{Mid}$