DESIGN AND MANUFACTURING OF UPPER LIMP PROSTHESIS

By

Hadia Madni NUST 2012 00395

Supervised By

Dr. Yasar Ayaz

HOD Robotics and Artificial Intelligence

School of Mechanical and Manufacturing Engineering,
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A thesis submitted in partial fulfillment of the requirements for the degree of Bachelors of Engineering in Mechanical Engineering

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June, 2016

National University of Sciences & Technology

FINAL YEAR PROJECT REPORT

We hereby recommend that the dissertation prepared under our supervision by: Hadia Madni – NUST-2012-00395 Titled: Design and Manufacturing of Upper Limb Prosthesis be accepted in partial fulfillment of the requirements for the award of Bachelors of Engineering in Mechanical Engineering degree with (_____ grade)

English and format checked by Ms. Aamna Hassan, Signature:_________________

Guidance Committee Members

1. Name:___________________________ Signature:_________________

2. Name:___________________________ Signature:_________________

3. Name:___________________________ Signature:_________________

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Declaration

I/We certify that this research work titled "*Design and Manufacturing of Upper Limb Prosthesis"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student
Hadia Madni
NUST 2012 00395

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Dedicated to my parents

Acknowledgments

First of all I would thank ALLAH Almighty, who gave me knowledge and dedication to be able to complete this research.

I would like to thank my parents for their endless support throughout my university career. Without their support and guidance, I do not think I would have made it through undergraduate engineering. Next I would like to thank my supervisor Dr. Yasar Ayaz for his supervision of this design project. His seemingly endless source of enthusiasm and intelligence made this project a reality.

In addition, I would like to thank DMRC for their support in the manufacturing process and design consultations.

Finally I would like my classmates from Mechanical Engineering class of 2016 and my friends including Aamin Fahad without whose support, the project would have never made it into the fabrication phase, Bilal Anjum for material and parts provisions and Hashim Khan who helped with material selections.

Abstract

Hand amputation is an extremely traumatic experience for a patient; it has been observed that patients that experience the loss of a limb have developed mental and emotional disorders. In order to improve the overall quality of life for hand amputee patients, a number of prosthetic devices are available on the market today. Many of these devices fail to approach the level of dexterity possible of the human hand.

Presented in this paper is the design of a prosthetic hand prototype titled Pro-Active undertaken by our team from RISE Lab SMME that attempts to duplicate some of the high dexterity of the human hand while keeping the cost and weight as low as possible. Using an adaptive grasp system and an innovative finger transmission design, the team aimed to design and fabricate an affordable, light weight, multi degree of freedom prosthetic hand prototype.

The transmission system of the prosthetic mechanism was the major focus of attention which needed to be compliant with three phalanges without the expense of significant added weight.

The work started with a detailed literature review of commercial and research prosthetic options. After a thorough study of research papers and articles, CAD models were prepared for the two identified prosthetic hands (Bebionic and iLimb) allowing us to understand their transmission mechanisms and specifications and a design incorporating their best features was prepared

The findings of the project predominantly from the mechanical engineering perspective were extensive. The team discovered the importance of the smallest factors in the whole assembly, Apart from that; the team discovered various alternative solutions to complex designs and issues during the fabrication stage. The final system that was fabricated was the simplest and most affordable and dexterous system that could have been prepared. A few problems the team encountered included material availability, costs and design complexity and local manufacturing limitations & inaccuracies.

Keywords: prosthetic, upper limb, dexterity, multi-degree-of-freedom

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Symbols

Al 1100	Aluminum Based Alloy
Al 7075	Aluminum Alloy with Zinc as main Alloying Element
E	Elastic Modulus
PIP	Proximal Interphalangeal Joint
MIP	Medial Interphalangeal Joint
DIP	Distal Interphalangeal Joint
ADL	Activities of Daily Life

Chapter 1
Introduction

RISE bionics group is a new found interdisciplinary research group founded under the super vision and agenda of Dr. Yasar Ayaz (HOD R&AI). The group aims to ultimately develop a state of the art fully functional robotic hand coupled with myoelectric control to be used by trans-humeral and trans-radial amputees. This aspect of research in bio-mechatronics is an international focal point with around 4 already commercial fully functional prosthetic hands and a large number of research prosthetic hands from research institutes around the world focused on the same goal that the RISE bionics team intends to play their part in.

For our prototype which was a first from the RISE bionics group, the mechanical part of the team was led by Miss Hadia Madni who was responsible for the design, and fabrication of the first prototype of the innovative prosthesis option.

This document contains all the literature review work, methodology, findings and drawings of the work done by RISE Bionics Group in order to completely manufacture their own first prototype of an affordable compliant prosthesis option that could be worked on further by subsequent teams. The group started their work on this project in September 2015.

The ultimate motive of developing a local affordable myoelectric prosthetic hand for trans-radial amputees is dependent on the success of this project and RISE Bionics Group SMME hopes that their work adds significantly to it.

1.1 Background

Hand amputations and loss of a limb fully or partially have been shown to result in anxiety disorders, pain syndromes and adjustment problems. According to statistics, 94% of the individuals with a severe hand injury resulting in an amputation experience symptoms associated with one of these disorders. Their symptoms generally include; cognitive difficulties, concerns regarding disfigurement and phantom limb sensation. In cases where reattachment is not possible due to the extent of injury, prosthesis options are available in order to regain some of the lost dexterity.

The human hand itself is extremely difficult to model; with our attempt to duplicate the high dexterity of actions it can perform, did we truly learn and appreciate the complex structure of human hand. The internal skeletal structure of the human hand and finger is shown in *figure*; the proximal, intermediate and distal phalanges in the finger, and the metacarpals in the palm. These bones have a network of tendons that connect to the base of each of the phalanges in order to curl the fingers for hand gestures.

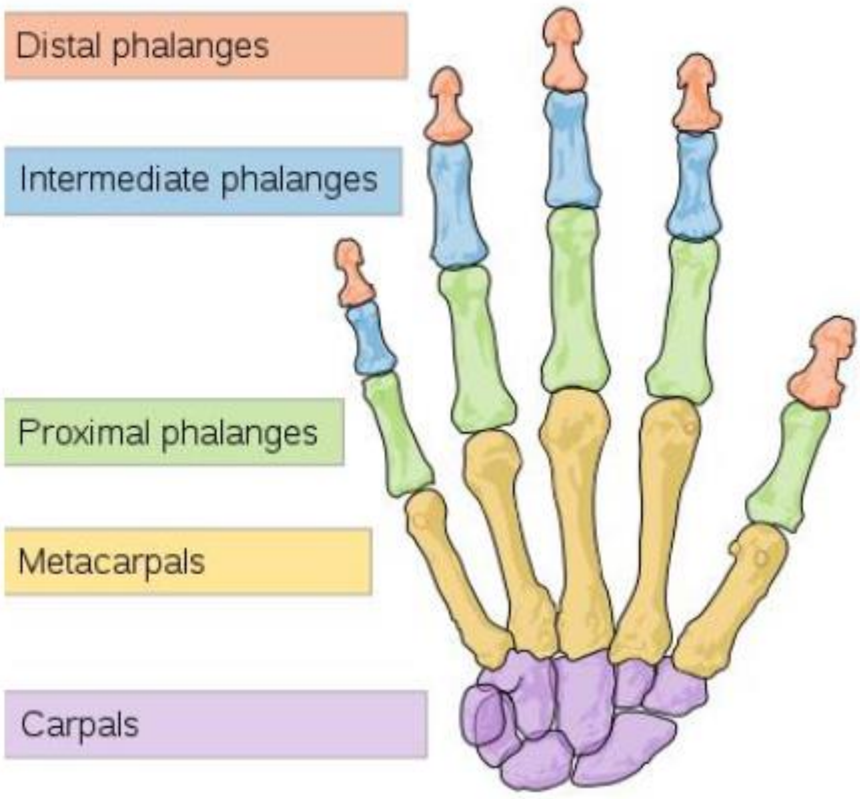

Figure1:a Bone Structure of Hand

The digitorum superficialis and profundus tendons, are connected from the base of the phalanges to the flexor digitorum muscles in the upper forearm. Upon contraction this muscle will pull on the tendons, which in turn will curl the fingers.

Our project comprised of designing of mechanisms for the curling and movement of fingers for gestures, locking mechanism for the thumb, and implementation of two types of transmission mechanism for the finger digits to achieve desired dexterity: the linkage based system and the pulley tendon based mechanism, both of which were combined into an innovative design for prototype.

1.2 Transmission

The two types of grasp transmission systems were compared according to their features shown in table and was thus decided that a linkage based mechanism will be employed in the index and middle finger, while the ring finger, little finger and thumb will work with a tendon based mechanism driven by pulleys.

Table 1:a Comparison of Transmission Mechanisms

Tendon Transmission	Linkage Transmission
High Strength to Weight Ratio	Higher gripping force at the expense of higher weight
Constant Application of Force	Greater load bearing capacity
Greater Time Delay and Power Losses	Quick Response
Instability and Non Precision of Grasp	Stable Grasp with capability to withstand large forces
Less Robust/ More Compliant	More Robust, Less Compliant
High Maintenance Frequency	Lower Maintenance Frequency
Precision Grip, Lateral Grip, Tripod Grip	Index Point, Power Grasp, Ball Grasp

1.3 Linkage Based Mechanism

The index finger and the middle finger which predominantly share the load and are involved in most Activities of Daily Life (ADL) have been designed according to a linkage based mechanism. The mechanism has been extracted from Bebionic with an added phalange for compliance according to the prosthetic hand design proposed by Tokai University, Japan in 2014. The linkage design consists of Aluminum links pivoted by pins to form a compound four bar linkage system. The bar linkages were driven by a crank getting torque from the motor shaft through the worm and worm gear assembly. Due to strict budget limits, Al 1100 was used for the links, while the pins were made of tool steel. The mechanism rested in a brass bushing and a mild steel crank connected to Delrin gears and the motor. The overall mechanism targets quick acceleration, robustness and lower maintenance frequency. Low weight and manufacturability were high priority secondary considerations. Manufacturability, ergonomics, low backlash, and chassis constraints were all high priority secondary considerations. Shown in Figure is the final assembly model of the linkage based finger design, which the index finger and middle finger of proactive employ.

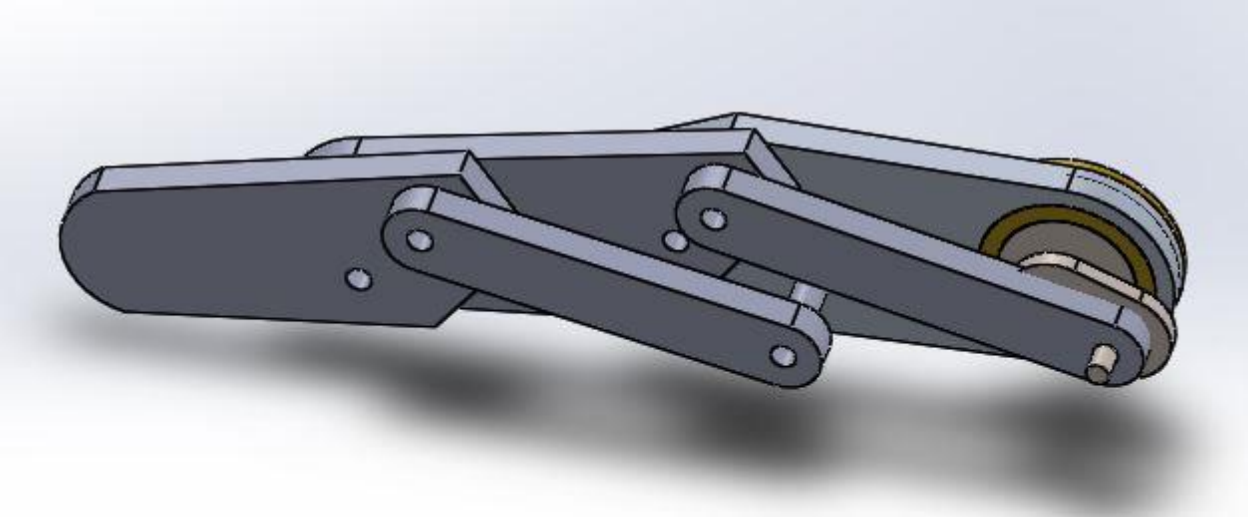

Figure1:b Finger with Compound Four Bar Linkage Design

There are multiple unique features that make the system ideal for the intended application. The crank mechanism, which the team has never seen implemented, allows the compound four bar to be driven into a curled shape when it encounters an object and serves as a replacement for planetary gears which are difficult to manufacture locally. The result was a functional and adaptively curling finger with compromised mechanical advantage as compared to a planetary gear system but higher dexterity in comparison with the Bebionic design because of an added distal phalange.

1.4 Tendon Based Mechanism

The tendon based mechanism is used in the ring finger, the little finger and thumb to add compliance to the fingers with lower weight despite slower response rate. The tendon wire we used was carbon fiber wrapped around nylon pulleys to achieve the desired curl. The pulley ratio was implemented by varying pulley diameters to achieve the anthropomorphic curl of proximal, intermediate and distal phalange in connection. The tendon is wound around a winch which is driven by a Delrin worm gear assembly. The pulleys act as pivot points for pin joints of Aluminum links. The tendons were kept in tension by the use of extension springs attached at the base which backdrive the finger when not in use. This system has been successfully implemented by using a DC geared motor for actuation. The tensioning of tendon wire was a major concern in this mechanism and the costs factored into additional weight because of aluminum links for phalanges.

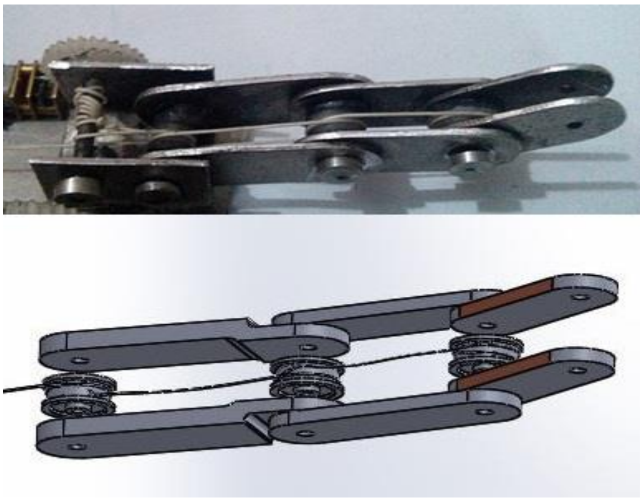

Figure 1.c Finger with Tendon Pulley Mechanism

1.5 Thumb Lock Mechanism

The locking mechanism for thumb was inspired from the bebionic and is manual. The thumb has two positions to set itself into a locked position according to lateral and ball grasp positions to account for circumduction in human thumb. The two locking positions are ensured using a toggle spring switch lock mechanism as shown in figure.

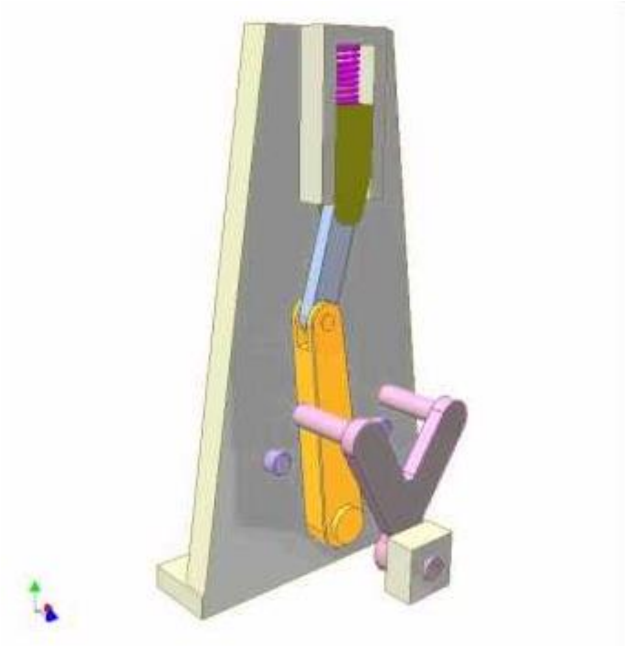

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Figure 1.d Thumb Locking Mechanism

A compression spring with a cylindrical plunger acts as the toggle mechanism shifting thumb axis. These two positions are manually adjusted and then the curling of the thumb is ensured through a motor pulling on a tendon cable wound around a nylon pulley.

1.6 Scope

The initial scope of this project was to design a fully functional prototype of a prosthetic hand integrated with EMG electrodes that could accurately mimic human motions that are generally considered Activities of Daily Life (ADL). A prosthesis with the ability to mimic all possible human hand gestures was too complex to be under the scope of this project but has been a primary focus for biomechanics research groups around the world.

Our goal was to develop a prosthesis having two locking positions for the thumb to ensure all 6 grasps that constitute the ADL allowing the articulations to appear as natural as possible. These six activities of daily life were:

- **Precision Grip**:
  It constitutes 30% ADL. For this grip, the index finger is the only powered joint it is usually associated with picking up small objects (fine manipulation).

- **Power grip (Cylindrical Grasp)**:
  It constitutes 35% ADL and for this grasp, all fingers are powered simultaneously. It is generally for activities involving holding cylindrical objects

- **Key Grip (Lateral Pinch**):
  It constitutes 20% ADL and for this grip, the thumb flex is the only powered joint. It is employed for holding thin objects e.g. spoon, money.

- **Ball Grasp (Spherical):**
  For this grasp, all fingers except the thumb are powered simultaneously providing maximum gripping strength on round objects.

- **Open Palm Grasp:**
  For this grasp, all fingers except the thumb are powered simultaneously.

- **Index Point:**
  For this function, only the index finger is powered. It is used for pressing buttons.

Initially the scope of the project included the actuation of 6 different gestures, and to include a 2 degree of freedom wrist joint to mimic the pronation/supination and curling/extending of the wrist. However, over the course of the year, the scope of the project was narrowed from its slightly over ambitious beginnings to focus on 4 grasps of the hand, namely, Open Palm Grasp, Power Grip, Lateral Pinch and Index Point and ensuring that these actions were emulated in the prosthesis as accurately as possible.

Chapter 2
Literature Review

The team had to go through an extensive literature review before the work on the designing of each system was started. A number of articles and research & conference papers were thoroughly studied for the initial stage of the project

The current major problem with most available prosthesis is that they lack the ability to accurate replicate the dexterity of the human hand. There are 19 joints alone in human hand, each with its network of individual muscles allowing for fine motion and multiple degrees of freedom. In order to achieve a more natural prosthesis, despite not being able to replicate all DOF of the human hand, the four postures previously mentioned were delved into.

2.1 Actuation

The literature review allowed a comparison between various drive trains or actuations methods. A study of various actuation methods and their benefits versus cons allowed us to reach the following conclusive table.

The specifications for each actuator was compared with a set of specifications rated in order of importance based on the requirements for possible designs, recommendations in research articles and journal papers and commercial actuators used in prosthetics.

Motor	Performance %	Bandwidth (Hz)	Energy Storage Capacity	Robustness	Specific Power (W/kg)	Volumetric Power (W/m^3)	Required Transmission	Self-Braking	Noise	Control	Safety
SMA	--	--	+	-	0	0	--	0	++	-	-
Pneumatic Cylinder	0	+	-	+	+	+	0	+	-	-	0
Hydraulic Cylinder	+	0	--	0	+	+	++	++	0	0	0
Pneumatic Motor	0	+	-	+	0	0	-	+	-	-	0

Hydraulic Motor	+	0	--	0	+	++	+	++	0	0	0
Ultrasonic Motor	-	++	0	-	0	0	+	++	+	-	-
DC Motor	+	+	++	+	-	-	0	0	0	++	++
Brushless DC Motor	+	+	++	++	0	0	0	0	0	+	++
Stepper Motor	0	+	++	++	-	-	+	+	0	++	++

Table 2:a Comparison of Actuation Methods

After considering various parameters including the ones mentioned in the table, we decided to choose a 12V 100 RPM DC geared motor for our application because of its availability, high payload, high torque and low speed among other characteristics.

2.2 Comparison of Existing Prosthetic Hands

In parallel with the selection of the actuator, we thoroughly studied and reverse engineered famous commercial and research prosthetic hands which lead us to the interesting results.

These results are mainly the background for this report and our project.

While studying general characteristics of prosthetic hands available commercially and analyzing their actuation and transmission methods against their weight and other outcomes we rated each mechanism and its specifications against our desired specifications.

During this step it was very important to review the recommendations and faults presented by each research group working on biomechanics that we reverse engineered and then design our hand accordingly.

The following table accurately displays our findings for commercial hands and their general characteristics that have published

Name	Developer	Weight (g)	No. of Joints	Degrees of Freedom	No. of Actuators	Actuation Method	Joint Coupling Method	Adaptive Grip
SensorHand (2011)	Otto Bock	350 – 500	2	1	1	DC Motor	Fixed Pinch	No
Vincent Hand (2010)	Vincent Systems	-	11	6	6	DC Motor – Worm Gear	Linkage Spanning – MCP to PIP	Yes
iLimb (2009)	Touch Bionics	450 – 615	11	6	5	DC Motor – Worm Gear	Tendon Linking MCP to PIP	Yes
iLimb Pulse (2010)	Touch Bionics	460 – 465	11	6	5	DC Motor – Worm Gear	Tendon Linking MCP to PIP	Yes
Bebionic (2011)	RSL Steeper	495 – 539	11	6	5	DC Motor – Lead Screw	Linkage Spanning – MCP to PIP	Yes
Bebionic v2 (2011)	RSL Steeper	495 – 539	11	6	5	DC Motor – Lead Screw	Linkage Spanning – MCP to PIP	Yes
Michelang-lo (2012)	Otto Bock	420	6	2	2	-	Cam design with links to all fingers	No

Table 2:b General Characteristics of Commercial Prosthetic Hands

After studying general characteristics, specific mechanical characteristics were compared to aid us in the design of our innovative prototype.

It was important at this step to analyze each mechanism against its force outputs and figures so that we could make recommendations and design our hand accordingly eliminating the features that have been proven to have problems. Most of the information we found was from research articles and review papers but some of it had to inferred from our reverse engineering models that we made of these commercial hands.

The reverse engineering was done according to images and specifications mentioned on official websites. Models were prepared based on the images displayed with their specifications in specification sheets. Their possible grips and grasps were also analyzed and characterized. These specifications obtained from research papers and kinematic analysis of existing commercial hands led us to the following comparative conclusions.

Name	**Grip Force**			**Range of Motion**						**Grasp Type**	
	Precision Grasp (N)	**Power Grasp (N)**	**Lateral Pinch (N)**	**MCP Joint (deg)**	**PIP Joint (deg)**	**DIP Joint (deg)**	**Thumb Flexion (deg)**	**Thumb Circumduction (deg)**	**Thumb Circumduction Axis**	**Grasp Speed**	**Achievable Grasps**
SensorHand (2011)	NA	100	NA	0 – 70	NA	NA	0 – 70	NA	None	Up to 300 mm/s at tip	Power
Vincent Hand (2010)	-	-	-	0 - 90	0 – 100	NA	-	-	Parallel with wrist axis	-	Power, Precision , lateral, hook, finger point
iLimb (2009)	10.8	-	17 - 19.6	0 – 90	0 – 90	-20	0 – 60	0 – 95	Parallel with wrist axis	200 mm/s	Power, Precision , lateral, hook, finger point
iLimb Pulse (2010)	-	136	-	0 – 90	0 – 90	-20	0 – 60	0 – 95	Parallel with wrist axis	1.2 s (power grasp)	Power, Precision , lateral, hook, finger point
Bebionic (2011)	34 (tripod)	75	15	0 – 90	10 – 90	-20	-	0 – 68	Parallel with wrist axis	1.9 (power grasp) 1.5 – 1.7 s (key grasp)	Power, Precision , lateral, hook, finger point
Bebionic v2 (2011)	34 (tripod)	75	15	0 – 90	0 – 90	-20	-	0 – 68	Parallel with wrist axis	0.9 (power grasp) 0.9 s (key grasp)	Power, Precision , lateral, hook, finger point
Michelanglo (2012)	70	NA	60	0 – 35	NA	NA	-	-	Compound axis	-	Opposition ,Lateral and Neutral Mode

Table 2:c Grip and Kinematic Characteristics of Commercial Prosthetic Hands

Our detailed analysis after the initial analysis and reverse engineering was narrowed down to Bebionic, iLimb and their versions. Their fingertip forces were analyzed and compared for comparative reference with our prototype.

Finger	Force (N)	Number of trails	Standard Deviation
Vincent Large (Index, Middle, Ring)	4.82 or 8.44	14 or 8	0.8 or 1.3
Vincent Small (little)	3.00	2	0.1
iLimb Large (Middle)	7.66	2	0.1
iLimb Small (Little)	5.17	2	0.1
iLimb Pulse Med (Index)	4.15 or 6.54	1	-
iLimb Pulse Med (Middle)	3.09 or 6.24	2	0.7 or 0.4
iLimb Pulse Med (Ring)	6.43 or 11.18	2	0 or 0.3
iLimb Pulse Small (Little)	4.09 or 8.56	2	0.1 or 0
Bebionic (Index)	12.47	1	-
Bebionic (Middle)	12.25	2	1.0
Bebionic (Ring)	12.53	2	1.1
Bebionic Small (Little)	16.11	2	0.2
Bebionic v2 Large (Index, Middle, Ring)	14.5	2	1.2

Table 2:d Individual Finger Tip Holding Force

Hand	Lateral Grasp			Palmer Grasp			Power Grasp		
	Total Force (N)	**No. of Trials**	**Standard Deviation**	**Total Force (N)**	**No. of Trials**	**Standard Deviation**	**Total Force (N)**	**No. of Trials**	**Standard Deviation**
iLimb Pulse	17.4 or 32.1	3 or 3	2.8 or 2.0	10.82 or 17.11	2	0.5 or 0.3	Large Grip (62.5 or 71.44) Small Grip (50.8)	Large Grip (1 or 2) Small grip (1)	-
Bebionic	17.61	1	-	29.47	1	-	77.37	1	-
Bebionic v2	16.4	4	3.2	22.53	4	1.5	62.4	6	10.3
Michelangelo	50.84	4	3.1	78.14	8	4.4	Grasp Type Unachievable	Grasp Type Unachievable	Grasp Type Unachievable

Table2:e Overall Grasp Holding Force during Grasp Postures

In addition to the commercial hands, we studied a few research hands from various biomechanics research groups and compared their actuation and transmission methods in addition to other general prosthetic hand characteristics.

Name	**Weight**	**Number of Joints**	**Degree of Freedom**	**Number of Actuators**	**Actuation Method**	**Joint Coupling Method**	**Adaptive Grasp**
TBM Hand (1999)	280	15	6	1	DC Motor with Linear Ball Screw	Compliant Springs	Yes
MANUS Hand (2004)	1200	9	3	2	Brushless DC Motor	Fied Coupling of MCP, PIP and DIP	No
DLR/HIT I (2004)	2200	17	13	13	Brushless DC Motor with Planetary Drive	1:1 coupling of two distal flexion joints	No
DLR/HIT II (2008)	1500	20	15	15	Brushless DC Motor with Harmonic Drive	1:1 coupling of two distal flexion joints	No
UNB Hand (2010)	-	10	5	3	DC Motor	Fixed Coupling of PIP to MCP	Yes
Smart Hand (2009)	520	16	16	4	DC Motor	Tendon Spring Based	Yes
Vanderbult Hand (2009)	580	16	16	5	Brushed DC Servo Motors mounted on forearm	Single Cable for each Finger	Yes
SouthHamption Hand (2001)	-	8	4	2	DC Motor	Wiffle Tree along finger	Yes

Table2:f General Characteristics of Research Prosthetic Hands

The comparative general characteristics analysis was followed by a force and kinematic analysis after reverse engineering, the results, the motion and force specifications' conclusions depicted in the table.

Name	**Grip Force**		**Range of Motion**						**Grasp Type**	
	Precision Grip (N)	**Power Grasp (N)**	**MCP Joint (deg)**	**PIP Joint (deg)**	**DIP Joint (deg)**	**Thumb Circumduction (deg)**	**Thumb Circumduction Axis**	**Thumb Flexion**	**Grasp Speed**	**Achievable Grasps**
TBM Hand (1999)	14	-	0 – 90	10 – 50	10 – 50	-45 – 70	Parallel with wrist axis	-	90 deg in 4-5 s	Power, Precision, Lateral, Hook, Tripod
MANUS Hand (2004)	60	-	0 – 45	0 – 55	0 – 70	10 - 85	45 deg towards thumb	-	Full grasp in 1.2 s	Power, Precision, Lateral, Hook
DLR/HIT I (2004)	7	-	0 – 90	-	0 – 90	0 – 90	Parallel with wrist axis	-	180 deg / s	Power, Precision, Lateral, Hook, Finger Point, Tripod, Counting
DLR/HIT II (2008)	10	-	0 – 90	0 – 90	0 – 90	-20 – 20	None	Same as fingers	-	Power, Precision, Lateral, Hook, Finger Point, Tripod, Counting
UNB Hand (2010)	-	-	0 – 90	0 – 90	-	0 – 120	Parallel with wrist axis	PCP Joint only	-	Power, Precision, Lateral, Hook, Finger Point, Tripod
Smart Hand (2009)	-	-	0 – 90	-	-	0 – 120	40 deg towards little finger from wrist axis	-	1.4 s for full open/ close Thumb flexion in 0.67 s	Power, Precision, Lateral, Hook, Finger Point, Tripod, Counting
Vanderbult Hand (2009)	20	80	0 – 90	0 – 90	0 – 90	-10 – 80	15 deg towards little finger from wrist axis	-	225 deg/s 0.4s to close	Power, Precision, Lateral, Hook, Finger Point
SouthHamption Hand (2001)	45	-	-	-	-	-	-	PIP Joint only	Full close < 1.2s	Precision, Tripod

Table 2:g Grip and Kinematic Characteristics of Research Prosthetic Hands

In conclusion from the literature review, we analyzed a linkage based system a tendon based system with their applications and then designed our model based on the results.

Chapter 3
Methodology

The methodology of the team's work involved 4 phases: Designing, Fabrication, Assembly and Conclusion. Each phase was given its required time during the complete period of one year.

To approach the design of this hand prosthetic, multiple designs was chosen from the literature study and extensive work was done to adapt and improve the design amalgam to fit the scope of this design project. The chosen design was the iLimb hand, SouthHampton hand, the Bebionic Hand and the Kazuki Hand; this design had many of the desired properties that were rated in order of importance.

The initial design for the individual pieces of the prosthetic was drafted on paper with sample dimensioning for relative design. This was followed by a machinability consult with the machinist resulting in a change in design of the finger linkages and the pulleys. After an improved design and a second machinability consult, the design was approved. The next step was generating a computer model of the prosthetic in Solidworks, and overcoming the major challenges of detailed dimensions and potential collisions.

Next a number of parts including motors, springs were obtained and incorporated into the prototype design. After the final design was completed, the drawings were submitted to the machinist, for fabrication and construction of the first prototype of the prosthetic hand.

The phases were all carefully planned out before execution, and even though a few problems arose during the design and the fabrication phase, the original timeline of the project was not exceeded.

3.1 Design

The designing phase was where the entire work began. The designing phase included the decision making and the knowledge gained through literature review.

After the literature review, and comparative reverse engineering analysis, we decided to allocate mechanisms according to the applications of fingers which is why the fore finger and middle finger were designed with a compound four bar linkage based mechanism while the ring finger, the little finger and the thumb were designed by a pulley tendon mechanism..

The reason for the former choice was because of the need for robustness, tighter grip, quicker response time, ability to apply greater force, lower maintenance frequency and the room for lower compliance and higher weight in the first two fingers. The latter choice was the because of the need for greater compliance, lower weight, higher weight bearing capability, and the allowance for greater response time and greater maintenance frequency in the ring finger, little finger and the thumb.

The motors used were 12V, 0.42 Nm nominal torque and 120 RPM DC geared motors.

For the fingers, the motor assembly drove Delrin worm gears with the reduction ratio of 5.4:1. The additional reduction lowered the speed, increased the input torque and shifted the axis of the motor shaft so as to incorporate it in a human hand dimensioned palm base sheet.

The compound four bar linkage mechanism was allowed for the reduced nominal torque so as to provide the nominal force output comparable with the Bebionic and iLimb. Its force diagram is displayed below.

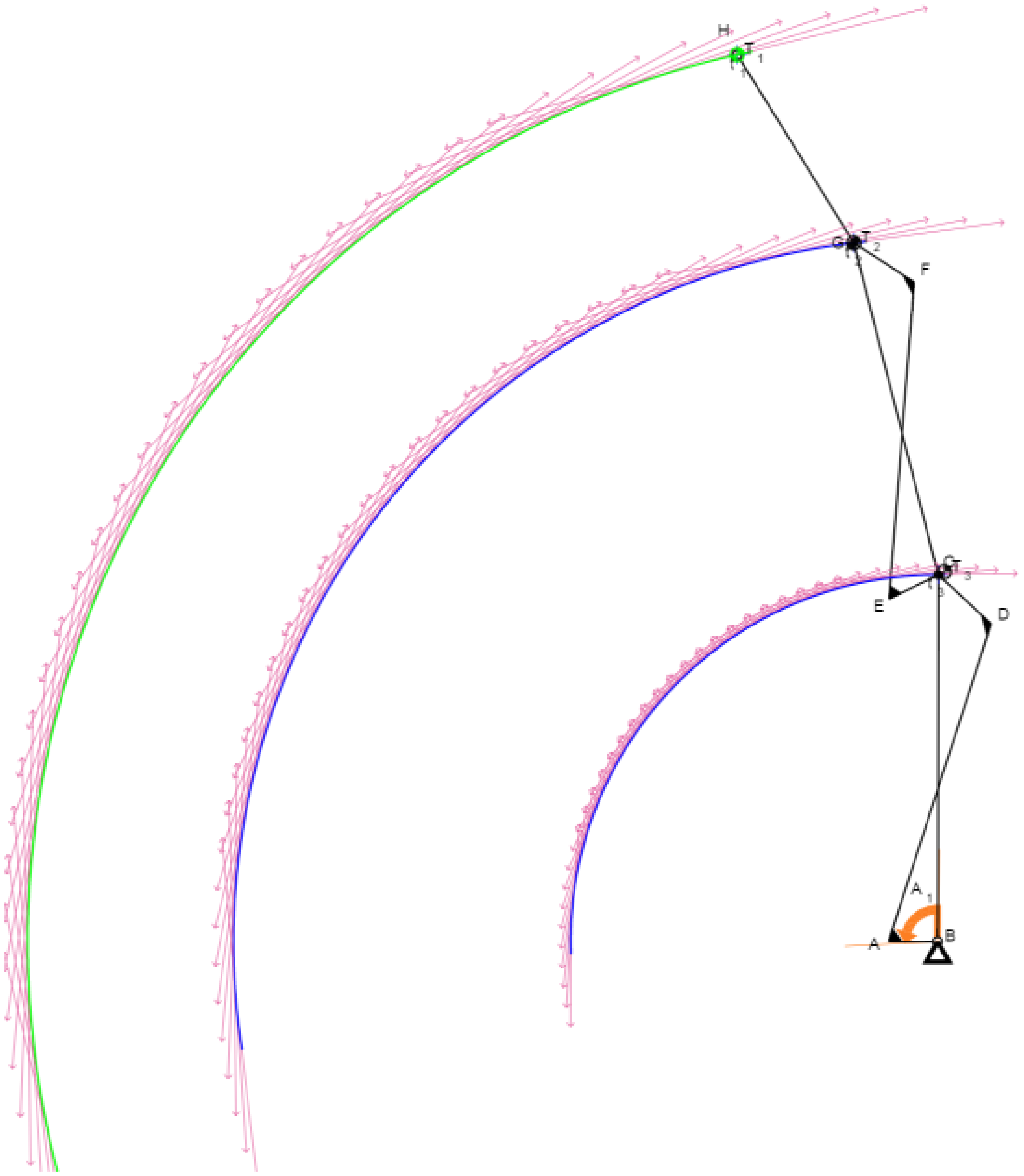


Figure3:a Range of Motion: Compound 4 bar linkage Mechanism

We initially decide for the compound four bar linkage to be driven by planetary worm gears but due to unavailability of worm gears in such dimensions and budget constraints, we had to compromise on the mechanical advantage by designing a crank mechanism inside a brass bushing driven by the motor through the worm gear assembly.

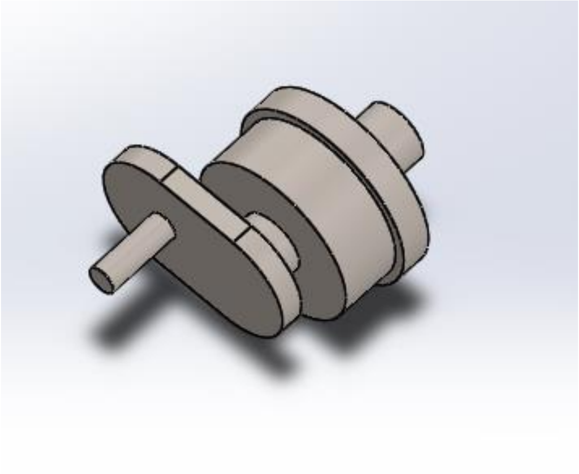


Figure3:b Crank Model

We had the fingertip and grasps force output figures to compare with from our literature review of iLimb and Bebionic. The compound 4 bar linkage was designed to have similar force, speed and torque characteristics.

The following list of figures displays the fingers' kinematic analysis with each joint under consideration. The free body diagrams with their forces and how the forces travel through the joints on the application of an externally defined force on the fingertip.

This analysis led us to accurately design our mechanism's torque requirements that would be suitable for the chose motors because motors were a major factor contributing in weight and size.

Our motors' dimensions were decided according to the space constraints in a human hand and the maximum torque, such a motor could provide.

It was a challenge to accurately design the mechanism to be able to run under the available torque. This analysis was performed in Autodesk Force Effect.

The images displayed are from our project's analysis in Autodesk Force Effect.

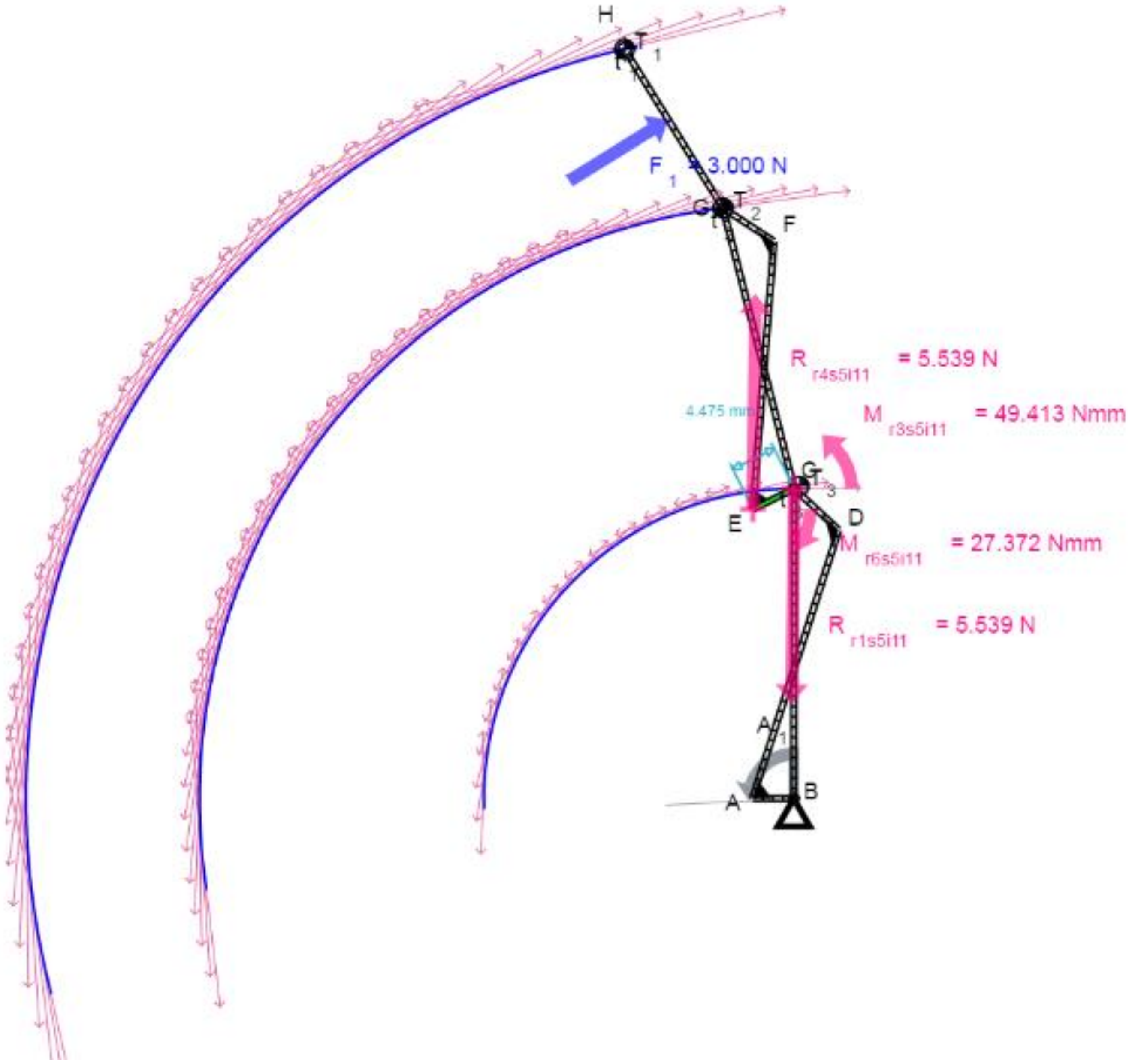


Figure3:c Compound 4 Bar Linkage - Kinematic Analysis - A

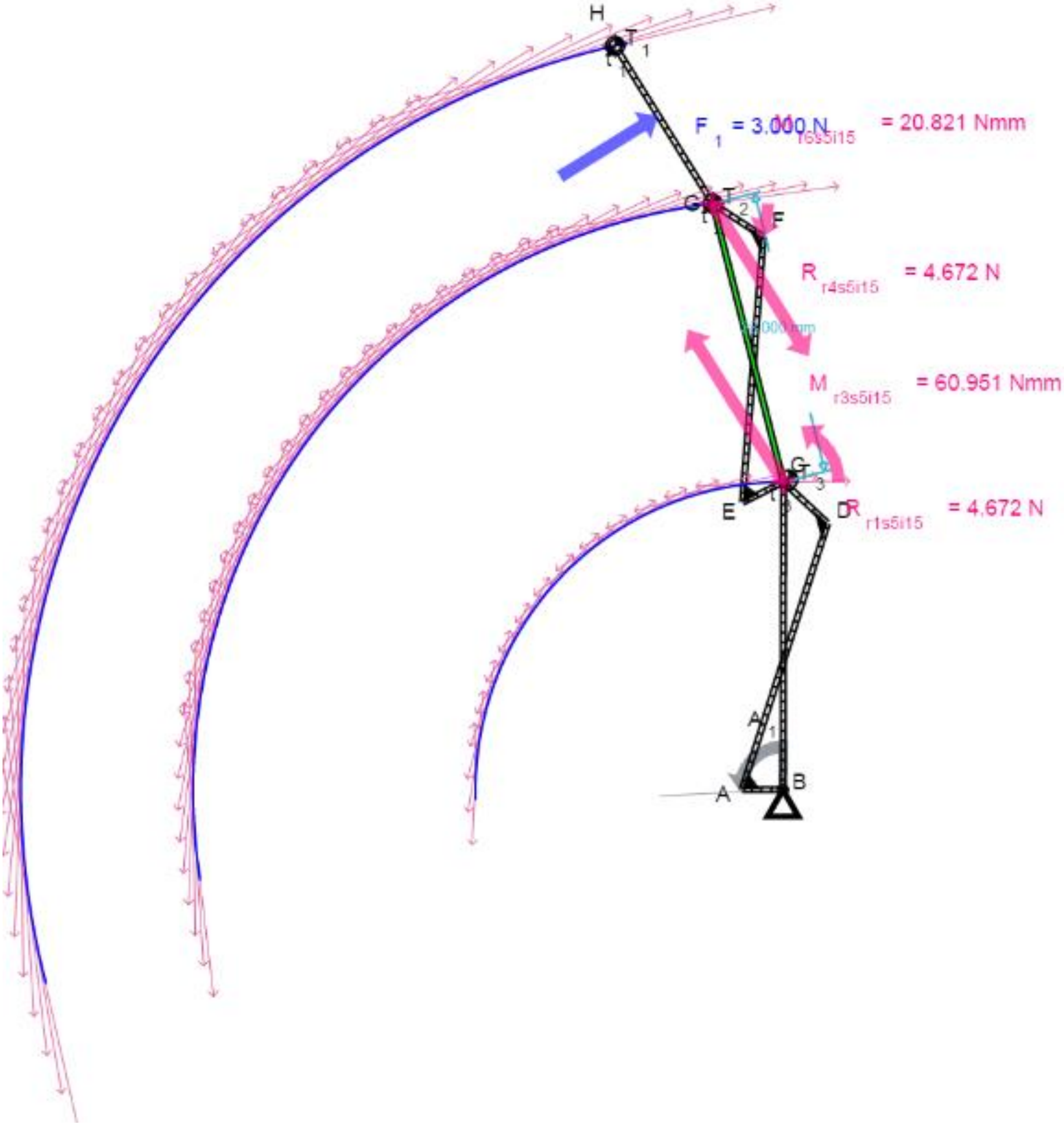


Figure3:d Compound 4 Bar Linkage - Kinematic Analysis - B

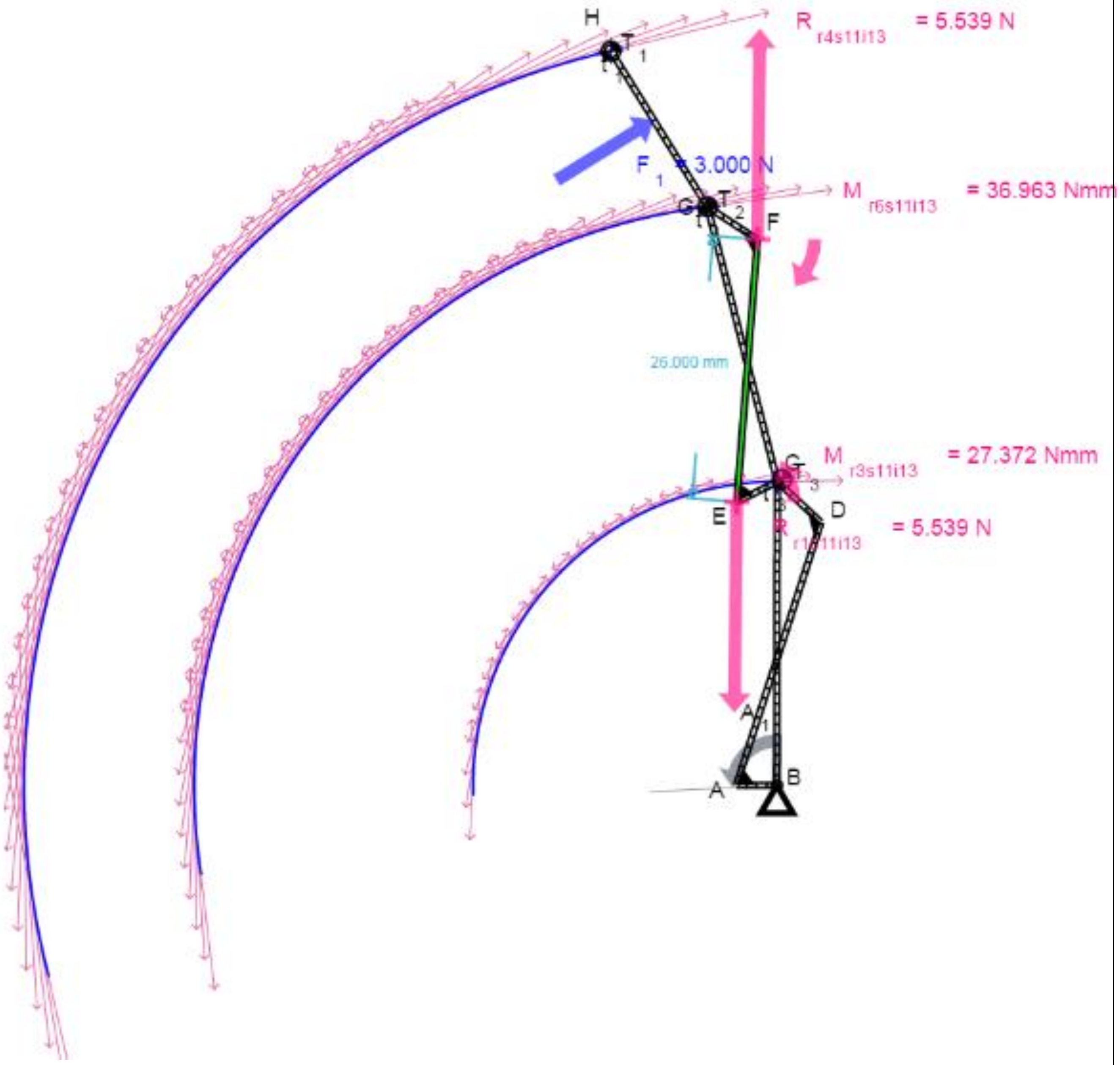


Figure3:e Compound 4 Bar Linkage - Kinematic Analysis - C

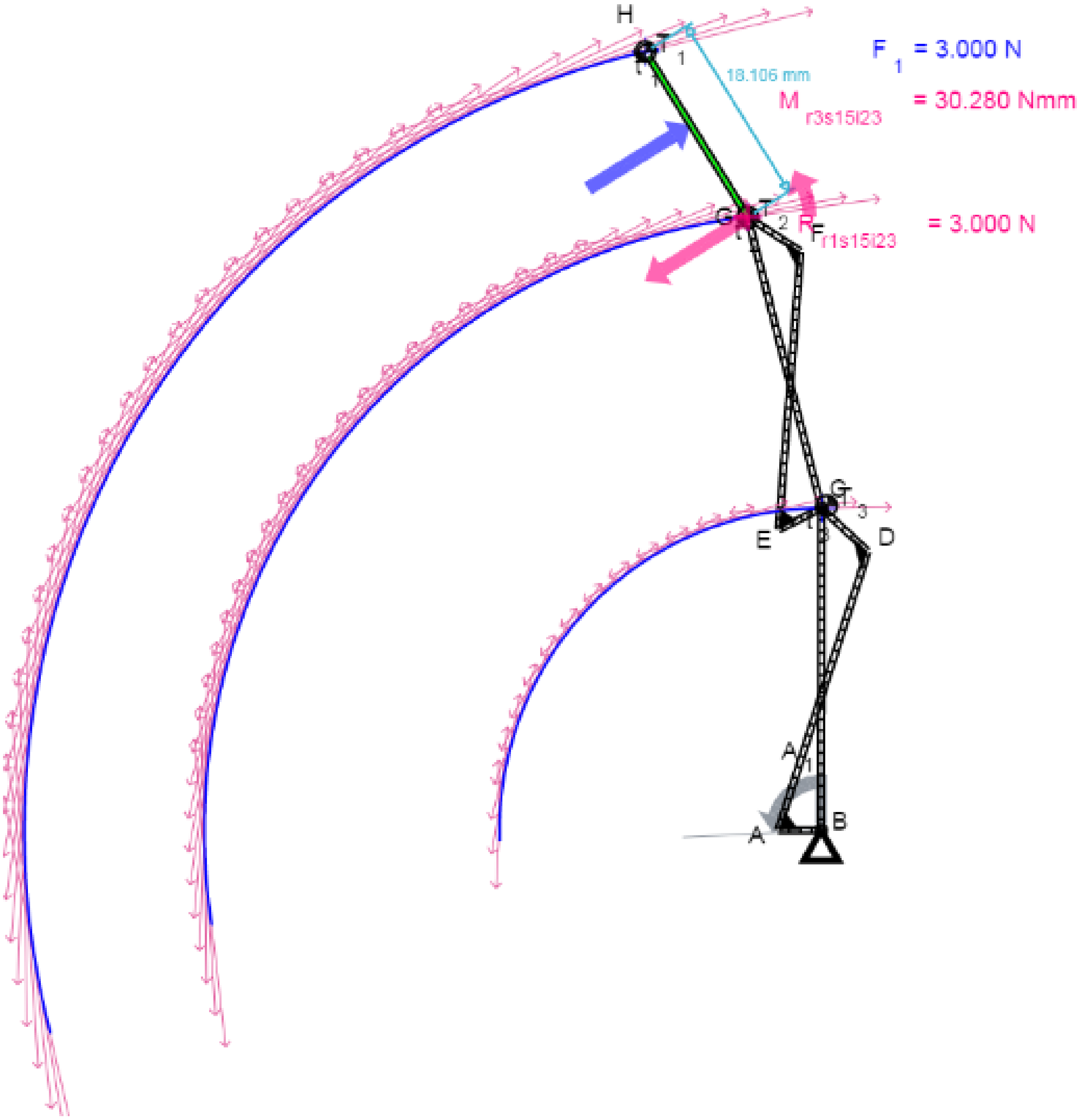


Figure3:f Compound 4 Bar Linkage - Kinematic Analysis - D

After the force analysis, we performed a kinematic analysis to analyze the displacement, velocity and acceleration with the trace point set to the fingertip. This motion analysis allowed us to design in competition with existing commercial hands.

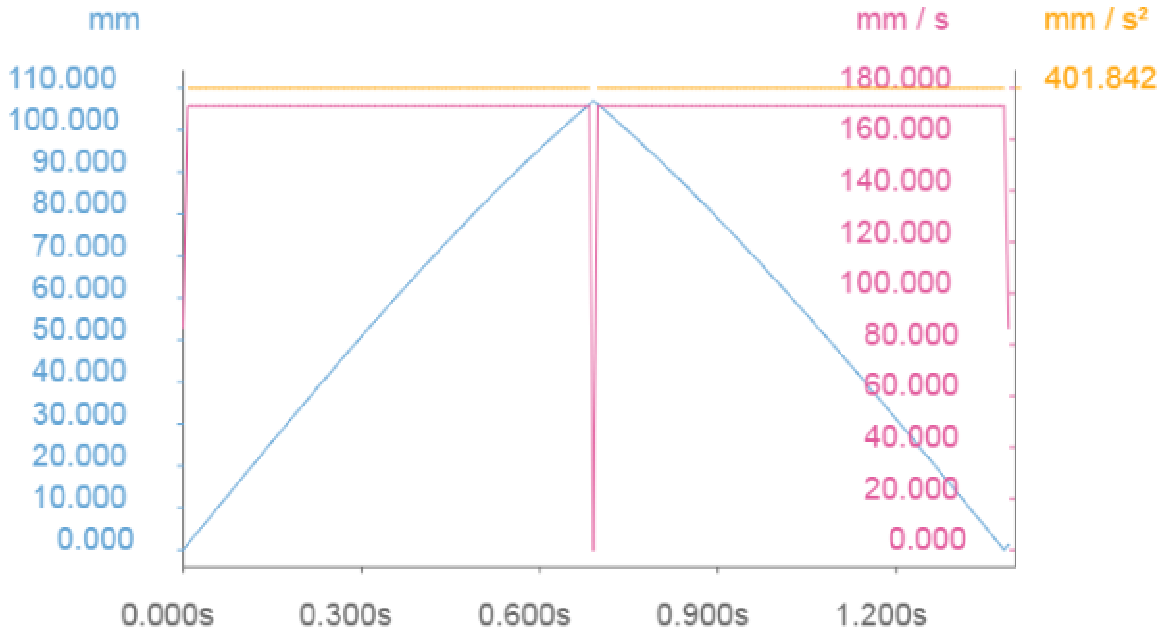


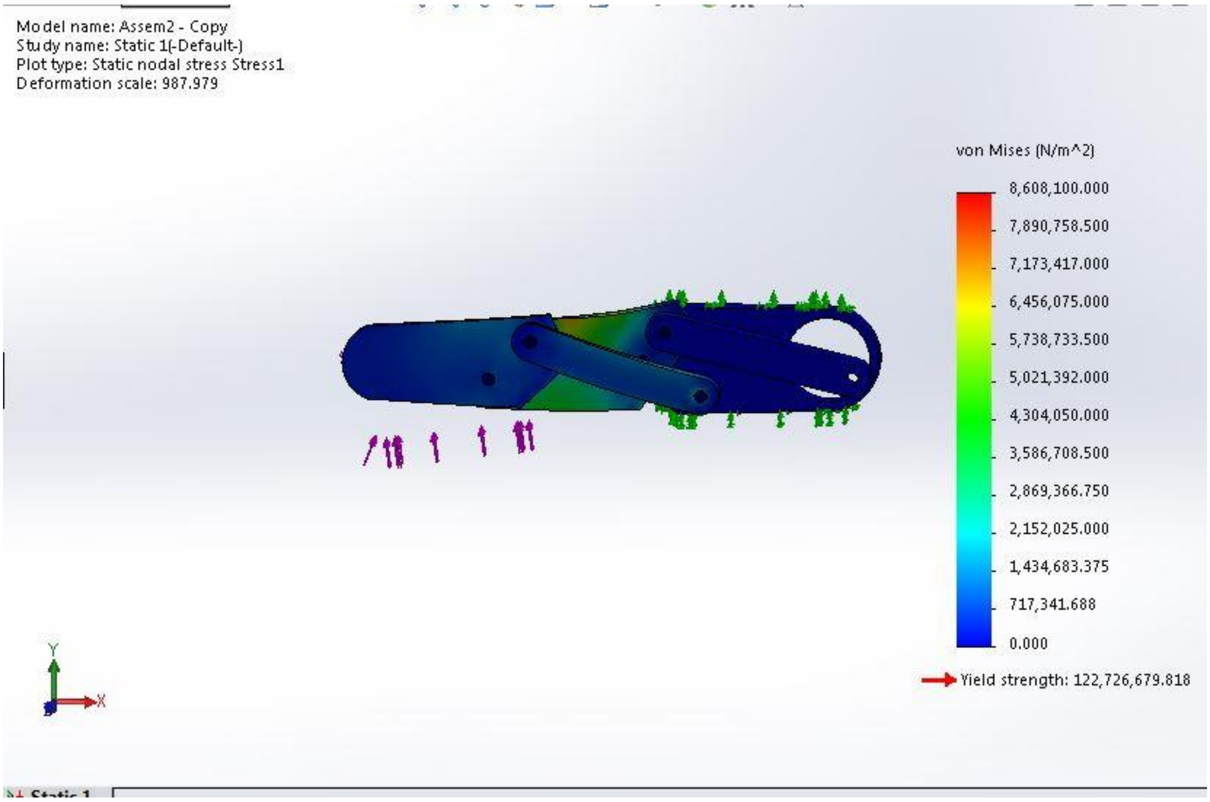
Figure 3:g Kinematic Plots (Displacement, Velocity, Acceleration)

The tendon pulley finger was designed according to the carrying pulley ratio being implemented in the speed of rotation of PIP, MIP and DIP joints. We designed the pulley diameters accordingly and set a diameter ratio of 5:9:11 for the ring finger and the little finger and set a ratio of 11:19 for the thumb.

The tendon belts featured could not be modelled in solidoworks due to software limitations which is where we employed Pro-Engineer Wildwire for accurate motion analysis.

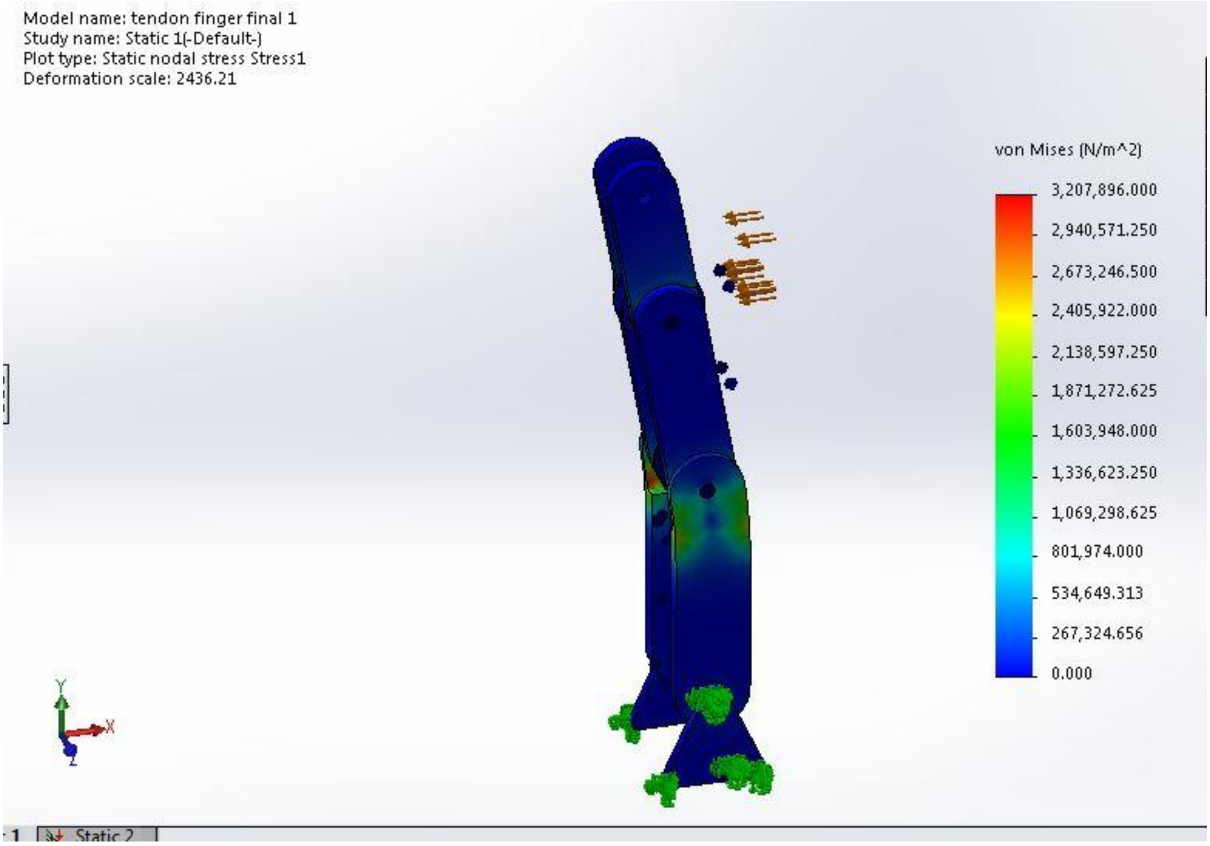
The thumb used a compression spring locking mechanism with two locking positions 85 degrees apart. To ensure two locking positiosn for the 4 types of grasps.

After the initial design and the Solidworks and Autodesk Inventor modelling and motion anaylis, we performed a detailed stress analysis to determine the weakest points to adjust our dimensions and material considerations accordingly.



Model name: Assem2 - Copy
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 987.979

Figure 3:h Stress Plot Compound 4 Bar Linkage Mechanism



Model name: tendon finger final 1
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 2436.21

Figure 3:i Stress Plot Tendon Pulley Mechanism

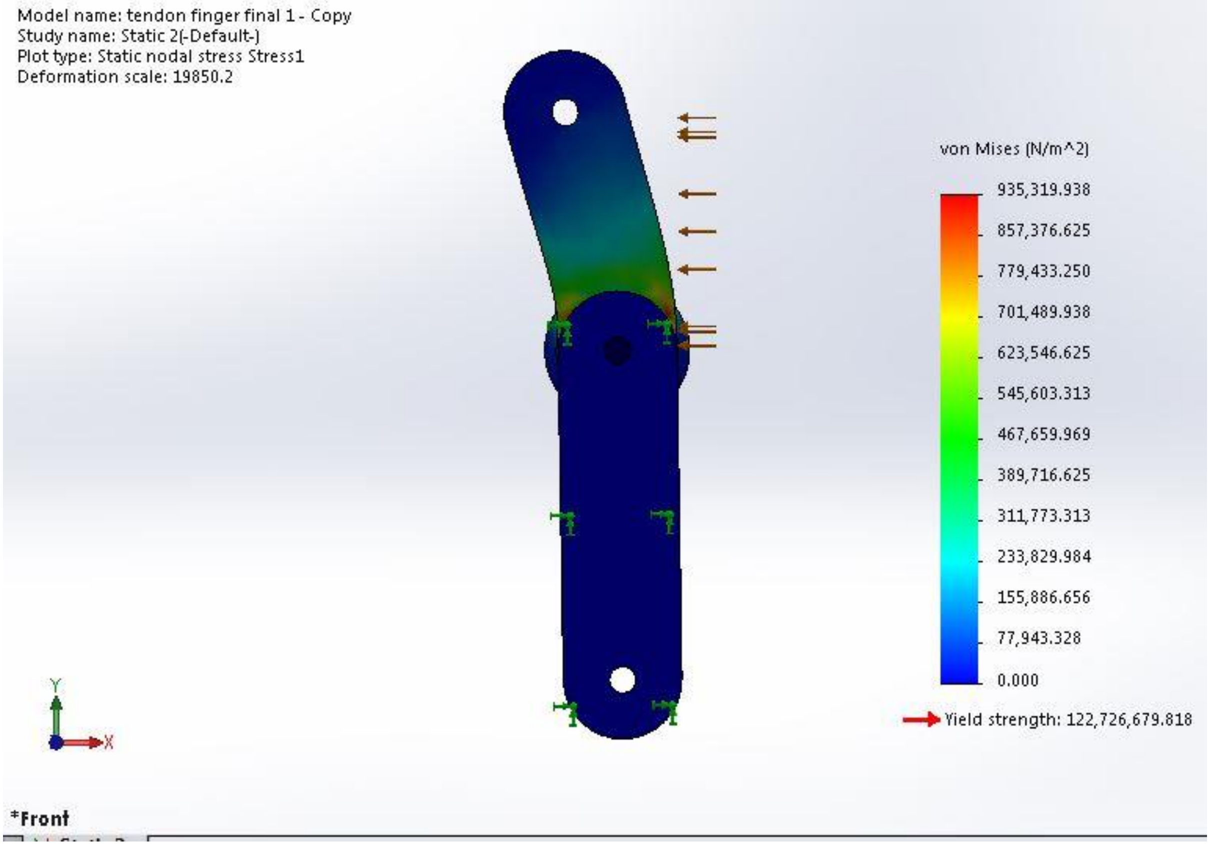


Figure 3:j Stress Plot Thumb Tendon Mechanism

The scale on the diagrams was set at an offset from actual scale to exaggerate the display of strain and displacement. The stress and displacement plots for both finger designs were plotted to validate our model in our initial design. The assembled drawing encountered many problems during the stress analysis, and the team had to remodel it a few times just to get it correct.

The design period for the team was the most effort and time consuming and the team worked incessantly on individual parts, their design, material specifications and the final assembly. The designs were prepared in SolidWorks 2013, and ProEngineer Wildfire 2014 which was the basic designing software for our project.

The drawings were made according to the dimensions previously set and according to human hand dimensions.

With time, modifications were made to the individual design and hence, changes had to be made to most of the parts accordingly. This brought problems as changes to one part drawing meant other parts also had to be modified so that they could all be assembled together to make the final assembly.

Once the individual part drawings were completed, the next phase was initiated: Drawing Assembly. This was a tough stage for the team, because small discrepancies in the dimensions meant that the assembly would fail numerous times. Besides that, the design that was finalized involved some parts that could have proved to be extremely difficult to manufacture using the traditional methods of tooling (since that was the team's only option due to budget constraints).

Once the assembly was complete, it was time to move to the manufacturing and fabrication stage.

3.2 Fabrication

The fabrication stage commenced as soon as the assembly drawings were completed. The team's first task was to select the material for each of the part of the steering system. That required accurate material selection that would not only withstand all the forces acting on it, but also be cost efficient since the team had budget constraints. Besides that, there were other factors including material availability that somehow limited our options with the material.

We compared the properties of various materials to reach our desired conclusions and to keep the weight under 500g.

Table 3:a Links Material Comparison

No.	Titanium	Nylon	Aluminum	ABS
1.	E = 113.8 GPa	E = 2-4 GPa	E = 68.9 GPa	E = 2900 MPa
2.	Requires cutting forces higher than steel	Good machinability	Good machinability	Difficult to bend but prone to stress cracking
3.	Corrosion Resistant	Shock Resistant	Moisture Resistant	High Temperature Resistant
4.	High Cost	Low Cost	Costs even lower than Nylon	Low Cost
5.	Toughness = 85 MNm^(3/2)	Toughness = 3 MNm^(3/2)	Toughness = 28 MNm^(3/2)	Toughness = 3 – 7.55 MNm^(3/2)
6.	Heavier than Al but Lighter than Steel	Light Weight	Light weight	Lowest weight

The team hence decided to use Aluminum Al 7075 where light weight was the main requirement, which was our linkages and palm base. However due to unavailability of Al 7075 the team decide to use the available option of Al 1100.

The pins were made out of tool steel for pin joints. The Acetal/Delrin gears were our only option in the dimensions we required the worm gears in. They showed lower noise but lower efficiency and greater slip as well.

Figure 3:k Delrin Worm Gears

The crank was designed out of Mild Steel and the bushing was made from Brass. The pulleys were made out of Nylon.

Figure 3:l Nylon Pulleys

The tendon wire was composite fishing line wire made from carbon fiber. The springs used stainless steel extension springs.

Table 3:b Tendon Wire Material Comparison

No.	Kevlar	Carbon Fiber
1.	Elastic Modulus = 70.5 – 112.4 GPa	Elastic Modulus = 125 – 181 GPa
2.	Strength to weight ratio = 993	Strength to Weight Ratio = 1013
3.	More flexible	Higher stiffness of fiber
4.	Higher capacity of Vibration damping	Less likely to dampen sharp vibrations
5.	Needs to be covered by water proof coating	Does not attract moisture
6.	Damages Plastic	Not susceptible to damage Nylon
7.	Expensive	Low cost
8.	Ultimate Tensile Strength = 2757 MPa	Ultimate Tensile Strength = 4137 MPa
9.	Difficult to cut	Readily available and easy to cut to shape

The team used simple fabrication techniques: Milling, turning, drilling, bench fitting etc. to get the desired results from the material that was purchased. The fabrication course took the team a couple of months to complete since a few parts had to be made several times in order to achieve perfection.

Aluminum provided sufficient strength without weighing too much. The parts were manufactured according to specifications but the team had to compromise on a few design parameters to be allowed for fabrication in the limited resources that we had available.

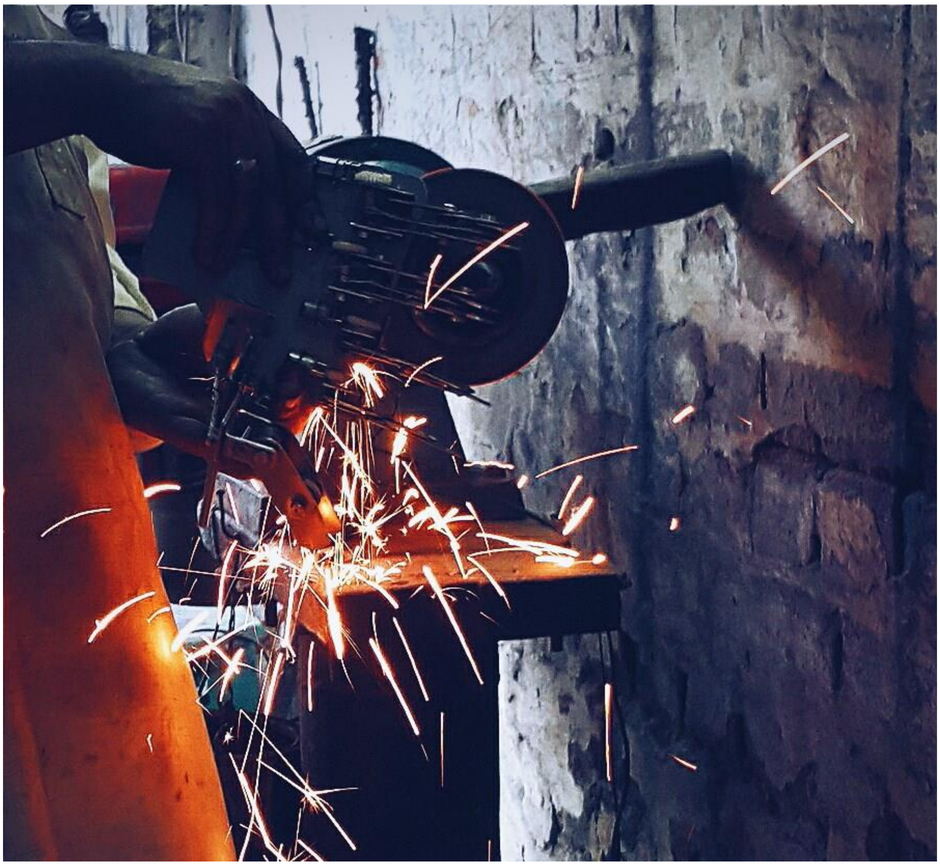
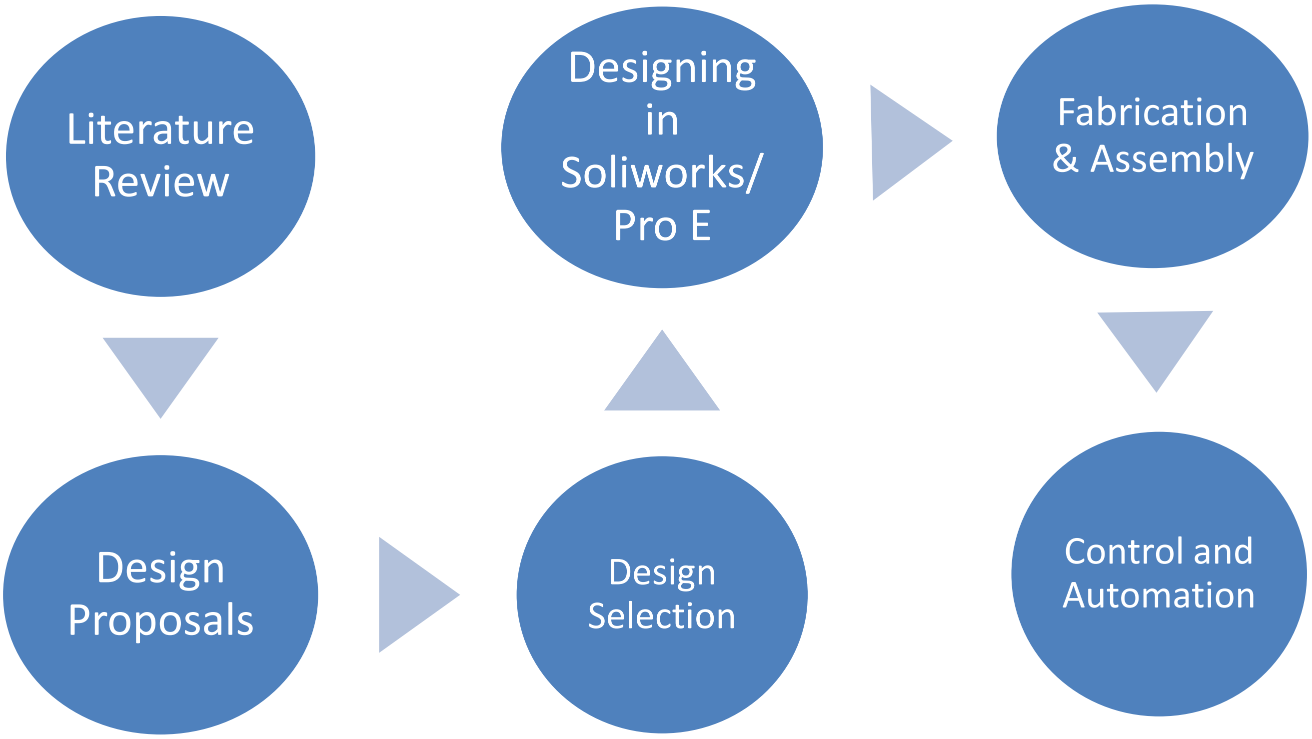


Figure 3:m Manufacturing Operations Under Process

Once all the fabricated parts were ready, assembling them all was an easy task for the team. And with that the prototype prosthetic hand was ready.

3.3 Project Strategy



3.4 Control and Automation

After the design and manufacturing, we had to drift from our project idea of using EMG electrodes to demonstrate a prosthetic due to reasons unavoidable. However the deliverables of the project from the design team were met. We tried to extend beyond the initially declare deliverables in order to show the four working grasps by using an Arduino controller and H bridges setup. This setup cannot be used for an actual prosthetic but due to unavailability of EMG electrodes; we had to use Arduino solely for the grasps' display.

Components are:

1. DC Geared Motor 12V and 120 RPM Motors
2. Arduino MEGA 2560
3. H-bridge L293d

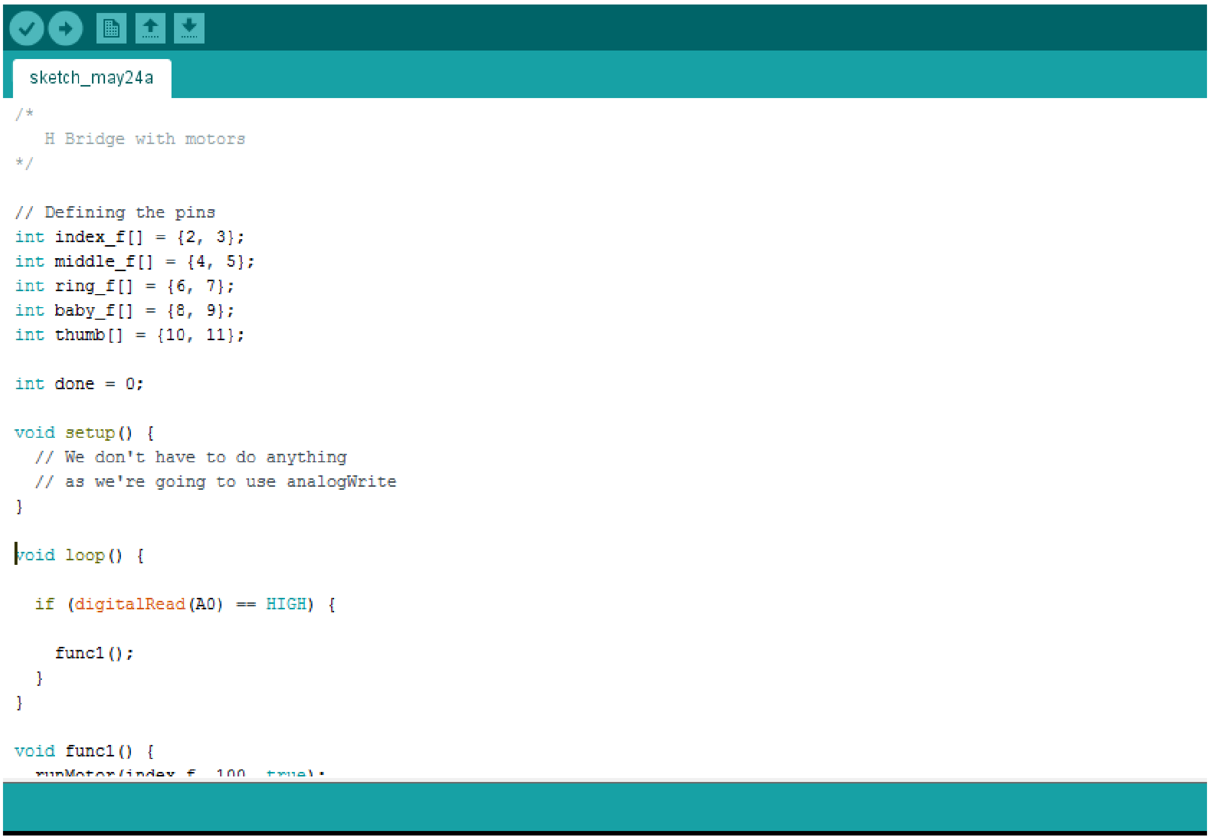
Mega Arduino Controller:

The Arduino Mega is a microcontroller board based on the ATmega1280 . It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started.

Figure 3:n Arduino Mega 260

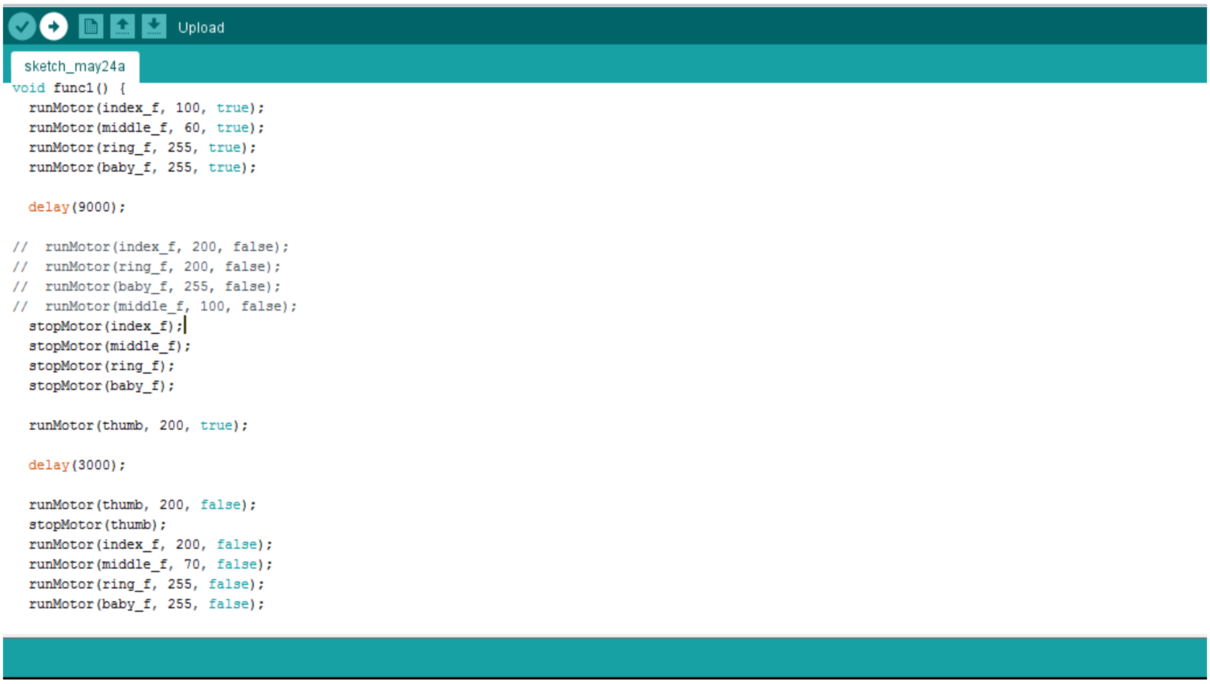
Our Arduino was using 10 output and 2 input ports.

Code for the Whole System:



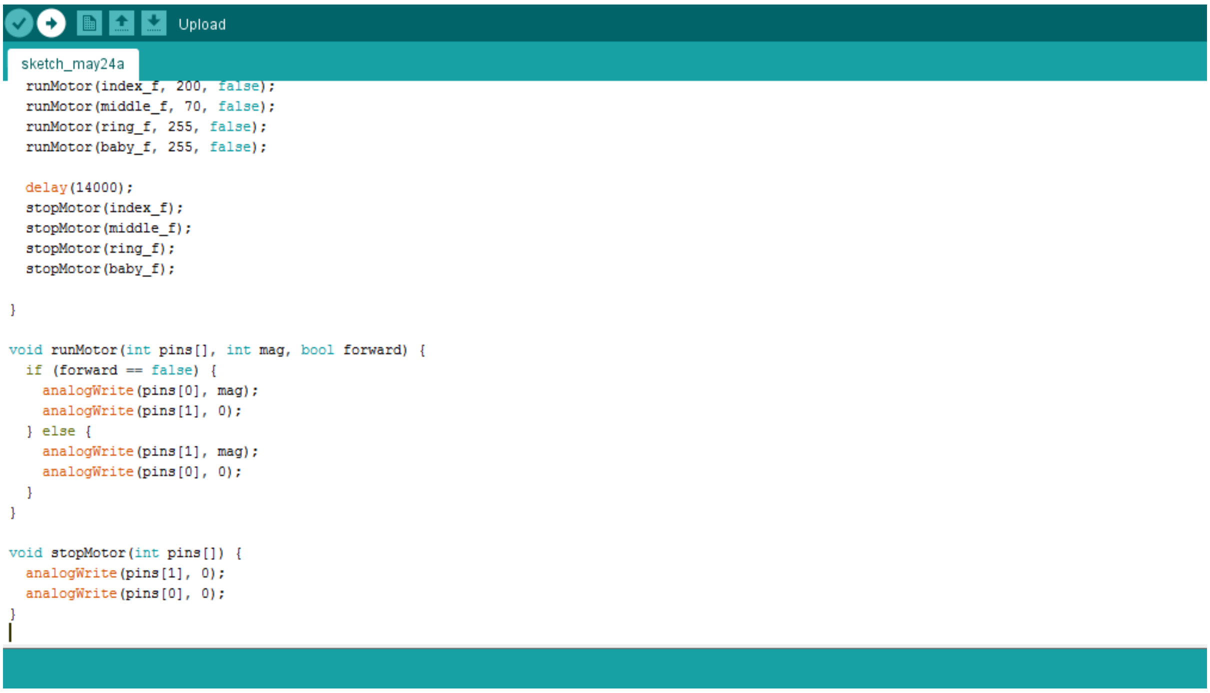
```
/*
   H Bridge with motors
*/

// Defining the pins
int index_f[] = {2, 3};
int middle_f[] = {4, 5};
int ring_f[] = {6, 7};
int baby_f[] = {8, 9};
int thumb[] = {10, 11};

int done = 0;

void setup() {
  // We don't have to do anything
  // as we're going to use analogWrite
}

void loop() {

  if (digitalRead(A0) == HIGH) {

    func1();
  }
}

void func1() {
  runMotor(index_f, 100, true);
```

Figure3:o Code for Grasps - A



```
void func1() {
  runMotor(index_f, 100, true);
  runMotor(middle_f, 60, true);
  runMotor(ring_f, 255, true);
  runMotor(baby_f, 255, true);

  delay(9000);

//  runMotor(index_f, 200, false);
//  runMotor(ring_f, 200, false);
//  runMotor(baby_f, 255, false);
//  runMotor(middle_f, 100, false);
  stopMotor(index_f);
  stopMotor(middle_f);
  stopMotor(ring_f);
  stopMotor(baby_f);

  runMotor(thumb, 200, true);

  delay(3000);

  runMotor(thumb, 200, false);
  stopMotor(thumb);
  runMotor(index_f, 200, false);
  runMotor(middle_f, 70, false);
  runMotor(ring_f, 255, false);
  runMotor(baby_f, 255, false);
```

Figure 3:p Code for Grasps - B



```
  runMotor(index_f, 200, false);
  runMotor(middle_f, 70, false);
  runMotor(ring_f, 255, false);
  runMotor(baby_f, 255, false);

  delay(14000);
  stopMotor(index_f);
  stopMotor(middle_f);
  stopMotor(ring_f);
  stopMotor(baby_f);

}

void runMotor(int pins[], int mag, bool forward) {
  if (forward == false) {
    analogWrite(pins[0], mag);
    analogWrite(pins[1], 0);
  } else {
    analogWrite(pins[1], mag);
    analogWrite(pins[0], 0);
  }
}

void stopMotor(int pins[]) {
  analogWrite(pins[1], 0);
  analogWrite(pins[0], 0);
}
```

Figure3:q Code for Grasps - C

Chapter 4
Results and Discussion

The objective of this project was to create, design and manufacture a hand prosthesis that accurately replicated the appearance and motion characteristics of the human hand. Initially the prosthesis was then expected to be able to interface with the output of the EMG signal classification system in order to control the motors that curl the fingers.

The EMG electrodes, unfortunately, could not be integrated with the system because of reasons unavoidable However according to the deliverables of the design team, a complete multi degree of freedom functioning model was built to accurately conclude that the design for the fingers and thumb was an effective model of both the appearance and motion characteristics of a human hand.
Our model could accurately mimic compliance and motion characteristics according to the systems involved and our initial innovative idea of varying the finger designs to achieve improved grasping abilities, gestures and force dynamics was proved.

Each finger could accurately provide a fingertip force over 3 N and the force varied according to the electrical signal provided to the motors.

The thumb locking mechanism was also and innovative design that could allow passive circumduction displayed in the demonstration of the prototype.

As it stands the prototype built demonstrates a proof of concept that it is possible to construct a prosthetic hand that could mimic the complex curling motion of the human hand.

Chapter 5
Conclusions and Recommendations

5.1 Conclusions

In Conclusive remarks the team would like to highlight the importance of dexterous and user friendly prosthetics that can mimic gestures.

Our design is by far one of the most innovative in terms of designs, force dynamics and power requirements. However manufacturing constraints hampered the progress. However we developed a fully functional metal Prosthetic hand that could replicate intricate movements of the human hand.

5.2 Recommendations

The project in question has been led to a successful end with regards to the scope of our deliverables. However in no way is the work complete. In the future, teams can try to tackle some of the problems we faced and were unable to resolve this year. Our first recommendation for future teams would be to keep the design theory in collaboration with the machinist right at the beginning of the project. A 3D printed option for the design would be a much more suitable option which we could not incorporate. We would also recommend future teams to make a tendon routing mechanism to be in high tension and gears with lower slippage.

We would also hope for the future teams to successfully integrate their design with EMG electrodes and allow for the prosthetic to be tested on amputees for feedback.

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