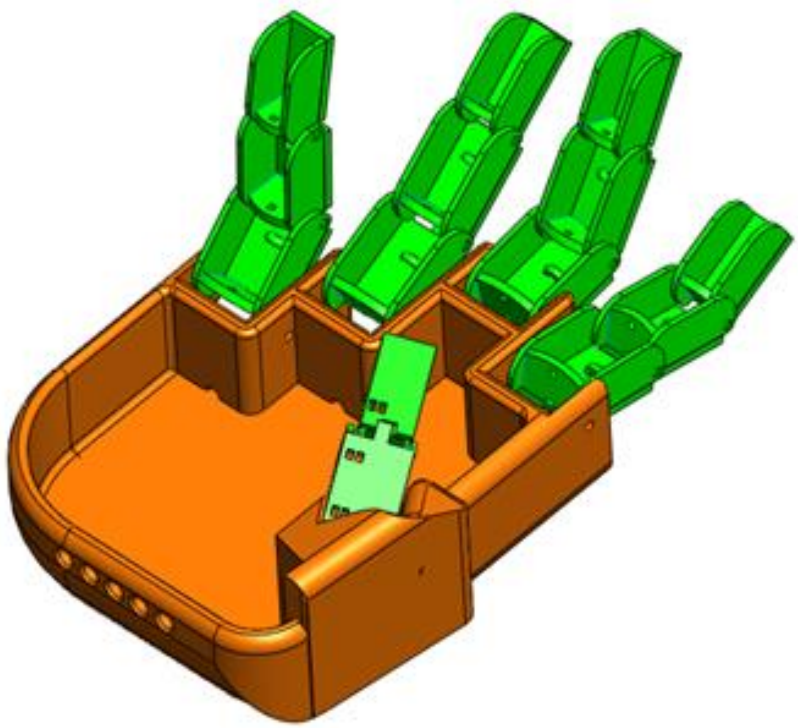
MSE 420

Design of Human Hand Prosthesis



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Contents

Table of Figures

Introduction

Lower extremity prosthetics are functional and readily available, but upper extremity prosthetics that essentially not advanced since the Civil War [1]. Currently available prosthetic hands in the market lack functionality and are cost prohibitive. The most economically feasible available today is a prosthetic hook, which has been in use since the 19th century.

Fig. 1.Prosthetic hook currently available in the market [5]

Hooks are simplistic and relatively cost effective, however they're limited in functionality as they cannot be used for complete articulation of motion that a user may desire to have for different tasks.

Most commonly used prosthetic hands offer better functionality than hooks, although it is not comparable to an actual hand. These prosthetic designs usually only include the thumb a two-three fingers. Some prosthetic hand designs allow for cosmetic gloves to be worn to cover them (as can be seen in Fig. 2).

Fig. 2. 2013 Mech hands for Adults (Liberating Technologies Inc.) [2]

Advanced prosthetic hands that can completely articulate all motions of the hand and even up to shoulder exist. However these are extremely cost prohibitive and not meant to be used for the general population.

Fig. 3 depicts functional prototype of a prosthetic arm developed with the help of $100 million dollars funding by DARPA.

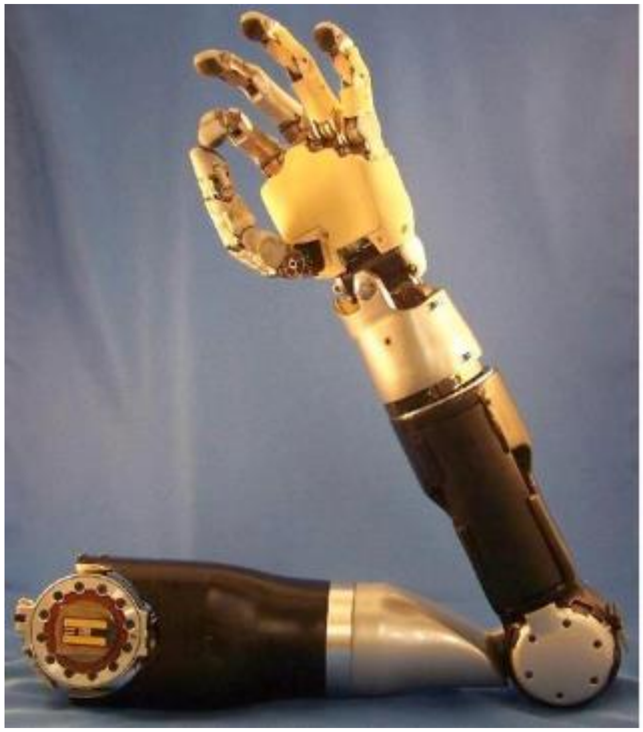

Fig. 3. Johns Hopkins APL arm [3]

Design Criteria

This project explores the possibility of a simplistic, economically feasible yet effective prosthetic hand. The goal is to maximize functionality while keeping the cost low. Ease of manufacturability is another concern, 3D printable CAD models are an easy and accessible way to share 3D designs. The whole hand can be 3D printed and assembled. Room for actuators and electronics also needs to be taken into consideration, so that anyone can freely add more functionality to the prosthetic hand. The design criteria can be summarized in the list below:

- Design a feasible prototype, simplistic, yet effective in design.
- Ease of manufacturability.
- Room for electronic actuation integration.
- Cost effectiveness.

Physical Design

Material Selection

Since 3D printing was opted for ease of manufacturability. Selection of materials was narrowed down to ABS and PLA, the two most commonly used and easily available 3D printable materials. The table below provides a good comparison between these materials.

	ABS	PLA
Tensile Strength	44.81MPa	57.8MPa
Flexural Strength	75.84MPa	55.3MPa
Tensile Modulus	2.21GPa	3.3GPa
Flexural Modulus	2.28GPa	2.3GPa
Density	1.04 g/cm^3	1.25 g/cm^3
Degradable	No	Yes

Table 1. Comparison of properties of ABS and PLA materials

It is clear that strength characteristics for ABS and PLA are similar, considering our application, the differences are not significant. Density for the two materials is also comparable. However, PLA is degradable whereas ABS is not. Taking into account such properties, we chose PLA as the choice of material.

Hinge Joints

The inter-phalange connections are crucial to the fingers' motion and basic functioning. They needed to be small in order to make sure friction was minimized; however, too small pivots will fail very easily and will not be able to withstand much tensile stress. We used Hertz contact theory to find an optimized diameter for the pivots of the hinges connecting the phalanges. We started off by assuming that the forces acting on the connections are the very high. We used this force at varying pivot diameter, keeping the outer hinge diameter constant; to estimate the maximum tensile strength using Hertz contact theory at different diameters. We used MATLAB for all the calculations involved and repeated the procedure for both ABS and PLA for comparison. After plotting the results, we chose a diameter of 3mm for our pivot's diameter. With a diameter of 3mm, the pivot can experience a maximum tensile strength of 1.7kPa. This was a plentiful as the two hinges at every phalange will be distributing the stress. Moreover, it is highly unlikely that the joints will be exposed to such high loading scenarios to begin with.

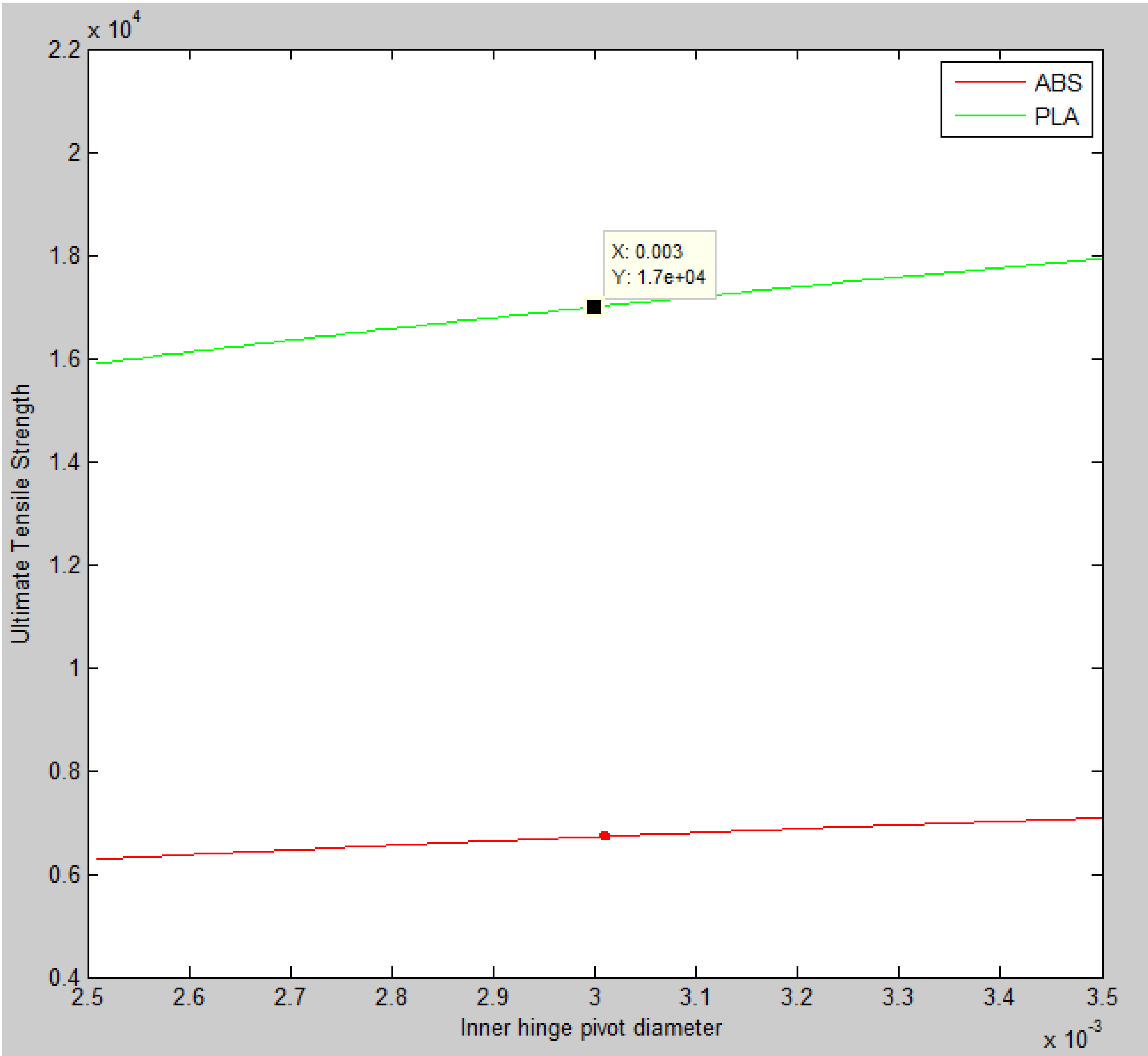

Fig. 4. Finding the optimum dimensions for the hinge joint using Hertz Contact Theory

Structure & Anatomy

The design is anatomically analogous to a human hand to a great extent. This ensures that we are able to mimic a lot of the functionality of the human hand. The image below in Fig.1 depicts the anatomical equivalence.

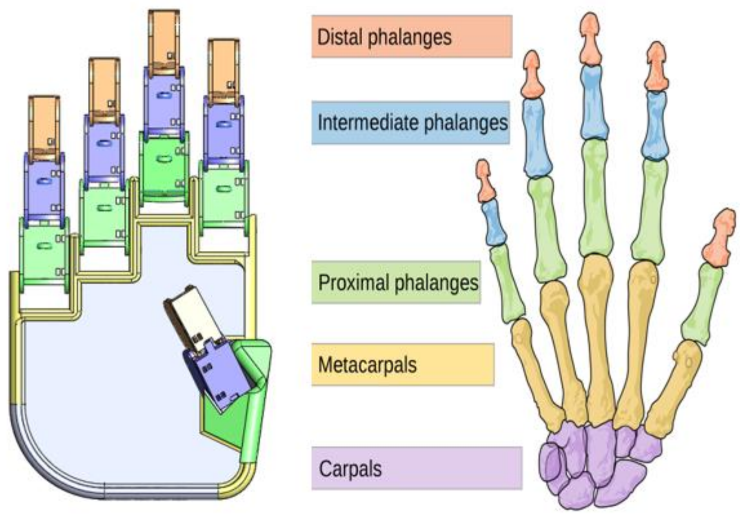

Fig. 5. Analogy between the structural design of the prosthetic hand and a human hand

The design includes distal, intermediate and proximal phalanges. The extrusions on the side of these phalanges act similar to collateral ligaments, and the extrusions on the back play the same role as volar plates, both prevent the inter-phalangeal joints from dislocation in the prosthetic hand. The parts of the palm that extends up to the proximal phalanges can be considered as the metacarpals. The bottom of the prosthetic hand includes holes through which wires for actuation of the digits go through (Fig. 3), these holes altogether are similar to the carpel tunnel.

This design allows us to meet the criteria that was set in the beginning, as basic hand motions such as gripping, pinching, pointing etc. can be performed by the prosthetic hand. The thumb's phalanges make an angle of 20^o with the plane of the palm, this was strategically chosen so that pinching can be performed using the thumb and middle finger, considering that the thumb is only capable of extension/flexion. The palm is designed to hold motors along with the worm drive gearbox for actuation of the fingers and the thumb. The worm drive prevents the digits from moving by their weight or any other undesirable applied force, as worm drives are self-locking and cannot be back-driven. This way the worm drive acts similar to tendons in the human hand that connect muscles (analogous to motors) in the forearm with the phalanges.

Fig. 6. From left to right: CAD model of a digit including the proximal, intermediate, and distal phalanges; 3D printed digit held in extension by the springs; 3D printed digit in flexion due to tension in the string.

Extension springs interconnect phalanges and help keep the digits in extension, this is the default orientation of the five digits. A string connects the phalanges to the actuator (motor/manual pull), tension in the string causes the phalanges to flex, more tension corresponds to more flexion. As soon as tension in the spring goes away, the counteracting springs cause the phalanges to extend and extension of the digit is achieved.

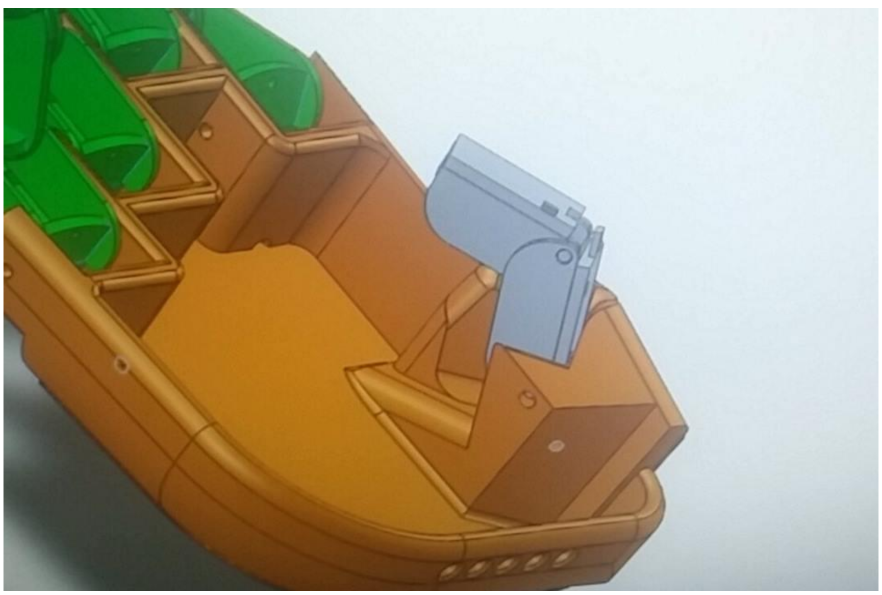

Fig. 7. CAD model showing the space for actuators and electronics in the palm, thumb placement, and holes at the bottom for strings to pull through.

Stress Analysis

We used finite element analysis from SolidWorks to perform various loading scenario simulations focusing mainly on the back stopper and hinge joints of each phalange.

For the first simulation, the strength of the back stopper was our primary point of interest. We performed a static loading simulation on the phalange. It was loaded at the tip of the back stopper and the whole phalange was fixed from the back stopper.

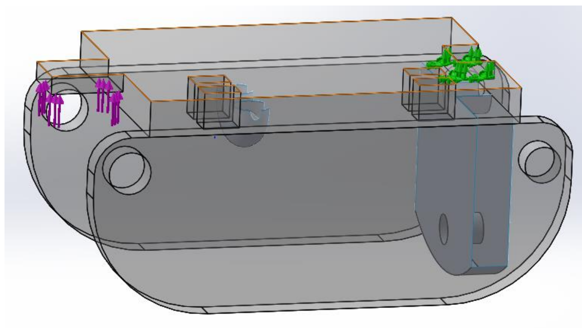

Fig. 8. Loading (purple) of the back stopper and fixed geometry reaction (green).

We loaded the stopper tip with 75N of force. This is an extreme case as each phalange is highly unlikely to be experiencing that kind of loading as the force would usually be distributed amongst the other phalanges. The stress distribution amongst the phalange from the simulation is a bit concentrated at the extension point of the stopper. We concluded this is because of the sharp edge adjacent to the stopper. This can potentially cause stopper to break off at such high loading conditions. However, we can very easily reduce the stress concentration by smoothening the sharp edge by adding fillets along the walls.

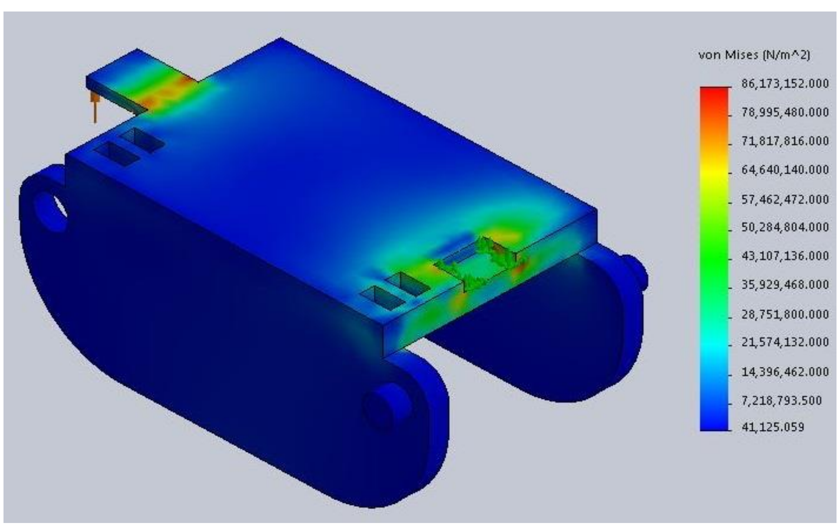

Fig. 9. Stress distribution along the phalange with the stopper as the point of interest

For the second simulation, we considered high forces from the sides of the phalanges. This time we ran a similar type of simulation, but with the inter phalange joints as our primary points of interest. We achieved this by fixing the joints as hinges for the boundary settings for the simulation and applied 100N of distributed force from the wall of the phalange. The main purpose of the simulation was to test the limits of the joints and the wall of the phalange which was acting like collateral ligament.

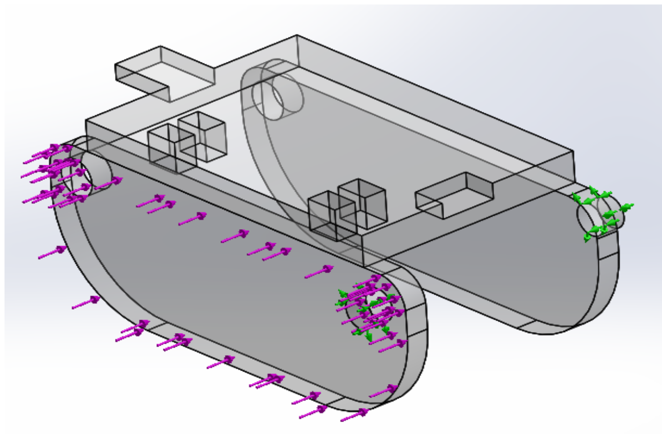

Fig. 10. Loading (purple) of the collateral ligament equivalent bar linkage and fixed geometry reaction (green).

The stress distribution amongst the phalange walls are well below the ultimate tensile strength of the material.

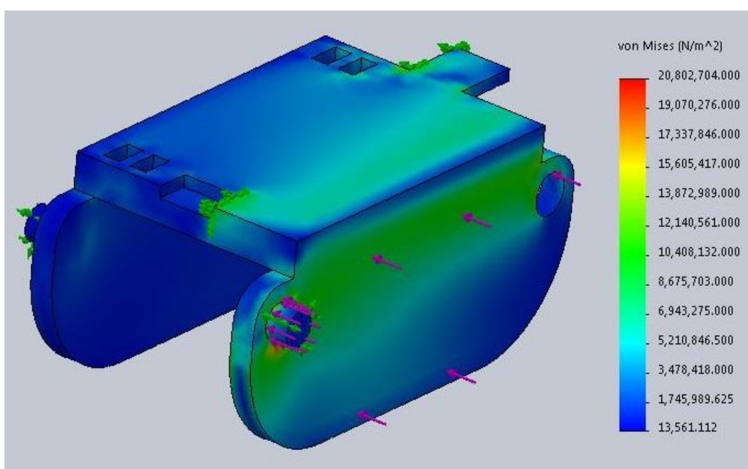

Fig. 11. Stress distribution along the phalange with the stopper as the point of interest

The results from the simulations are summarazied in the table below:

Scenario	Maximum Tensile Strength
Stopper overload	28.4 MPa
Side overload	86.7 Mpa

Conclusion

We successfully designed a functional prosthetic hand within strict deadlines. The prosthetic hand is environment friendly and very cost effective. However, due to manufacturing difficulties the prototype did not perform as we expected, however, it did perform some basic hand motions. It is very rigid and is able to withstand loads of around 7kg [4].

Future recommendations

- Integrate sensors and actuators for automations.
- Add fillets at the back stoppers to reduce stress concentrations.
- Add force sensors to get feedback from various grips.
- Use a combination of different fishing lines to increase the load bearing capabilities of the hand.
- Find a more optimized position for the thumb.
- Use springs of a slightly lower spring constant for a better de-energized state of the prosthetic.

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