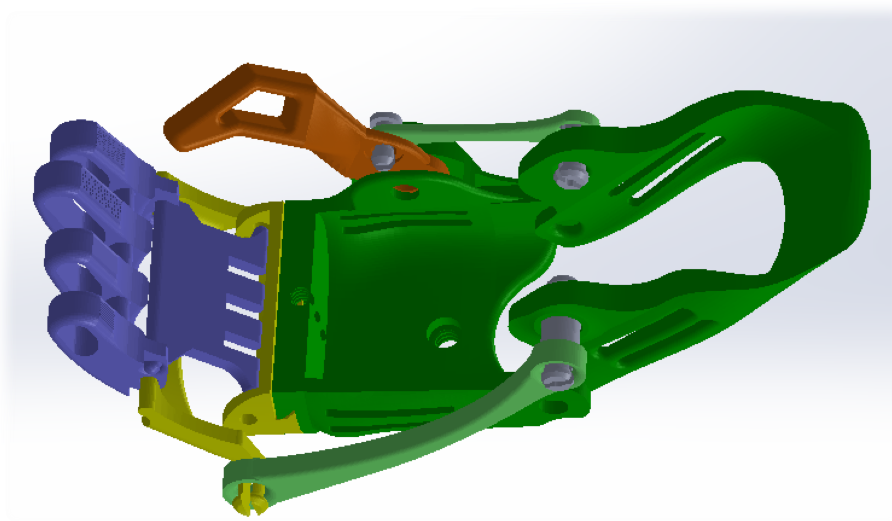
3D Printed Prosthetic Hand

MEC178: Designing for the Human Body



<u>Team "Handy Solutions"</u>

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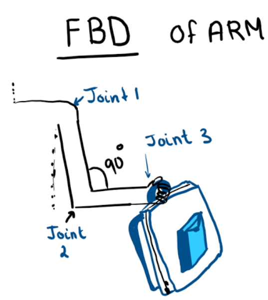
Biomechanics Overview

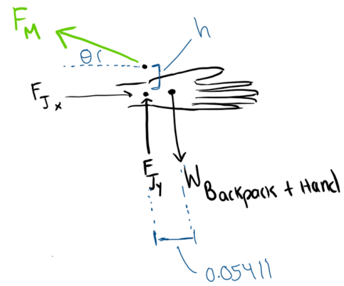
Hands perform a wide range of movements typical in everyday life, from picking up water battles to opening doors. These actions are made possible by the collaboration of bones, ligaments, and tendons.

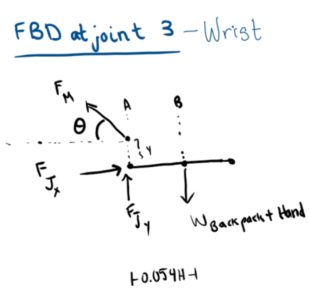
A typical human hand is composed of 27 bones in the wrist and fingers. The wrist is composed of 8 bones called the carpals, which connect to the radius and ulna in the forearm and the phalanges in the hand. These bones are attached to the ulna and radius by radial and ulnar collateral ligaments that restrict side-to-side movements. On the dorsal side are the ulnocarpal and radioulnar ligaments, which provide stability and prevent over-extension. The phalanges are composed of 3 sections - the distal, middle, and proximal - that are attached by the distal interphalangeal (DIP), metacarpophalangeal (MCP), and proximal interphalangeal joints (PIP), respectively. The DIP, MCP, and PIP also have collateral ligaments to prevent side motion of the joints, and the PIP and MCP have volar plates that prevent overextension of the fingers [1].

Tendons in the hand connect these bones to muscles and allow high tensile loads to be withstood and transferred to the muscles further up the arm. The main tendons are the flexor and extensor tendons. The flexor digitorum profundus (FDP) tendons connect to the distal bones and the flexor digitorum superficialis (FDS) ones attach at the middle bones. Both connect to the metacarpals and pass through the wrist to connect to the corresponding FDP and FDS muscles, which contract and extend to allow bending of the fingers. The dorsal side of hands has extensor tendons that connect similarly to provide tension and allow stretching of fingers [2]. The thumb is unique with its additional degree of freedom at the base, but it also has just two main tendons, the extensor pollicis brevis and the abductor pollicis longus, that allow flexion and extension. At the base of the wrist the flexor retinaculum bridges across the carpal bones and attaches on the palmar muscles located on the thumb and pinky finger. To provide overall tension, the flexor carpi radialis and flexor carpi ulnaris tendons connect muscles in the forearm to the wrist [3].

Our prosthetic design is targeted for individuals with underdeveloped hands but proper function in their wrist. Because the design relies on wrist movement to actuate hand movement, we investigated forces in the wrist when lifting a 15 lb (~66.75 N) backpack, assuming a rigid hand that won't buckle from the weight.







$$\Sigma F_y = 0 = F_{M_y} + F_{J_y} - W_{B+H}$$

$$\Sigma F_x = 0 = F_{J_x} - F_{M_x}$$

$$\Sigma M_A = -W_{B \cdot H} \cdot (0.054H) + F_{M_y} \cdot y$$

θ between forearm & wrist $= 0$

$\therefore F_{M_y} = 0$

Contact force angle

$$\theta_J = \tan^{-1}\left(\frac{F_{J_y}}{F_{J_x}}\right)$$

The free body diagram analyzes the forces at the wrist joint for a 5’8’’ (~172cm) tall male weighing 150lb (~667.2N). We assume that the forearm and wrist are at a static 0° angle. The load is applied at the center of the palm, with a hand length of 0.108H and forearm length of 0.146H, with variable H representing the individual's height [4]. The average weight of the male hand is 0.6% of body weight [5] and the arm’s neutral supination has a mean distance of 3.2cm for the attachment of the distal bicep tendon [6]. The dominate muscle for stabilizing the wrist is assumed to be the palmaris longus, attached at the flexor retinaculum. Because the flexor retinaculum sits above the carpals, we assume the force exerted by the palmaris longus tendon and muscle is done about 1cm above the contact joint point. Solving the equations of equilibrium reveals the contact force at the wrist to be 654.4N (~147.1lbs) at an angle of 6.15 degrees. The muscle force exerted at the flexor retinaculum contact point is 650.7N (~146.3lbs), which is 9.75 times greater than the original load.

Initial Design and Testing: Iteration 1

3D printing an entire prosthetic hand overnight is a huge advantage for its quick turnover time and ease of customization. The initial draft requires time for troubleshooting (for example, multiple parts had to be reprinted several times because printing in large batches is more likely to fail from the part coming loose) but when files are finalized, it’s easy to reprint a new hand should the prosthetic need modifications or repair later, especially for growing children. Calibration does take effort, however: shrinkage post-print is difficult to predict and account for in the modeling process. Different machines and filaments may lead to parts with slightly different sizes so maintaining consistency even when printing the same 3D model can be a challenge. Even small tolerance errors can throw off the overall fit of the prosthetic: in this initial iteration, the shafts wobbled significantly in their holes after assembly, which led to posts breaking off from fatigue quicker than expected even for a 3D printed part.

The design we chose to investigate uses wrist motion to actuate the fingers into a grabbing position (see Appendix A, meeting minutes, for selection discussion). Designed by Atomic Lab, it requires minimal additional materials: the only additional supplies it requires are a screw and Velcro for attachment onto the arm [7].

A total of six tests were performed to test the functionality and strength of the 3D printed hand, and an additional handshake test was conducted to test the social response to the prosthetic. The tests were chosen to cover a wide variety of tasks and functions that a prosthetic would be asked to do in the daily life of a user (see Appendix A, meeting minutes, for discussion).

The first experiment, in which a ball was thrown using the prosthetic, was used to test the function of the hand in a stereotypical playground activity. This experiment was chosen because a younger patient would want to engage in “normal” playground activities despite their disability. Next, we tested the prosthetic ability to open different types of doors. Doors are a common occurrence in society so being able to easily operate any door encountered would be a helpful benefit, especially if the other hand is occupied. This test would also test the strength of the hand, particularly in the fingers, joints, and in torsion. A typing test was designed to test the prosthetic in a common task that requires dexterity and coordination. Next, a series of experiments were performed to test the ability to pick up (defined as lifting and holding *prone* objects), grab (lift and hold *upright* objects), and hold (tested weight limit of hand) objects. These experiments were chosen to see how well the prosthetic interacted with different everyday items. Lastly, a handshake test was performed for fun to see the social reaction to our prosthetic.

Tests performed and their respective results are summarized below:

Test	Outcome
Throwing	The hand was unable to pick ball up off ground, but once the ball was in the prosthetic it could be thrown accurately 85% of the time for many distances. Holding onto the ball was more of an issue than strength and accuracy.
Opening Door	Prosthetic had minimal grip strength on the smooth, metal door handles and was therefore unable to open door that required a handle or knob to be held on to. The hand was unable to "pull" a door, but it was able to "push" a door without buckling by using the palm of the prosthetic.
Typing	The prosthetic was able to type decently well, but only with one finger at a time. The fingers also slid across the keys instead of pressing due to low friction on the fingertips and loose tolerances in the joint connections. Typing using only the prosthetic, roughly 15 wpm were able to be achieved. However, the prosthetic was not very comfortable to type with, quickly leading to fatigue
Grabbing	Only able to grab objects with a diameter of approximately less than 3" such as lotion bottles, highlighters, and pens, or objects with a large groove in its body (e.g. Gatorade bottle). Larger items, such as water bottles of various materials and shapes, were mostly unsuccessful in being grabbed and lifted in the air due to its slipping against the plastic fingers and thumb. The prosthetic was able to grab a pen and hold it securely enough to write on paper!
Picking up	The hand was mostly unsuccessful in grabbing objects of various sizes, shapes, and weight, such as pencil cases/pouch, phones, computer mouse, and keys (see appendix B for videos). Objects that had less height were harder to grab, due to the inconvenient position of the thumb. The hand was only successful in picking up a thin book by gripping it on the thinner side, but even a phone slipped out from the grip due to the lack of friction.
Holding	The hand was able to pick up a Gatorade bottle by digging the thumb into the groove, so we filled that bottle with different weights to gauge a maximum weight for the hand's grip strength, which turned out to be around 1.25lb: more weight would case the thumb to slip and lose its grip on the bottle's groove. In an attempt to break the hand and access failure propagation, we tried picking up an empty 5lb plastic crate. However, the grip of the hand was simply too weak to enclose the hand slot and lift the basket; the weight would cause the fingers to slip open.
Handshake	We asked 15 people to shake hands with our prosthetic. 50% of people said the physical feel was "average" or better, 40% said that the experience was "awkward" while another 50% said it was a "neutral" experience, and 90% of people said they would shake the hand again if presented with it. It was noted that the thumb felt too far away to properly engage.

From the results of our tests, we identified a key issue to be insufficient grip strength. Specifically, the compression force and friction between the thumb, finger, and palm were inadequate to pick up and hold objects. Any objects that had a diameter of over 3” (e.g. water bottle), had a slippery surface (e.g. metal can), or had weight that exceeded around 1.25lb (e.g. door) were incompatible with the picking up and pinching action of the prosthetic. Even when it can close around an object, the pads didn’t have enough purchase and friction to maintain a tight hold. The provided grip strength did allow us to pick up very light objects such as writing instruments or objects with a deep groove for the thumb to dig into, but it had poor performance in picking up a ball to throw, opening doors, and grabbing objects on tables. The fingers’ lack of independent movement limited the actions the hand can perform, shown in the typing test for dexterity. The general overall robustness of the prosthetic was lacking due to tolerance issues: screws and pins used to assemble the hand broke easily, and the pins fit loosely in corresponding holes, making the whole assembly unstable.

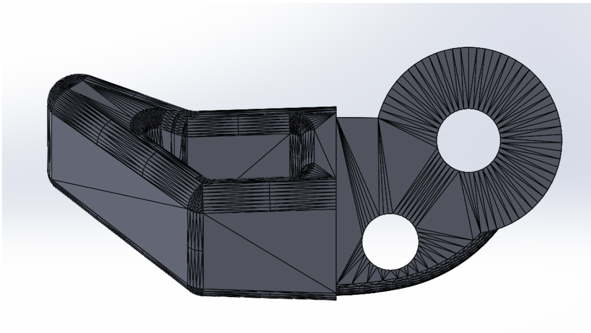
Brainstorm and Re-Designing: Iteration 2

When thinking about criteria for re-designing the prosthetic, we wanted to improve upon what we considered the limiting features preventing it from being as functional as possible in a variety of the tested categories. The ability to grab and hold onto objects was prioritized as the most important function of a hand but also the weakest aspect of our prosthetic. From there we brainstormed ways to improve the design (see Appendix A, meeting minutes, for discussion notes) and settled on 3 changes that would improve the gripping capabilities of the prosthetic:

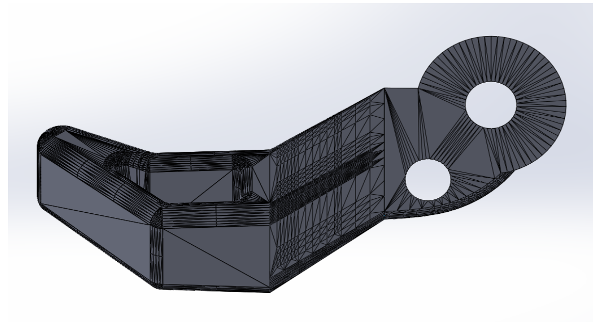
1. Thumb geometry (adjusting the length to account for the inconvenient location)
2. Finger pads (adding 3D geometry to assist gripping capabilities)
3. Wrist (addition of set screw and hole for locking a “grab” motion).

The thumb was originally in an awkward location where it did not contact any of the fingers upon closing, making it difficult to pick up and hold onto objects that had either a large diameter or lay low on flat surfaces like a book, for which pinching with finger tips would be necessary. By re-designing the thumb, we hoped to improve the prosthetic’s ability to pick up objects. The next change we decided on was adding 3D printed geometry to the pads and tips of the fingers to increase grip strength. This was chosen to address the problem of items falling out of the prosthetic grip, both when picking up objects and holding on to them. Putting a material with a high coefficient of friction on the fingers would achieve the same result, but we wanted to avoid using resources outside of 3D printing as much as possible to prevent accessibility issues. We also decided to add a set screw to the wrist section of the prosthetic so that the wrist could be easily locked in place. The intent of this change was to improve the grip endurance by allowing the hand to be locked into a closed position, reducing fatigue in the user’s wrist and allowing for semi-permanent closure to be achieved with little effort.

The thumb of the prosthetic was redesigned to be 15 mm longer and approximately 10 mm further apart from the palm of the hand. Changing the thumb curvature in this way creates a more convex geometry on the side of the hand, thereby providing a wider grip that can warp around objects. This allows for improved performance with the manipulation of items with larger diameters, such as water bottles and cups, in addition to objects that require pinching at the finger tips, as seen in testing with keys and balls (see Appendix B for videos of testing).



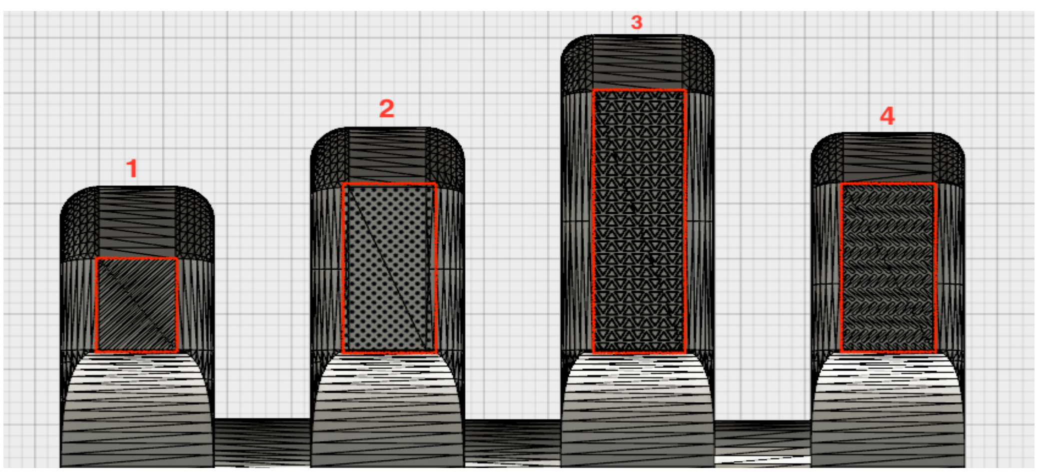
Original Thumb



Redesigned Thumb

For redesigning the finger pads, inspiration was drawn from textures seen in everyday objects that are designed to assist with gripping, such as grooves or ridges seen on water bottles and shoes. The patterns were made with the capabilities of standard 3D printer nozzles in mind, so the widths are greater than the 0.35mm minimum extrusion thickness and heights are in 0.05mm increments [8]. Each of the four long fingers in the new design features a different pattern, which would be tested individually to see which is most effective for maintaining a grip on objects. The geometric parameters of the patterns (heights, widths, etc.) should also be varied to find an optimal size, especially considering the discrepancy between a 3D model and its actual print. For example, all of the heights in the designs are currently 0.2mm, but that can be changed in 0.05mm increments (depending on the specs of the printer).

3D Geometries on Finger Pads (originally flat)



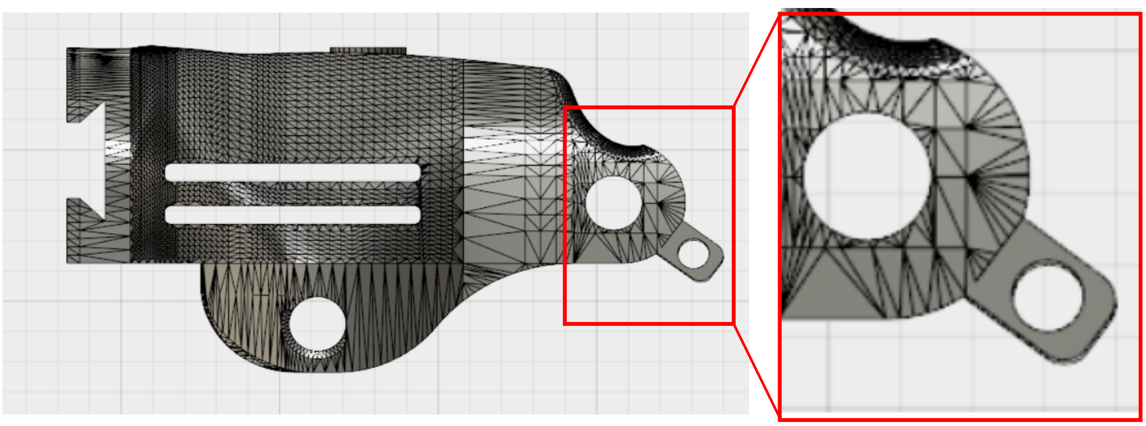
1. The first design features raised ridges at 45^{o} angles. The grooves are angled to account for holding objects oriented both horizontally and vertically.
2. The second design has a grid of small 0.35mm diameter circles. The idea is that the circles would put more concentrated force at certain spots and catch on an object's surface roughness.
3. The third design's idea is similar to the second design's, except that the circles are replaced with equilateral triangles (1mm edges) whose corners can frictionally catch onto an

object’s surface. The posts are also tapered 20° so that soft materials such as fabrics and rubber can wedge in between the triangles, making them easier to pick up.

4. The fourth texture was inspired by a Dunlop pattern for plectras used in playing guitars: the alternating 45° angles form a herringbone-like weave to catch on objects at multiple angles (instead of the first design’s singularity).

To add the locking feature at the wrist joint, a set screw and hole were added on the wrist section assembly (zoomed in figure below). When the user flexes their wrist to activate the fingers, they can use their other hand to tighten the set screw to create a friction lock with the upper arm portion of the prosthetic. This allows the user to apply a stronger force over time to gripping objects for they will not become fatigued, allowing the user to better manipulate heavier objects. To release the grip, the user can simply loosen the set screw, and the prosthetic resumes its normal use.

Hole Extension Added to Wrist



While these design solutions are proposed to address the hand’s limited gripping abilities, additional testing should be performed to confirm their utility. For example, the extension added to the wrist might fatigue easily when locking the wrist, so the thickness of the tab might need adjustment to avoid that issue. Parameters of the 3D geometries (heights, diameters, etc.) should be varied for optimization, as mentioned earlier. The lengthened thumb is good for picking up larger objects, but the distance might decrease grip strength due to the longer moment arm.

References

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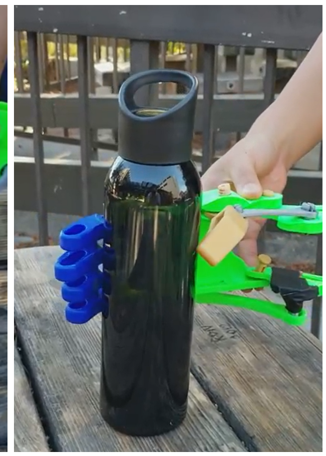
Appendices

Appendix A: Meeting Minutes

Meeting minutes can be found in [this Google Drive folder].

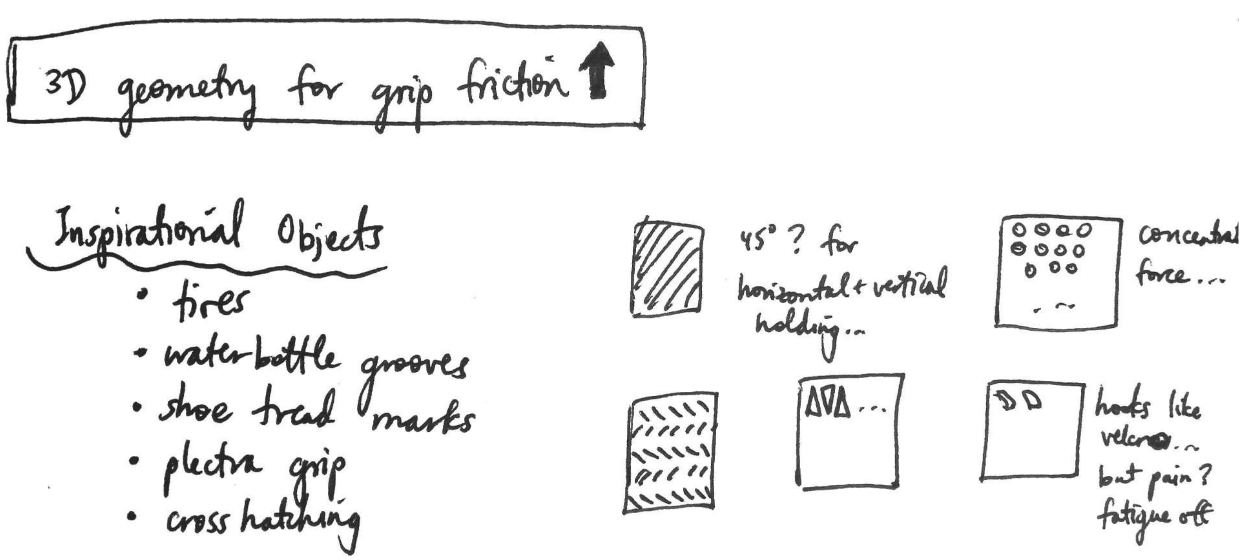
Appendix B: Testing Documentation



Videos and pictures from testing can be found in [this Google Drive folder].

Appendix C: Sketches for Redesign



Additional sketches can be found in [this Google Drive folder].

Appendix D: Presentation Slide