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Free-Body Diagram Analysis and Movement Design of a Functional Prosthetic Hand

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HONORS THESIS

Certificate of Approval

Free-Body Diagram Analysis and Movement Design of a Functional Prosthetic Hand

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Free-Body Diagram Analysis and Movement Design of a Functional Prosthetic Hand

Submitted in partial fulfillment

of the requirements

for the Murray State University Honors Diploma

Hayden Christopher Smee

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II. ABSTRACT

The loss of a limb is a devastating event to an individual on both physical and psychological levels. Despite decades of advancements in medicine, occupational health, and general safety in society, most people know someone or have encountered individuals affected by limb loss. This project created a prosthetic hand designed to aid those individuals. The hand is a predominantly 3D-printed prosthetic hand that includes an individually moving index finger and opposable thumb capable of grasping a full soda can weighing 385 grams (0.85 pounds). Numerous design solutions for the actuation of the fingers and thumb were considered and rejected. Cable actuators and four individually moving fingers with four motors presented too many challenges. Teams of students responsible for mechanics, electrical components, hardware, and CAD modeling cooperated to design a system of two four-bar linkages actuated by four small motors. A mathematical approach was taken to begin the design process, as variables such as force and torque were necessary for selecting motors. One key concern of the movement team was to calculate the coefficient of static friction, μ_s, applicable to the contact of aluminum and polylactic acid filament. Subsequent calculations yielded the minimum amount of gripping force needed from the fingers and thumb, a required 6.68 N supplied to each side of the can. Free-body diagrams provided the basis for approximating and understanding the forces acting on the object in question. The final design solution complies with two additional important goals for the Project C. L. A. W. S. team: a human-like appearance to lessen the daily psychological impact on the patient caused by the need for a prosthetic and a total manufacturing cost under our designated budget of $2,000. A functioning prototype is expected for delivery at the end of EGR 499 in May 2023.

III. INTRODUCTION AND MOTIVATION

To fulfill the requirements for completing the Engineering Physics curriculum at Murray State University, senior students must spend two semesters participating in a collaborative design project [1]. Students work together in small teams to design, analyze, and prototype a project selected from an approved list. Completion of the design and analysis demonstrates communication skills, as well as an understanding of multiple engineering disciplines and the application of the design process. Choosing the right design project was the first important decision the team considered for the year-long experience. Despite having no expectations of developing something innovative enough to eventually patent and put on the market, designing a product that tangibly helps people was a requirement for moving forward with the project. Many projects are made for the purpose of erasing minor inconveniences or perhaps even everyday struggles most people don't realize they have; however, our goal was to identify an obstacle people truly struggle with. It became evident that a delve into biomedical engineering research on prosthetics and psychological analyses of amputees was a pre-requisite for understanding the project goals.

Our project was the design and fabrication of an affordable prosthetic hand capable of grasping a full soda can without dropping it and an empty soda can without crushing it. These objectives, alongside the last names of the team members (Campbell, Lepore, Austin, Webb, and Smee), are the inspiration for the name of Project C.L.A.W.S. The grip strength of the prosthetic is controlled via feedback received from a force sensor in the thumb. Our group of engineers was divided into four teams, each with a different design focus. The electrical team's task was to design circuitry and write code for the processor that controls the movements of the hand. The modeling team's assignment was to model and 3D print the components of the hand via computer-aided design software. The hardware team's task was to assess, purchase, and integrate force sensors and motors into the design. Finally, a movement team whose task was to design the moving parts of the prosthetic and calculate needed force estimates. I led the movement team and assisted with tasks as needed by the modeling team.

This thesis uses terminology associated with the anatomy and physiology of the human hand. Information from [2-5] will be provided to ensure understanding, while Figures 1 and 2 pictorially model a human hand to explain the basic components we attempted to recreate. A finger is composed of three bones called phalanges. These bones, named starting from the base

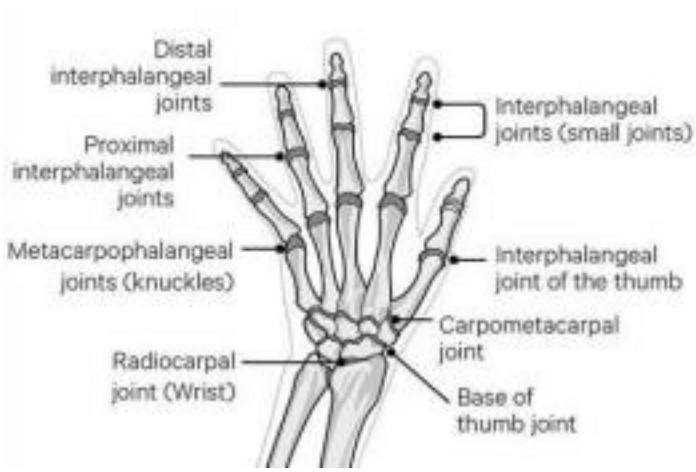

Figure 1: Anatomy of the Human Hand

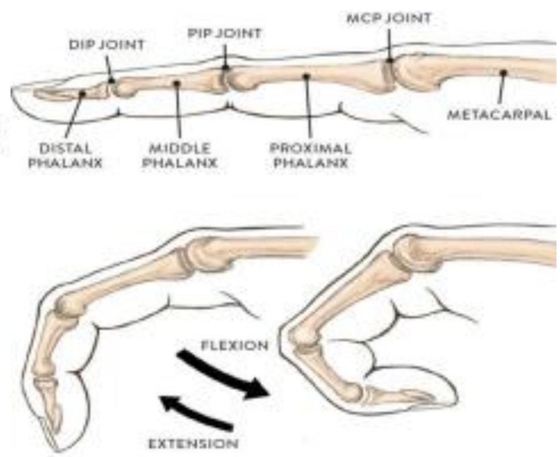

Figure 2: Diagram of Flexion and Extension

of the finger and moving outward, are the proximal phalanx, middle phalanx, and distal phalanx. Three accompanying joints connect these bones: the metacarpophalangeal (MCP) joint between the proximal phalanx and the metacarpal bone, the proximal interphalangeal (PIP) joint between the middle and proximal phalanges, and the distal interphalangeal (DIP) joint between the middle and distal phalanges. Squeezing the finger inward in a trigger-like motion is referred to as flexion, while the reverse is called extension.

As a member of the movement team alongside another colleague, I assisted in the design of a prosthetic that functions as similarly to a human hand as possible while considering constraints and the simple objective of the project. Our goals included maintaining high standards of dexterity, quality, comfort, and efficiency while keeping costs low and creating a relatively simple design. Creating a hand that can grip and hold an object with up to 15 pounds of force was our most ambitious goal, as this is the approximate grip strength of an average human hand [6]. Reaching this goal has always remained secondary to simply picking up a full soda can; a fraction of a human hand's maximum capabilities is required to accomplish this. The majority of the initial design phase was spent conceptualizing the fingers for the hand. Extensive research into modern prosthetics proved how important individually moving fingers are to the human-like appearance and functionality of the prosthetic. Building a hand with fingers of relatively similar size to human fingers is equally as important for our goal when we consider the impact of realistic appearance on the mental health of the patient. These constraints, combined with our intended project budget of $2,000, informed our two primary goals of making a functional hand at a minimal cost. The level of complexity of the fingers' actuation method will determine the level of complexity of the assembly of the prosthetic. As a member of the movement team, keeping this level of complexity as low as possible while still achieving the project goals, is of paramount importance. Most prosthetics on the market utilize an actuator for each finger that transfers intended movement to each of the three joints in the finger; the challenge of designing our own system to accomplish this spares us from using 12 total actuators—small motors to move each joint in each finger—but demands an intricate mechanical system to actuate each joint simultaneously with few motors. Another overall design goal was to achieve a higher degree of dynamic independency than the last iteration of the project [7] while applying the force needed to grasp an object without dropping it.

Another key component for the movement to address was the design and movement of the thumb. Although a thumb has fewer joints to actuate, it is the complex anatomy and dexterity of the human thumb that contributes to its usefulness. This particular task required input from the other three teams to find the truest balance between complexity and simplicity to accomplish our goal of grasping an object. Our entire senior design team contributed hours in discussion about the thumb alone. To complete the most important objective of our project, the movement of the thumb will be along two combined axes to mimic the fluid a motion allowed by human thumbs. The hardware team's pair of selected motors turn the thumb inward before actuating flexion.

IV. DESIGN SOLUTIONS CONSIDERED

Early in the design process, my partner on the movement team and I struggled to split our mechanical analysis tasks evenly. A proper balance was only found as we approached final design decisions late in the semester; most of the following concepts in this section served as benchmarks for our functionality goals and inspired creative steps towards our final design.

As mentioned previously, the entire senior design team was well aware of the high quality of the prosthetic hands currently on the market. Many employed individually-moving fingers and were coated with an outer layer to more closely resemble the appearance of human skin. We initially made ambitious design decisions in an effort to match the quality of these expensive, complex machines. Our hand would employ five individual motors to actuate the four fingers and the thumb individually. Our teammate in charge of modeling the hand realized there was not enough space in the palm to house the motors while maintaining a realistic thickness for the palm of the hand. Next, the discussion began of how to reduce the number of motors while still allowing the fingers to move individually. Our most ambitious hand design included several buttons that each corresponded to unique finger positions such as a peace sign, the grasping motion for the current objective, or the hand shapes needed to play rock-paper-scissors. Controlling each of the four fingers individually proved too big a challenge when we realized we did not have the space for five motors.

Realizing that the complexity of our design was too ambitious, we made radical design decisions that we later found to be much too simple. Wanting the hand to accomplish nothing more than our objective of picking up a full soda can, the movement team conceptualized a claw-shaped hand with three digits. The design was easily actuated and manufactured but was a major hindrance to the mental health considerations we strived to maintain from the point of view of the patient. Research on how aesthetics affect a patient's mental health was conducted and it was found that patients find "self-confidence" in two different stages [8]. In the first phase, the patient is still psychologically adjusting to the loss of a limb. In this phase, a prosthetic that appears more realistic increases the patient's acceptance of the prosthetic. The functionality of the prosthetic is secondary to its appearance in this stage of the patient's journey. In the second phase, the patient is more accepting of the loss of their limb, so a more functional and less cosmetic prosthetic is acceptable to them. While the goal of this project has a larger focus on functionality, having a prosthetic device that looks like the limb it was designed for is still important. Despite being the simplest way to accomplish the goal of grasping an object, other parts of the objective not being met led us to abandon the claw design for our project.

The movement team seriously considered only two methods for actuating the four fingers and the thumb. What seemed the simpler method was a spool and cable actuating system. Motors in each finger would turn spools and increase the tension in the cables, thus pulling the joints and

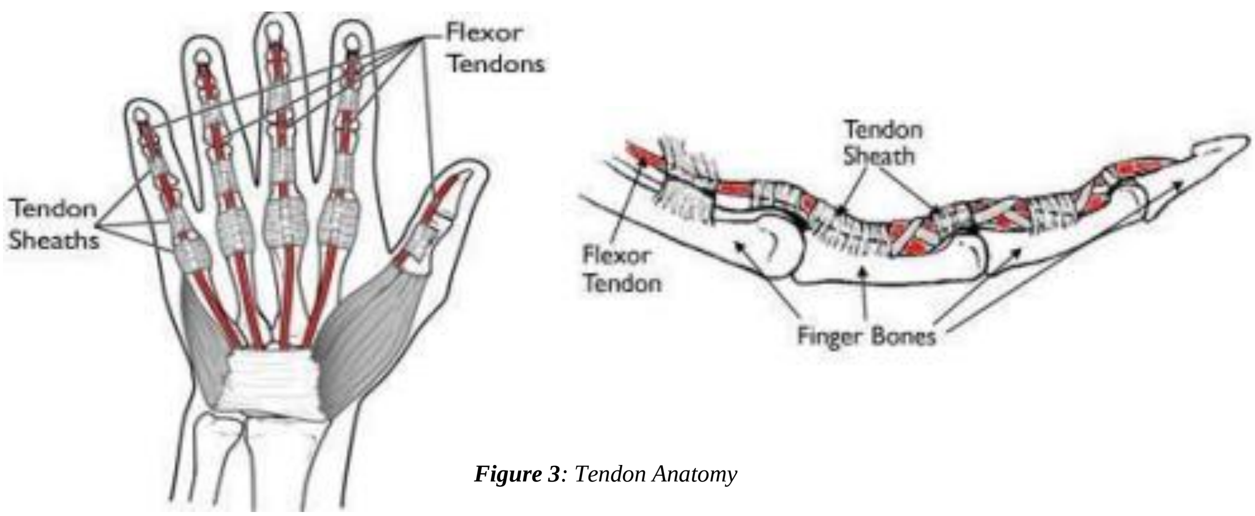

***Figure 3**: Tendon Anatomy*

fingertip into a grasping position. The design seemed much simpler before drawing how the fingers would actually move; multiple spools would have to be placed in each digit. Muscles and tendons work to allow bending and straightening of the finger. When bending, the tendons move through a tunnel of tissue. Figure 3 shows the anatomy of the tendons along the fingers and was found in [9]. The design of a pulley system was for the cables to rotate over a spool. An example design of a pulley system for a prosthetic hand is shown in Figure 4. However, when looking at how the finger will return to a normal position, the team struggled with how the tension in the cable would affect the return movement. Therefore, a different design for the bending of the finger was pursued.

Gripping strength and friction are the two forces responsible for the can being held in the hand's grasp. Careful calculation is required to maintain the prosthetic's grip on the can without crushing or dropping it. Reducing the required gripping force also reduces the forces transferred through the prosthetic's finger joints and, subsequently, reduces the torque demanded of the finger's actuator. Such a reduction simplifies the design and construction of our prototype and enables the use of smaller motors that more naturally fir the base of the prosthetic. Another attempt to reduce the required grip force was to design the pinky finger such that it could be pulled in closer to the palm than the other fingers. It would then act as a platform for the can to rest on while it was being squeezed by the other fingers. The pinky would have to be reinforced

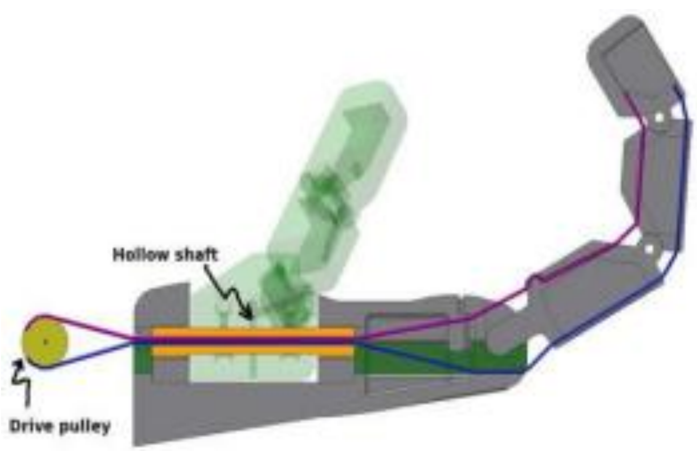

Figure 4: *Pulley System Considered*

more so than the other fingers but would potentially allow us to accomplish our goal of holding the object if the motors failed to provide us with enough force from the fingers. The main issue with this design was that the pinky could not move underneath a can while it sits on a surface. The hand would have to raise the can enough for the pinky to slip underneath. Such a movement would require the hand to lift the can without the support of the pinky. Since reducing the force required for that gripping and lifting movement was the intent of the alternate pinky design, the design was abandoned.

V. FINAL DESIGN SOLUTION AND ANALYSIS

Though our final version of the prosthetic hand design has many similarities to the 2018 iteration of the project, we have made several key improvements to its functionality. Much of my design analysis informed the other teams as they finalized their design decisions. The movement team's final method for actuating the fingers was a dual four-bar linkage mechanism. We decided to integrate only three motors into the hand to reduce weight and conserve space; one motor actuates the thumb, a second actuates the index finger, and the final actuates the middle, ring, and pinky fingers simultaneously. This decision significantly limits us on how many motions can be made besides the shape needed for grasping the object. Our final thumb design is heavily inspired by the previous iteration of the prosthetic hand project; a motor turns the entire thumb inward towards the palm of the hand, and a larger motor actuates the four-bar linkages to provide gripping force.

Numerous questions needed to be answered before final design decisions could be made. I constructed a free-body diagram under many mathematical assumptions to simplify my ability to find needed values.

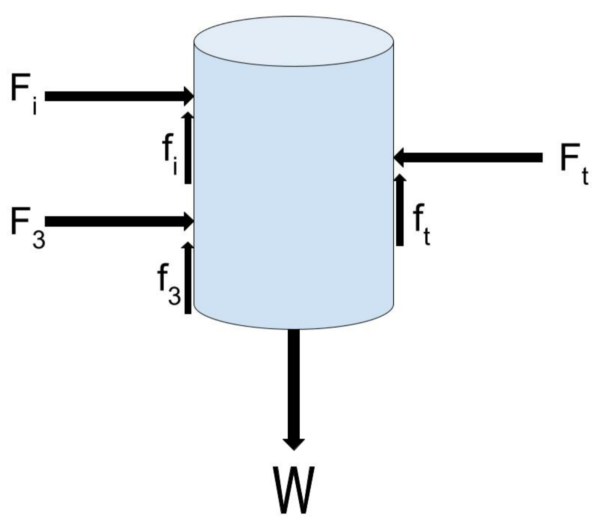

***Figure 5**: A simplified free-body diagram of the forces acting on the can*

For our purposes of estimation, the action of the fingers and thumb gripping the can are represented by F_i, F_3, and F_t (in Newtons): the gripping force supplied by the index finger, the resultant gripping force of the other three fingers actuated by one motor, and the gripping force by the thumb, respectively. The weight *W*—found by multiplying its mass by the gravity constant—is also measured in Newtons. Full soda cans are 0.85 pounds on average; the movement team decided to round this value up to one pound (4.45 Newtons). Forces represented by f_i, f_3, and f_t are due to friction and found by multiplying each gripping force by the appropriate coefficient of static friction, μ_s. The free-body diagram assumes a two-dimensional scenario rather than three-dimensional. A 3D cylinder shape is used for Figure 5 to distinguish the can from an ordinary rectangle. The sum of the forces of the fingers directly opposes that of the thumb in direction and magnitude. Using this diagram, I would be able to calculate the total force required to maintain the can's static condition in the grasp of the hand.

Estimating the coefficient of static friction between the aluminum can and a 3D finger was the first design challenge I faced. Many commonly used materials have friction coefficients that can be found on the internet, but the value to use for my purposes could not be realistically approximated without experimentation. To begin, I 3D printed a 0.5" x 0.75" x 1" block to replicate the surface area of the fingers in contact with the can. I sanded and used a smooth piece of aluminum as a ramp to slowly lift on one end until the block began to slide. This situation can be represented by the free-body diagram below.

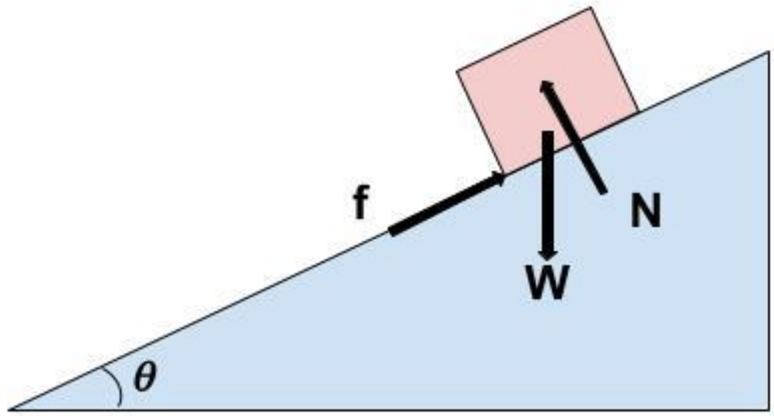

Figure 6*: A free-body diagram of an experimental printed block on inclined aluminum surface*

The testing showed that the block began sliding at an average angle of 18.4° and provided me with enough information to begin calculating μ_s with the following equations. Mass *m* was found to be 400 grams. A standard value of 9.81 m/s^2 was used for *g*.

$$\sum F_y = N\cos(18.4°) + f\cos(18.4°) - mg \quad (1)$$

$$\sum F_x = N\sin(18.4°) - f\cos(18.4°) \quad (2)$$

Equations 1 and 2 yielded a result of 0.0102 Newtons for *N* and a value of 0.333 ±0.0221 with 95% confidence for the needed coefficient of static friction after ten experimental runs.

Having found the missing piece of the puzzle, I was then able to calculate the fingers' gripping forces necessary for the hand to hold the full can in place. Equations 3 and 4 below were derived from the original free-body diagram represented by Figure 1 and are used to calculate values for friction forces as well as the aforementioned gripping forces. Below equations 5 and 6 are based on previously described mathematical assumptions.

$$\sum F_y = W - (f_i + f_3 + f_t) \quad (3)$$

$$\sum F_x = F_i + F_3 - F_t \quad (4)$$

$$F_t = F_i + F_3 \quad (5)$$

$$f = F\mu_s \tag{6}$$

The equations found the total gripping force from the thumb should be 6.68 N while F_i and F_3 were 3.34 N each. These values were what was needed to calculate torque and select the right motors for accomplishing our objective.

A four-bar linkage was then designed that allows the DIP, PIP, and MCP joints to move. As shown in Figure 7, this design provides dynamic improvement from the previous iteration of the prosthetic hand project. The two linkage mechanisms are connected by a coupling linkage allowing them to move simultaneously. Sizing the linkages was done after the modeling team provided the movement team with preliminary finger designs based on the previous iteration of the project. In order to maintain a finger size consistent with what we saw of the 2018 prosthetic, we simply approximated linkage lengths that could fit inside the phalanges. Keeping all four fingers the same size was important for the modeling team's desire for printed part interchangeability. Countless extra pieces would be printed, and being able to use any of the segments for any of the pieces was a solution to cut down on waste. Designing fingers of equal

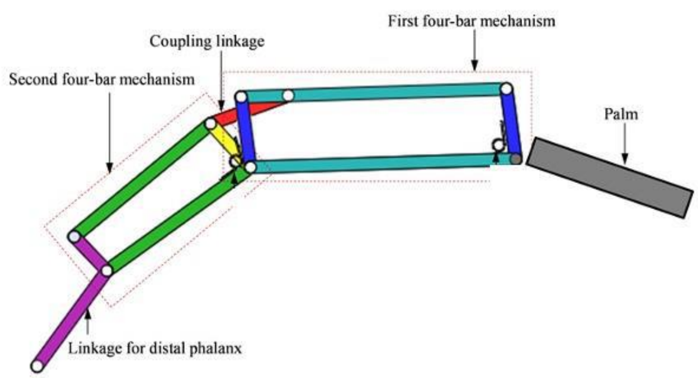

Figure 7: *Four-Bar Linkage Design*

length also replicates the natural human finger adjustment that typically happens when picking up a can. With the size constraints of the palm, our group decided that the middle finger, ring finger, and pinky finger would move together, the index finger would move independently, and the thumb independently. The prosthetic hand can grip a can and pinch with the fingers moving in this configuration. Two motors drive the thumb; one motor will move the thumb into the opposed position, while the other motor will move the thumb in flexion and extension. The thumb is set at a fixed angle of 165 degrees to provide the best contact surface area while gripping.

During the prototyping process, it became clear that my contributions to the assembly of the prosthetic would be limited. My senior design colleagues were responsible for the 3D printing, wiring, programming, and purchasing additional materials as needed. Thus, I shifted my focus to what had been seldom discussed and generally overlooked: increasing the coefficient of static friction with a "skin" material. By testing a few materials that could coat the contact surface on the fingertips, I could calculate how much less force should be required to grasp a full soda can. Our printed version of the distal phalanx bone was the first subject. Using the same testing procedure illustrated in Figure 6 with 95% confidence and 10 runs, I found the value of μ_s to be 0.45 ±0.0334. This slightly higher value reflects the inaccuracy of using a perfectly rectangular 3D-printed block instead of an asymmetric finger segment.

Next, three substances were independently applied to the finger segment before returning it to the smooth aluminum testing surface. The first and least helpful material was 0.75-in electrical friction tape, which yielded a value of 0.725 ±0.0182 for μ_s. Fingers from basic gardening gloves were the other two options for skin—one coated in latex and the other in polyurethane. Static friction was calculated as coefficients of 0.865 ±0.0169 and 0.794 ±0.0136, respectively. By inspection, one can see that the polyurethane surface on the other pair of gloves is distributed unequally. Randomly placed splotches of thicker coating litter the palm and fingers of the glove, which causes inconsistent friction calculations for different parts of the glove; the thickest part of the polyurethane glove was used for experimentation. The surface of the latex gloves was chosen for the final prototype of the prosthetic because of its reliably higher friction coefficient value. I repeated the experimental procedure shown in Figure 5 to estimate how much force would need to be transmitted from the fingers to the can using the latex μ_s value of 0.865 ±0.0169. The thumb would now be responsible for supplying 2.58 N, with the new value for F_i and F_3 being approximately 1.29 N in turn. These values indicate a 61% decrease in force needed to hold the can without slipping thanks to a 161% increase of the coefficient of friction. Further friction testing will allow the movement team to calculate how much friction would be required to lower needed torque values, perhaps enough to incorporate different motors into our design. Combining the use of a skin material and the actuation of the index finger independently of the other three advances our prosthetic beyond the previous iteration of the project.

VI. CONCLUSIONS

The final design for our prosthetic hand takes small steps towards fulfilling the user's physical and mental health needs by combining partial functionality with as human-like an appearance as could be designed. As improving upon the past iteration of the project was the benchmark for this project, incorporating actuation methods that separate the index finger from the other three fingers is considered an accomplishment. Both grasping and pinching are possible using our current design. Future iterations of the prosthetic hand project should be challenged to actuate all five digits independently, a lofty goal for us at the beginning of the academic year. Designing a dual four-bar linkage to actuate the fingers presented many challenges for the design team before and during the prototyping phase of the semester. Our team's 3D printing specialist was forced to print the smallest pieces of the mechanism several times to ensure the accuracy required for unobstructed movement. If my colleague focused on movement design and I could begin this project again with the knowledge we have now, I am confident that a mechanical system with many parts would not be given a second thought. Using cable actuators that attach to all three phalanges in each finger would be much less difficult than building a flawless mechanical system.

My colleagues on this project have contributed many hours diagnosing various movement-related issues and experimenting with solutions not detailed in this thesis. One of the most unexpected, last-minute obstacles to finger movement is the original dual four-bar linkage system does not actuate the distal and middle segments in flexion while the proximal segment rotates; thus, only one finger segment is moving to the desired grasping movement. Figure 8 shows the proximal phalanx segment before any design alterations. A large hole was added to both sides of the segment with enough room to allow free rotation of a square rod piercing

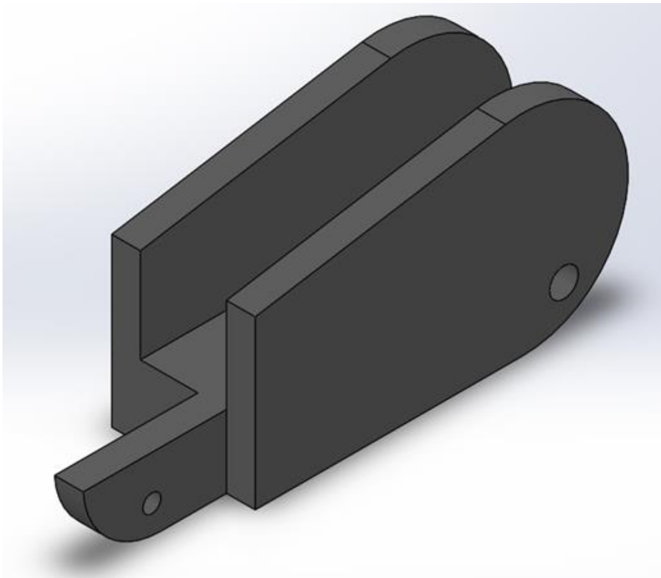

Figure 8*: Original Proximal Segment Design*

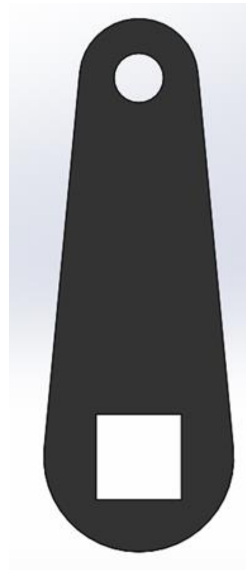

Figure 9*: Linkage Hole for Square Rod*

through each proximal segment. The first linkage piece in each finger was then redesigned to rotate via the square rod. Figure 9 shows the addition of a square hole to the linkage design. Overcoming this design obstacle marks the beginning of the final prototype assembly process. A working prototype will be provided by the early May 5^{th} deadline set forth by EGR 499.

Motors supplying adequate torque cannot be shipped to campus quickly enough for the team to test my calculations or hold a soda can, but motors we plan to use instead will still prove that our improved linkage system actuates the phalanges correctly. Stress calculations by SolidWorks show that our original design could not provide the force of an average human hand without yielding, but using our preferred motors would allow for a much heavier test object than a full soda can. I intend to conclude my work on this project by calculating exactly how much weight can be supported by our hand using the motors we had available versus the motors needed to accomplish the original goal.

VII. REFERENCES

[1] Austin, Natalie, et al. “Design to Accomplish Responsive Feedback in Picking Up an Object with a Prosthetic Hand.” Murray State University, 2022.

[2] Wadsworth, Carolyn T. “Clinical Anatomy and Mechanics of the Wrist and Hand.” Journal of Orthopedic & Sports Physical Therapy, vol. 4, no. 4, 1 Apr. 1983, pp. 206–216., https://doi.org/10.2519/jospt.1983.4.4.206.

[3] Estay, Danilo, et al. “Development and Implementation of an Anthropomorphic Underactuated Prosthesis with Adaptive Grip.” MDPI, Multidisciplinary Digital Publishing Institute, 24 Sept. 2021, https://www.mdpi.com/2075-1702/9/10/209.

[4] “Osteoarthritis of the Hand and Wrist.” Versus Arthritis, Versus Arthritis, https://www.versusarthritis.org/about-arthritis/conditions/osteoarthritis-of-the-hand-and wrist/.

[5] “Trigger Finger: Symptoms, Treatments.” Cleveland Clinic, Cleveland Clinic, https://my.clevelandclinic.org/health/diseases/7080-trigger-finger--trigger-thumb.

[6] Belter JT, Dollar AM. Performance characteristics of anthropomorphic prosthetic hands. IEEE Int Conf Rehabil Robot. 2011;2011:5975476. doi: 10.1109/ICORR.2011.5975476. PMID: 22275674.

[7] Gullixson, Alexander. “Movement Design of a 3D Printed Prosthetic Hand.” Murray State University, 2018.

[8] Sansoni, Stefania & Wodehouse, Andrew. (2015). Psychological Distress and Well-Being in Prosthetic Users – the Role of Realism in Below-Knee Prostheses. 10.13140/RG.2.1.3002.7681.

[9] “Flexor Tendon Injuries - Orthoinfo - AAOS.” OrthoInfo, American Academy of Orthopedic Surgeons, https://orthoinfo.aaos.org/en/diseases--conditions/flexor-tendon-injuries/. [10] Gopura, R. A., and D. S. Bandara. “A Hand Prosthesis with an under-Actuated and Self Adaptive Finger Mechanism.” Engineering, vol. 10, no. 07, 2018, pp. 448–463., https://doi.org/10.4236/eng.2018.107031.