On the Development of a Low-Cost, Lightweight, Under-Actuated Prosthetic Gripper

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Abstract— **Complex, heavy and fully actuated prosthetic hands have dominated the research community over the past decades. Traction has been growing in simple, lightweight, under-actuated designs and therefore an opportunity to further contribute to these designs. This paper focus on the development of a two finger tendon driven, actuated gripper that uses a single Dynamixel motor to power both fingers. The hand weighs only 170g and is capable of a grip strength of 33N while still being able to full extend and contract in less than a second. The finger and palm pads have been designed using the knowledge gained from studying patterns from animals but the final result that proved the best was the baseline of a flat non-rigid pad.**

The proposed prosthetic hand is experimentally validated through two tests: i) grasping experiments with everyday life objects, ii) force exertion experiments.

I. INTRODUCTION

Having the ability to grasp objects allows humans and robots to interact and manipulate their environment in technical and meaningful ways. These include controlling a a phone, operating a motor vehicle and tasks as simple as eating and drinking. In terms of prosthetic or robotic gripers currently available the majority are fully actuated, heavy and expensive. These do offer the potential to interact with objects similar to a human hand however, they cost between $4,000 to $75,000 depending on how accurately it replicates a human hand [1]. This cost is to significant for the majority of amputees that are missing an upper limb. Approximately 540,000 people are dealing with this in the USA and this number is expected to double by 2050 [2]. Therefore, there is a significant need for a low cost, lightweight prosthetic gripper which can be achieved through under actuation. This will mean amputees that can't afford grippers in the thousands, will still be able to manipulate everyday objects similar to that of a normal human hand. In this paper, we focus on the design and development of an extremely lightweight two finger design that is tested on everyday objects. The rest of the paper is organised as follows: Section II presents related work, Section III details the design and development of this hand and Section IV evaluates the results of the manipulation of everyday objects. Section V discusses the results and Section VI concludes the paper and discusses the future directions.

II. RELATED WORK

The current prosthetic and robotic grippers tend to be either anthropomorphic hands, or two or three finger gripper that looks more like a claw than a hand. The major advantage of an anthropomorphic is the ability to manipulate everyday objects as they were intended such as grasping a marker or mug as they were designed for [3]. A two finger gripper would be able to pick up the objects but not as intended which would prevent the objects being used as intended such as writing with the marker or drinking out of the mug. There is however, many benefits of two or three finger grippers as they have fewer moving parts which means fewer points of failure. It also allows the overall weight to be lighter along with the potential to use less actuators and optimise the power from them through reduced tendon routing. An alternative design uses the idea of replicating the index and thumb grip of an anthropomorphic hand. This was done by changing the number and length of each phalanx, such as the index finger having three and the thumb just two. They saw improvements when performing power grasps, precision pinches and lateral pinches compared to fingers of equal length [4].

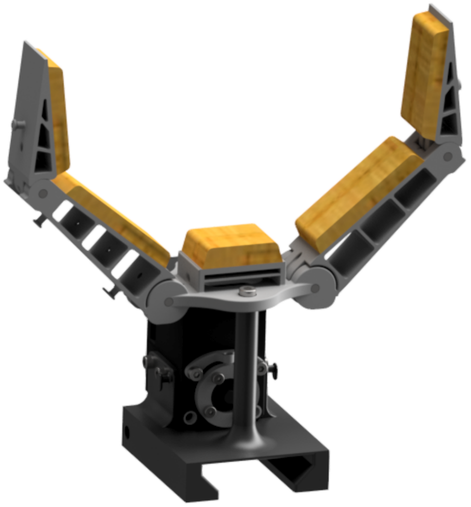

Fig. 1. The proposed low-cost, lightweight and highly Under-Actuated adaptive prosthetic gripper.

To reduce the weight of prosthetic grippers the motor size needs to be reduced as that is the major weight. This can be done by using extra pulleys that will maintain the gripping force of the hand, however this is at the consequence of hand actuation speed. Therefore the gripper needs to be able to increase the coefficient of friction with the surface and increase the amount of contacting surface area to counter the reduced grip strength. There are two main ways to go about this i) Using compliant fingers that are able to deform around the object and ii) adding semi-rigid pads like silicon to the fingers and palm while optimising the pattern on the pads.

In regard to a compliant gripper design a number of designs have been inspired by orgami such as the 'Twister' [5]. The fingers are just a combination of 3D printed joints that bend and deform as a tendon is tightened. They start of straight and at full tension they are curled over. This doesn't just increase surface area it also allows more complex objects to be grasped as its not limited to two or three joint at set locations. Compliant designs are also useful when having human to robot interaction as it isn't rigid which decreases the chance of injury. Another compliant 3D printed design uses cellular fingers that has the characteristics of an auxetic honeycomb structure, which is initially hard to model, however once it is, the pattern can just duplicated. It provides the benefits of increased energy absorption which prevents damage from high pressure uses and has reliable deformation. Most importantly it allows for tune-able mechanical properties of each section of the fingers [6].

Fin Ray gripper comes from fin-ray effect which is inspired by rays of fishes and is used as a flexible construction to transfer forces [7]. This design has been used by a range of gripper designs to allow the fingers to deform around objects increasing surface area contact. An optimised Fin-Ray finger, was done through optimisation of the angles of the ribs that are used in the fingers which was done using CATIA. This allowed for increased deformation around objects increasing surface area and therefore being able to pick up heavier objects. This resulted in an increased grip strength of 40% [8]. Other designs include using more ribs at the same angle which will jam with one another when the ribs are deformed past a designed point. This increases stiffness and rigidity to the fingers that can be tuned to allow for more force to be applied when gripping [9]. Different sized objects work better with different amounts of deformation therefore a program was designed to optimise the length of the fingers, the rib pattern and rib spacing [10]. This program can be further improved using machine learning to evaluate the deformation of the hand to different objects using a camera [11].

In terms of increasing the coefficient of friction between the finger and the object a range of designs have been explored. The most novel is an orgami inspired gripper that uses extra actuators within the fingers that is able to modulate the friction of the fingers. It does this by dynamically changing the pattern of the silicon pads. It also allows the fingers to perform dexterous in hand manipulations of the objects, such as moving an object up and down the fingers [12]. The majority of designs have found that some form of silicon pad is ideal, but the shape and pattern used does vary between papers and the objects they used to test with. An optimised Fin-Ray used silicon pads that were 4mm thick and had a pattern that copied the form of a tree frogs toes that can be described as hexagon patterns. They found this to be the most effective for their tested objects [8]. A detailed study on silicon pattern designs compared 37 design variations on 1377 grasping orientations and surfaces. Their baseline was just a rigid printed surface that had a success rate of 28.7%. Electrical tape which is considered an industry standard had a success rate of 68.7%, gecko designs similar to that of the frog performed even better but an optimised silicon design came in first with 93.7%. The results were that gecko inspired designs was very good but theirs was better which was similar to that of mill-scale. They believe it was better as the objects tested were rougher which meant mill-scale was more effective, as gecko designs are better at smooth surfaces [13]. Mill-scale designs are further backed by [14] who found it was very useful when the surface had moisture or lubricant on it as the gaps in the patterns allowed the substances to disperse. A novel design used an octopus inspired vacuum gripper design on a silicon pad. The design allowed for increased flexibility and adhesive force compared to regular suction cup designs, which works the best on smooth surfaces like glass [15].

In terms of the shape of the silicon pads a study was done that compared, cube(flat), sphere(convex) and cylinder shapes according to their friction coefficient at different contact angles. The cube performed the best overall with improved frictional shear. However, they found it was best to match shape of the pad with that of the surface to allow equal force distribution. The edges of the pad should also be rounded to reduce a near zero contact patch being caused which will lead to in increased slip [16]. In terms of installation of the pads HDM was found to ideal which uses sacrificial walls which means the fingers can be printed in one piece, silicon poured in and set then the walls removed [17].

III. DESIGN

The design of the prosthetic gripper is inspired by the Fin-Ray effect and the published designs of Fin-Ray grippers. A major issue found with the designs was the inability to pick up objects heavier than 0.5kg. So a range of design improvements were made to increase this to the desired strength of 2kg.

Fig. 2. The initial prosthetic hands that were used to test tendon routing and rigidity when the hand is assembled. On the right is the first iteration and on the left is the second that aimed at reducing the weight of the overall assembly.

Initial designs are shown in Fig. 2 had a range of design flaws such as the lack of compliance in the fingers and the overall weight of the design that was 200g.

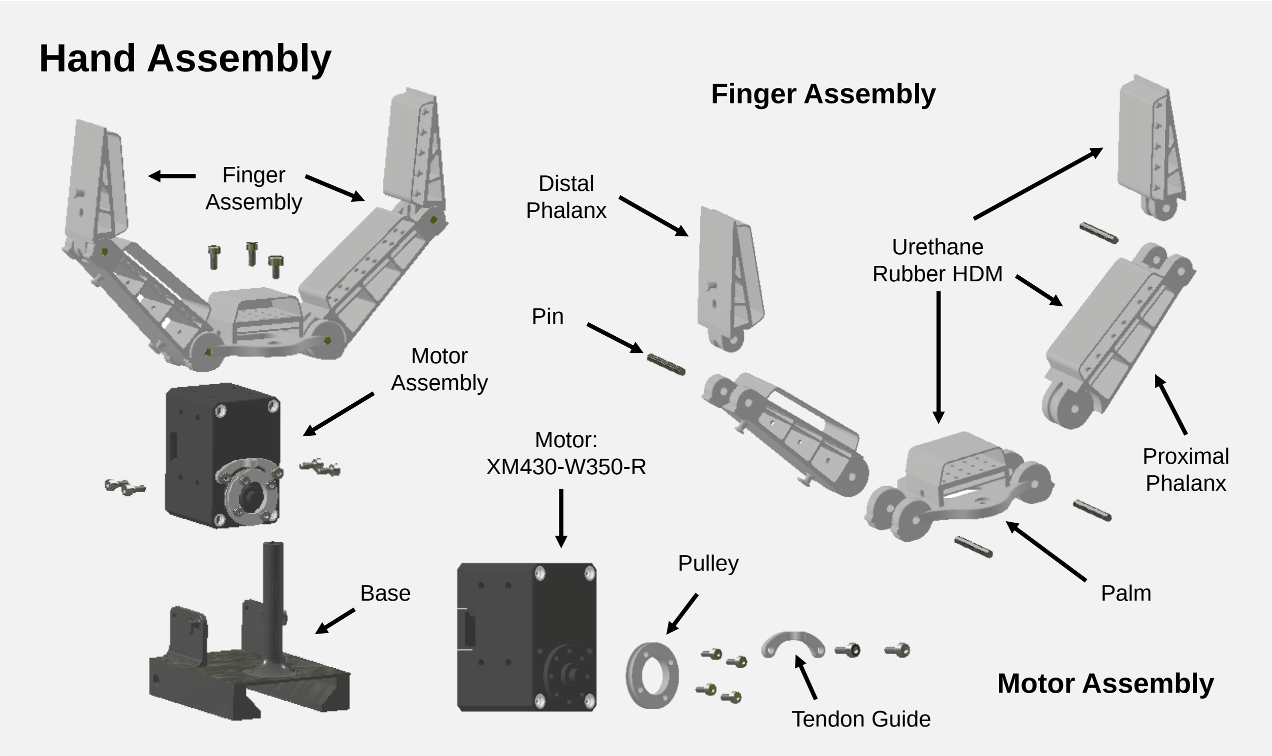

Fig. 3. The proposed highly under-actuated prosthesis, exploded into multiple sub-assemblies that is the finger and motor assembly.

A. Overview

The final design is shown exploded in Fig. 3 with the main features broken down as the finger and motor assembly. Design features such as the sacrificial walls that are used to create the finger and palm pads are not shown. The a two finger tendon actuated design was chosen due to its simplicity and the ability to achieve the overall goal of being lightweight and therefore low cost.

B. Gripper Base and Palm

The base of the hand is very simple mostly consisting of a dovetail slot that allows it to be attached to the robotic arm for testing and object manipulation. Simple brackets are printed to the base that bolt into the sides of the motor and a single shaft at the front is used to brace the outside of the palm. It's important to note that the motor is mounted so the horn where the tendon attaches to is on the center-line of the base. This means that it is in the center of the robotic arm which means no offsets need to be accounted for when programming motion. The motor selected was the XM430-W350-R which has a stall torque of 4.1Nm of torque and weighs 82g. This was selected over a MX-64AR as even though it has a higher stall toque of 6Nm the extra weight is not worth it which is 53g more. To pick up all the objects the lower torque motor would be enough and the weight saving is significant enough to take the risk. The shaft has a threaded insert at the top of it that slots into the groove in the palm Fig. 4. This allows a very short bolt to be used to secure the palm.

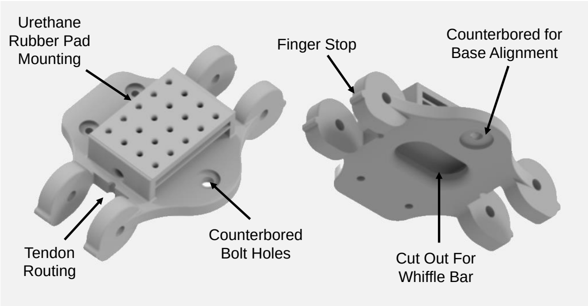

Fig. 4. The palm of the prosthesis with key components highlighted such as the tendon routing and finger stops to prevent over extension.

In Fig. 4 there are key features highlighted such as the counter-bored holes for the mounting features, cut outs to reduce weight and increase travel distance for a differential. There are also mounting features for the semi-rigid pads that is made up of holes so that the urethane rubber can go through during bonding and harden on the back surface. This means there isn't need for external mounting features that would reduce the flex and compression of the palm pad.

C. Gripper Fingers

As mentioned earlier the finger design originates from the Finn-Ray effect but standard designs are unable to pick up heavy objects. To counter this an extra joint was added to allow it to deform more in the middle and allow the fingers to deform around the back of objects. Being around the back of an object will allow increased gripping strength and force applied to the object. However, due to the material used to print the fingers being PLA there is very little deformation or compliance in the fingers. Therefore resulting the in design origin just allowing the design to maintain strength while being extremely lightweight. In Fig. 5 other features are highlighted such as the pad mounting that is same design as the palm on the proximal but different for the distal. The distal had to have different mounting features due to the thickness of it at the finger tips. The hole sizes vary on the joints to allow a pin to fit tight on the outside features and loose on the rotating features, like the top of the proximal and base of distal.

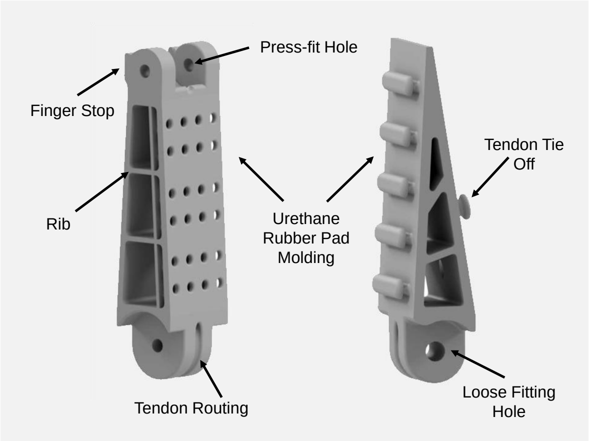

Fig. 5. The finger design with the proximal on the left and distal on the right. Sacrificial walls that are used for the finger pads are not shown.

To allow the fingers to pick up small objects like a credit card or a washer finger nails are created by filing down the finger tips till they are sharp which is roughly 0.2mm thick.

D. FEA Analaysis

To allow for design optimisation and validation before the final design is experimentally tested, a test piece is printed from the same FDM printer using the same filament PLA. The test piece looks exactly the same as that in the model seen in Fig. 6. It was then fixed to a vice and deformed from both mounting points, the first at 70mm and then the second at 110mm out. The weights used were 250g, 500g and 750g. The deformation of the tip was measured and then compared against the deformation seen in an ANSYS model of the same part that varied the Young's modulus. Once the material properties were determined the model was validated and could be used for more complex models like the fingers.

As a safety factor and to allow for a margin or error the fingers were initially tested with no ribs. The tests were i) a point load on the distal phalanx to replicate a pinch grip, ii) a larger circular object was loaded against the proximal phalanx to imitate a power grip. Lastly iii) tested out of plane bending through a point load acting on the side of the distal which represents the weight an object resting on it like the chuck of a drill. The results from all these tests showed minimal deformation and stresses less than 50% of the yield stress.

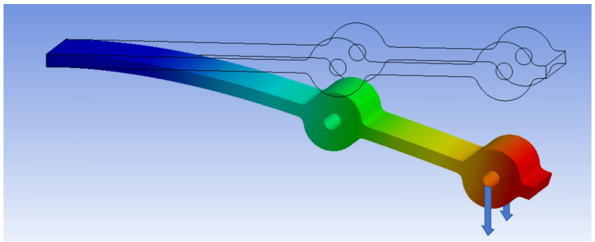

Fig. 6. ANSYS model of a test piece being deformed to allow the material properties to be tuned to match a printed version of it. Blue represents no deformation and red represent maximum.

Ideally ribs are used to tune the deformation of the fingers, however due to the material properties being to rigid even without any ribs and a wall thickness of 1mm there is very little deformation. An example of this is shown in Fig. 7 with deformation of less than 2mm is seen. Therefore it was accepted that there would be little to no deformation even without ribs so ribs were added back in the orientation specified by [8] to ensure strength and durability.

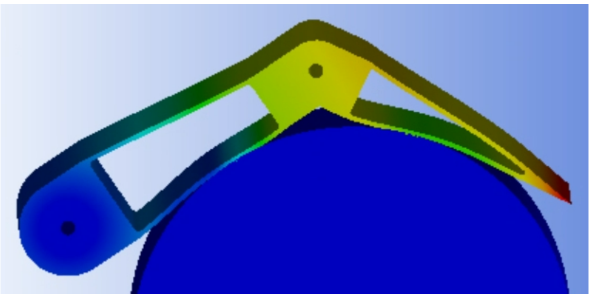

Fig. 7. A complete finger is shown in a power grip around a circular object in an ANSYS model. Finger pads were not used as it would have increased the complexity of the model. Blue represents no deformation and red represent maximum.

E. Gripper Actuation

To control the fingers using only one motor multiple tendon routing options were explored which are seen in Fig. 8. Option 1 is using no differential which means both fingers are routed directly to the pulley that is attached to the horn of the motor Fig. 3. This means they both close at the same time and if one is jammed the other is unable to move. Option 2 uses a differential that is just a whippletree bar that means that the fingers can move individually or at the same time dependant on the force applied to each finger. The tendon guide is used to ensure the whippletree bar is pulled directly down and not on an angle that would favour one finger over the other. For the intended testing the robotic arm that is connect to the gripper will be positioned in a way that the object is central between the fingers which means no differential is needed so option 1 is selected. If the object can not be guaranteed to be centered relative to the hand option 2 should be used.

Routing through the actual fingers is done through a channel that follows the blue line seen in Fig. 8, it is then tied off at the mounting features seen on the distal and again

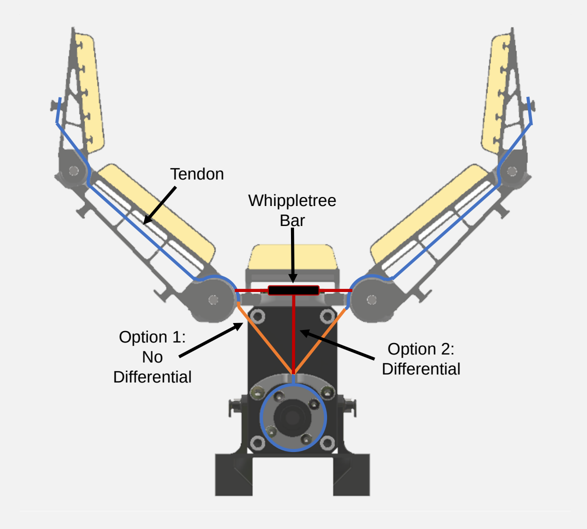

Fig. 8. A cross-sectional view of the hand is shown, that highlights the tendon routing along with multiple differential options.

at the pulley. The channel aimed to have no tight or sharp bends in the tendon route to reduce friction and increase the overall grip strength. No pins were used at bending points as the PLA fingers printed with 100% infill was found to be strong enough and reduced the overall weight and complexity of the design.

To ensure the fingers close as intended when then tendon is tightened, rubber bands are used at the joints which results in the proximal closing in first and then the distal. These rubber bands also reset the position of the hand once the tendon is loosened with stops on the palm, and fingers to prevent over-extension. Springs were not used as they're much harder to tune than rubber bands.

F. Finger and Palm Pads

Vytaflex 30 Urethane rubber pads are used on all contact patches of the gripper, these being the fingers and palm. This was selected over softer alternatives that have lower duormeter readings as the pads needed to stay fixed to the hand and not just peel off or tear easily when used. They also needed to withstand repeated testing. Any harder than this the gains from using pads would decrease as it needs to be able to compress into different features of the objects it interacts with.

The shape of the pads are flat by design as studies showed that overall it will result in more contact area when gripping a range of objects [16]. Edges are rounded to prevent interference as the fingers close and according to [16] prevent areas of almost zero contact area. The thickness of the pads vary, with the fingers being 5mm and the palm being 7mm, the palm is thicker as it allows greater compression and therefore increased contact area that will help in power grips.

In terms of the pattern on the pads, five designs were investigated. These designs are shown in Fig. 9, with a) being the baseline with no extra pattern, b, c, d, e) are all evaluated against one another and the baseline to determine the best design for the gripper. It was found that b, c, d) all showed potential and would be ideal when the surface had moisture on it. The last design e) needed to be made from a softer material as the design that is inspired by octopus was unable to actual form suction against surfaces. Overall a) the baseline was selected as the surfaces ranged but would always be dry which means greater surface area in contact with the object would be the best.

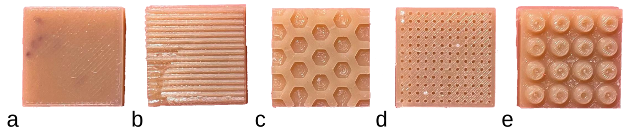

Fig. 9. The range of tested patterns on the finger and palm pads, a) is the baseline, b) is spikes that is a variation of mill-scale, c) an interpretation of the pattern on a frogs toes and d) is made up of voids. Lastly, e) is suction cups that have been designed based of an octopus's' tentacles.

IV. EXPERIMENTS AND RESULTS

To evaluate the final design it was tested in a grasping challenge. This tested its ability to pick up a range of objects while maintaining control, the robotic arm that is controlling the hand is then moved around to ensure the object is firmly grasped. The hand is also evaluated by its overall weight and maximum grip strength using a dynometer.

Fig. 10. The proposed highly under-actuated prosthesis gripping a hammer in a pinch grip around the head.

Shown in Fig. 10 a hammer which was one of the eight objects tested has been picked up by the gripper in a pinch grip and it proved to be the most difficult.

TABLE I

RESULTS FROM GRASPING CHALLENGE.

Object	Weight(kg)	Success (Yes/No)
Small Washer	0.0001	Yes
Credit Card	0.004	Yes
Fork	0.03	Yes
Chain	0.1	Yes
Wrench	0.24	Yes
Hammer	0.65	Yes
1.5 L Water Bottle	1.5	Yes
Drill	1.97	Yes

Table I shows all the objects tested, their weight and if the gripper was able to pick up the object in a firm grasp. As the results show than hand was capable of grasping all the objects. The overall weight of the hand was 170g and the maximum grip strength was 33N.

V. DISCUSSION

In terms of the actual design it was found a smaller base could be used with smaller dovetail slots that would of reduced weight, the shaft on the base could also have been replaced with mounting brackets attached to the motor which is the most rigid part of the hand.

From the objects grasped the hammer was the hardest as the weight of it is mostly centered around the head of the hammer. This means it has to be picked up from here to reduce large torques being placed on the hand, however a power grip around the head of the hammer was not possible due to the slope of the head and the fingers being too short. Therefore it had to be grasped using a pinch grip which caused the motor to get very close to overloading. The chain is articulated which makes it very hard to grasp without it slipping out when only two finger are used. Therefore to achieve a sturdier grip more fingers should be added through an optional attachment or fixed permanently.

The maximum grip force was 33N and the max of the motor at 10mm away from the horn which is where the tendon is located on the pulley is 40N. Therefore through the routing there is a loss of 7N that is most likely caused by the torques added to the tendon from the different mounting points and frictional losses throughout tendon channel.

VI. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, it was proposed that a lightweight, underactuated design was possible and demonstrated the ability to manipulate a range of everyday objects of weights up to 2kg. It was designed using iterative 3D printing, ANSYS simulations and grasping experiments. The design originated from the Finn-Ray effect but due to the rigidity of the printing material it allowed for a lightweight design rather than a compliant one. Tendon routing was done without any differential but the design allows for one to be easily implemented. Finger pads were developed from a range of patterns with the baseline having the best overall potential.

Regarding future directions, their is a plan to try different 3D printing materials such as nylon using SLS printing and TPU through FDM printing. These materials are less rigid and will allow more compliance and deformation in the fingers which will allow for more surface area contact. There is also plans to test a combination of a more rigid proximal phalanx with a less rigid distal. The overall weight of the prosthetic hand can be further reduced through the design of the base, palm and thinning of the finger walls and ribs.

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