

Lightweight Custom Composite Prosthetic Components Using an Additive Manufacturing-based Molding Technique

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Abstract— Additive manufacturing techniques are becoming more prominent and cost-effective as 3D printing becomes higher quality and more inexpensive. The idea of 3D printed prosthetics components promises affordable, customizable devices, but these systems currently have major shortcomings in durability and function. In this paper, we propose a fabrication method for custom composite prostheses utilizing additive manufacturing, allowing for customizability, as well the durability of professional prosthetics. The manufacturing process is completed using 3D printed molds in a multi-stage molding system, which creates a custom finger or palm with a lightweight epoxy foam core, a durable composite outer shell, and soft urethane gripping surfaces. The composite material was compared to 3D printed and aluminum materials using a three-point bending test to compare stiffness, as well as gravimetric measurements to compare weight. The composite finger demonstrates the largest stiffness with the lowest weight compared to other tested fingers, as well as having customizability and lower cost, proving to potentially be a substantial benefit to the development of upper-limb prostheses.

I. INTRODUCTION

Additive manufacturing, or 3D printing, has become a widely accessible and cost-effective method of prototyping due to its ability to quickly create custom modeled parts out of inexpensive thermoplastics and resins. A common method of additive manufacturing, fused deposition modeling (FDM), uses an extruder head that lays down a filament in discretized layers to create a final part. The thermoplastic filament, acrylonitrile butadiene styrene (ABS), is commonly used in this process due to its high impact resistance, toughness, and light weight. This has made 3D printed ABS a prevalent choice for open-source prosthesis hands with products like the Cyborg-Beast or the Raptor Hand [1,2], which are intended to allow for a low-cost prosthesis that is also customizable. Although 3D printing has made custom prosthetic designs accessible to the public, it lacks the durability and strength to make these devices practical, which then have many shortcomings compared to commercially manufactured terminal devices.

In this paper, we describe a fabrication method utilizing inexpensive 3D printing techniques to produce molds that are then used in a multi-material molding process. We

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Figure 1. Fingers from the 3D Printed Cyborg Beast hand [1], the Bebionic v3 [3], and Composite prosthetic finger created using additive manufacturing molding techniques.

demonstrate the concept in the context of a lightweight prosthetic finger design that includes a lightweight epoxy foam core, a durable composite outer shell, and soft urethane gripping surfaces. We experimentally test structures built using the process to compare the strength and weight to other fabrication options, and show that the process produces components with high strength, stiffness, and low weight.

In the subsequent sections, we investigate the current manufacturing methods of both open-source and professional prosthesis. In Section III, we propose a new method that bridges the gap between highly customizable open-source 3D printed prosthetic hands and the professional prosthetic hand market. This process originated with the Hybrid Deposition Manufacturing method proposed in [4], but has been modified to allow for the use of composite materials such as carbon-fiber. This method results in finger/hand components that are lightweight, durable, and include gripping surfaces like those used in the professional prosthetics market, see Fig. 1. We present results of strength tests comparing the various manufacturing methods to support the proposed method. The goal of this method is to improve and refine future terminal device designs to create a cost-effective, customizable, durable, and lightweight prosthetic hand.

II. CURRENT MANUFACTURING METHODS

A. 3D Printing - FDM

The current fabrication process for open-source hardware generally includes modeling the solid part geometry in a computer aided design package (CAD) and then 3D printing it in ABS or polylactic acid (PLA) plastic [2] using the most common FDM printing technique. The printing software allows the users to determine the infill amount, therefore allowing the part to be printed partially hollow to save material and reduce weight at the expense of a potentially weaker component. A significant advantage of FDM

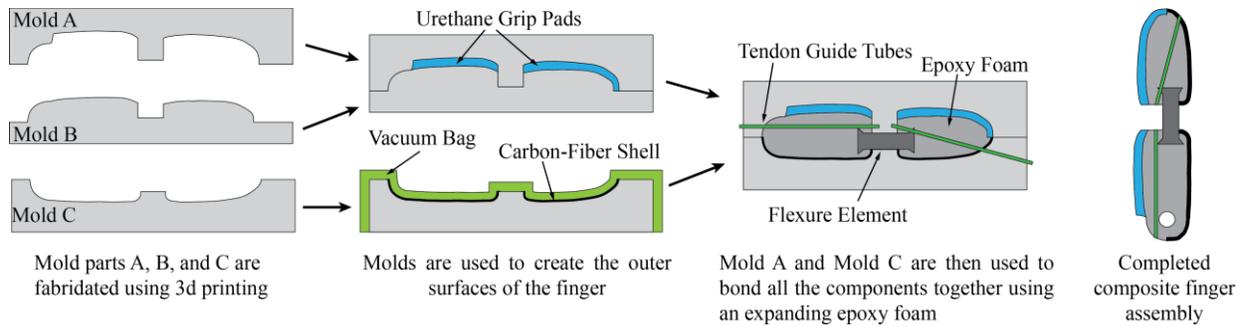


Figure 2. Illustration of the multi-step manufacturing process for fabricating a composite finger using 3D printed molds.

printing of prostheses is that it allows users to quickly customize the shape and size of components to fit an individual patient. For open source hands like the Cyborg Beast Hand, these components are made available online for anyone to print or scale as needed, which is useful, for instance, when children quickly grow out of a prosthesis [2].

One current limitation to FDM printing is the limited number of materials available. When part strength and stiffness is a requirement, most 3D printed parts and materials fall short since they are mostly limited to thermoplastics. Attempts have been made to reinforce 3D printed parts to make them more durable; however, this only provides marginal improvements [5-7]. New printing methods are also being implemented that allow for the 3D printing of composite structures with Kevlar and Carbon Fiber [8]. Although this method may prove beneficial in the future, its processes are currently still under development.

B. Professional Prosthesis

The current fabrication process for commercially available prosthetic hands generally includes a combination of injection molded plastic and cast or machined metal components. The materials include glass-filled Nylon, titanium, and aluminum [3,9]. Urethane rubber grip pads are injection molded and adhered to the surface of the finger tips and palms to increase the grip of the smooth metal or plastic. All joints (usually pin joints) are assembled, and connected to the aluminum or steel frame and then attached to the actuation system.

The major limitation of this method is that machined titanium or aluminum components are expensive, and the tooling required for Nylon injection molded components limits the customizability of the design. It is likely that only a small number of sizes of the hands are available due the large tooling cost associated with another size option and customizable features specific to each patient are not possible. For example, the i-limb Ultra myoelectric prosthetic hand is only available in sizes medium and small [10].

III. CUSTOM COMPOSITE PROSTHESES USING ADDITIVE MANUFACTURING MOLDING TECHNIQUES

In this section, we will walk through our process of creating custom composite components utilizing 3D printing to produce professional grade prosthetic component while

maintaining the customizability for individual patients. This method is appropriate for prosthetic hand fabrication since the personal nature of prosthetic hands requires frequent design changes and customization for each patient. The method we have developed is roughly based on the hybrid deposition manufacturing (HDM) techniques described in [4]. We have modified the technique to include the use of composite carbon-fiber shells for added strength and rigidity.

A. Motivation and Overview

The influence for the material composition of our composite prosthetic hand is derived from the manufacturing of ultra-lightweight structural components used in Formula 1 racecars and aerospace components. Here composite materials with various core structures are used to create materials with the highest possible strength to weight ratios. Typical carbon-fiber techniques are rarely used on components as small as prosthetic hands or fingers due to the part contour complexity. Our method of fabrication has overcome many of the previous limitations and allowed us to fabricate prosthetic fingers with the same materials and techniques used in high grade aerospace components.

The desired prosthetic finger composition consists of three main layers; the carbon-fiber structural shell located on the back and sides of the finger, a lightweight foam filler material that serves to bond the internal components together, and a soft urethane grip surface that mates seamlessly with the shape of the structural shell. Each of these individual elements, as well as the fully assembled finger, can be fabricated through the use of three custom molds. Mold A, consists of the geometry of the front of the finger up to the parting line between the grip surface and the carbon-fiber structural shell. Mold B mates together with mold A and forms the inside surface of the urethane grip pad. Mold C, mates together with mold A but forms the back outer surface of the finger. An illustration of the three molds is shown in Fig. 2.

B. Custom 3D Printed Mold Fabrication

Our process uses multi-part molds created from the customized finger geometry. First, the desired finger geometry is created in CAD software. The parameters such as length, thickness, and even joint stiffness can be directly

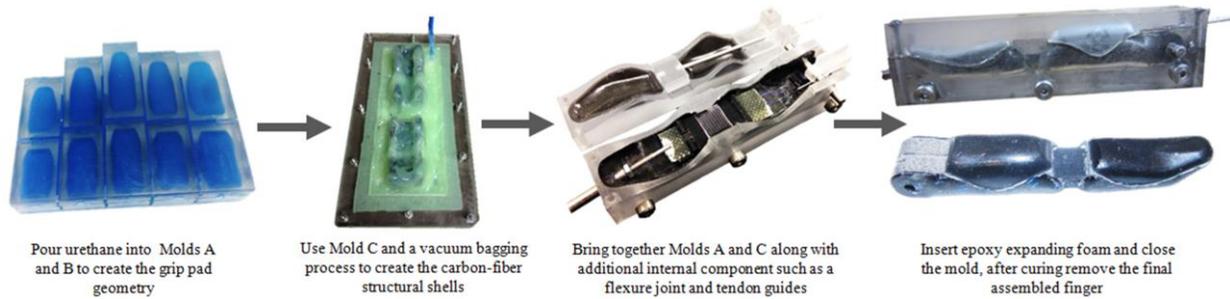


Figure 3. Images of each step in the process for fabricating a composite finger using 3D printed molds.

altered for each patient. A set of small molds are then automatically created from the desired finger geometry.

The mold is then split along the gripping surface lines and a parting line analysis is then done to minimize undercuts. Significant undercuts can result in die lock, preventing the removal of the solid part from the mold. If necessary, the mold can be split lengthwise and printed in two parts with bolting features that can be removed if die lock occurs. The molds are then printed on an Objet printer using VeroClear material [11]. Alternatively, the molds can be printed in ABS using a standard FDM printer although the authors have been able to achieve better mold surface finish using an Objet, polyjet style printer. The actual material strength of the mold is not important. However, thin walls can lead to potential deformations in the finger geometry. This results from the internal pressure build-up of the expanding foam during the final in-mold assembly step.

C. Fabrication of Individual Elements

After the three molds have been printed, they are coated with a wax based or polyvinyl alcohol (PVA) mold release. Molds A and B are brought together to create the geometry of the grip pads on the anterior side of the fingers. To prevent grip pad defects, it is important for the urethane material to be placed in a vacuum chamber before being placed in the mold to degas the resin. In the case inconsistencies persist in the final part, it is recommended to incorporate risers and air vents into the Part B mold to release excess trapped gases. After the urethane material has cured, Part B is removed and excess flashing or riser material is trimmed from the grip pads.

Immediately after the grip pads are cast, the carbon fiber half of the mold, denoted as Mold C in Fig. 2 on page two, should be prepped with a PVA mold release. Two layers of 200 gsm 3k 2x2 twill weave carbon-fiber dry cloth is placed in the mold and trimmed to the appropriate size. To improve overall strength, the orientation of the carbon weave should be offset by 45 degrees between the layers. Epoxy resin is then flooded over the dry carbon-fibers. A custom silicon vacuum bag, as seen in Fig. 3, is then placed over the wet carbon to remove excess resin and apply pressure to the inside surface of the mold. Once the epoxy resin has fully cured, the vacuum bag and absorption layers are removed and the carbon shell is trimmed to the edges of the mold.

D. Full Mold Assembly and Final Finger Fabrication

Next, all the previous components are integrated into one final part using mold Parts A and C and additional inserts. Before closing the mold all the necessary inserts and joints are placed in the correct locations. Epoxy expanding foam (Sicomon PB400 [12]) is poured in the middle of the two halves to join the shell and the grip pad to make a finger. The expanding epoxy foam core acts as a lightweight internal structure and a glue to bond all the components together. Please refer to Fig. 2 for details of the full finger assembly mold process. Carefully painted PVA mold release was used to prevent the expanding foam from bonding to selected surfaces such as the center of the flexible urethane finger joint. It is acceptable to allow some of the foam to overflow in this process to reduce pressure and purge additional air. After the recommended amount of curing time the finger can be removed and lightly sanded to remove any flashing from the parting line.

This finger is durable with its carbon fiber shell but also very light with its foam core which bonds joint members and other additional inserts into the finger. The resulting fingers, seen in Fig. 4, have grip pads to improve grasping capabilities, flexure joints to promote out of plane bending, and outer carbon shells for added strength and durability.

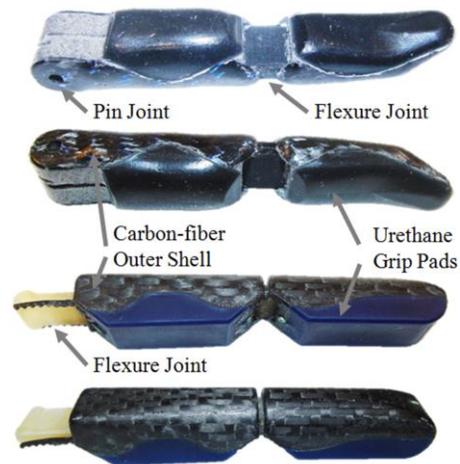


Figure 4. Example composite fingers made from epoxy expanding foam and a carbon-fiber outer shell. The urethane flexure joint connects the distal and proximal digits and the grip pad covers common contact areas.

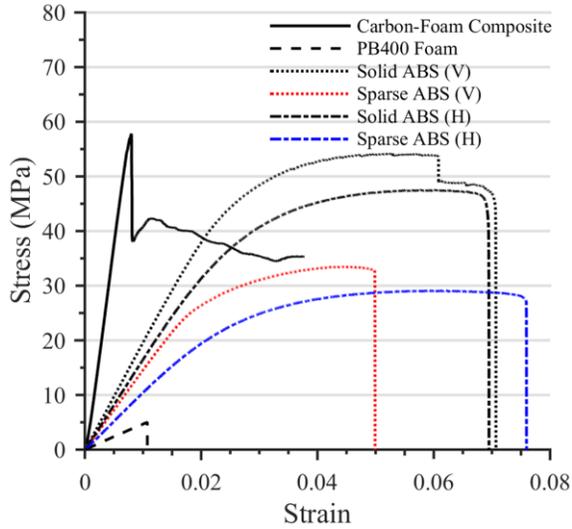


Figure 5. Stress-strain relationship for each specimen - Two layer carbon-fiber with PB400 expanding epoxy foam internal core, PB400 expanding foam, solid printed ABS vertical (V) and horizontal (H) print, and sparse printed ABS vertical (V) and horizontal (H) print. All samples were tested to failure.

Different inserts such as a pin joint, tendon tensioning mechanisms, and PEEK tubing to reduce tendon friction are used in these finger examples. The palm structure of the hand is fabricated in a similar process.

IV. MATERIAL TESTING

Three different measures were used to evaluate the performance of our manufacturing method as well as other manufacturing methods commonly used in prosthetic hands. These methods included a strength analysis, weight analysis, and a discussion of the advantages and disadvantage of the composite molding process. The core materials we will test include 3D printed ABS plastic in both solid and sparse raster filled, epoxy expanding foam, and carbon-fiber composite structures. For reference, we will also include information on the strength of aluminum 6061 since it is also a common material used in commercial prosthetic hands.

A. Strength Analysis

TABLE I: BENDING TEST RESULTS

Specimen	Weight (g)	Density (g/cm ³)	Yield Stress (MPa)	Max Strength / Weight Ratio (GPa*cm ³ /g)	Max Stiffness / Weight Ratio (GPa*cm ³ /g)
<i>Sparse Printed ABS</i>	17.5	0.71	26.3	0.037	2.03
<i>Solid Printed ABS</i>	23.3	0.95	43.5	0.046	2.08
<i>PB 400 Epoxy Foam</i>	9.3	0.39	6.3	0.016	1.33
<i>Two Layer 2x2 Carbon Twill - PB 400 EEf</i>	11.3	0.46	56.4*	0.123	16.51
<i>6061 Aluminum**</i>	65.2	2.70	276	0.102	25.52

*Yield stress was equal to fracture stress, **Calculated based on [14]

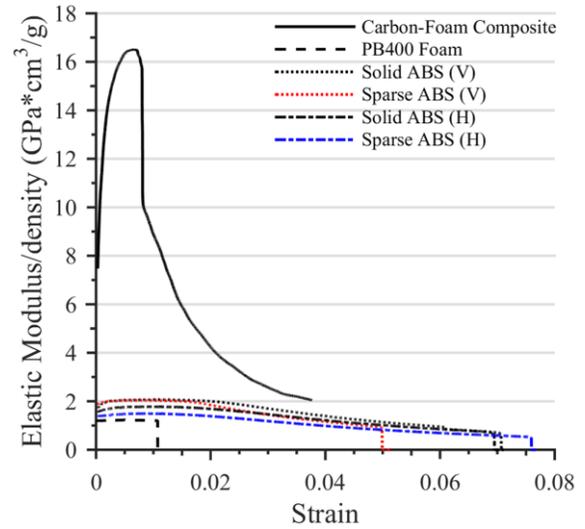


Figure 6. The stiffness to weight ratio for each test specimen - Two layer carbon-fiber with PB400 expanding epoxy foam internal core, PB400 expanding foam, solid printed ABS vertical (V) and horizontal (H) print, and sparse printed ABS vertical (V) and horizontal (H) print. The ratio is determined by the elastic modulus at a given strain divided by the specimen's density.

To evaluate the relative strength of each manufacturing method, rectangular bar specimens were tested using the ASTM D790 flexural three-point bending test [13]. For each manufacturing method, five specimens were tested. The specimens were rectangular blocks measuring 8.3x19.1x152.4 mm and were sized according to the standard. When testing 3D printed ABS plastic, the layer direction was noted to evaluate the effect of different printing orientations. In a horizontal test the specimen width was parallel with the print tray and extruder layer orientation, while in vertical tests the sample width was oriented vertically on the print tray. For the carbon-fiber shell test specimens, the carbon-fiber was placed on the top and bottom of the foam. No carbon-fiber was placed on the sides of the specimen to better replicate the open shell of the fingers in from the proposed manufacturing method.

In order to compare the different materials, each specimen's weight and density were recorded; the stress during the three point bending test was also calculated. A stiffness to weight ratio was then determined for each specimen in order to evaluate the optimal material, shown in Table 1. The stress-strain relationship for each specimen is shown in Fig 4. The stiffness to weight ratio is plotted versus strain as shown in Fig 5. It is seen that the epoxy expanding foam has the lowest average weight of 9.25g, but also has the lowest stiffness to weight ratio. The carbon-fiber with epoxy expanding foam specimen has the next lowest average weight of 11.3g, and also has a significant stiffness to weight ratio of 1.65 GPa*cm³/g. This ratio demonstrates the added strength and durability of using carbon fiber, with the low weight of the epoxy expanding foam. The calculated values from 6061 aluminum were based on known material properties found in [14].

B. Weight Analysis

To evaluate the weight of the fingers, we fabricated equivalent models of a 50th percentile female sized middle finger. The proximal and distal links of each finger were connected with a urethane flexure (Smooth-On PMC [15]) and a two layer grip surface (Smooth-On Vytaflex [16]) was added to each finger. For the epoxy foam core fingers, the grip pads and flexures were molded and embedded into the foam, while, for the 3D printed parts, grip pads and flexures were bonded on using adhesive. The quantity of adhesive was measured out to be 0.3 additional grams for the ABS printed fingers shown in Table 2. The finger weight was estimated for the machined aluminum finger using the total volume of the finger CAD model and the density of aluminum [14]. The weight of each finger fabricated with each respective material is shown in Table 2. The expanding epoxy foam with and without carbon fiber maintain the lowest weight, with a weight of 8.6 and 8.5 grams respectively. The aluminum is almost four times the weight of the foam fingers, having a weight of 31.6 grams, however, it is unlikely that aluminum fingers would be fabricated to be solid aluminum.

C. Molding Advantages and Disadvantages

Inconsistencies such as surface finish and quality were observed. In order to evaluate internal part inconsistencies, parts were cut in half to evaluate.

One advantage of additive manufacturing is the ease of production. A custom model can go straight from design to manufacturing in a matter of hours. Although additional time is required, the durability of a solid printed finger is similar to that of the composite though significantly heavier. Errors associated with using additive manufacturing to create prosthesis fingers include print errors, adhesion loss, and print inconsistency. First, the type of printer used when creating prosthetic fingers has a sizable impact on the quality, strength, and resolution of the part. Printing errors on lower quality printers can lead to open contours and failed parts. Sometimes these errors occur in internal contours or support structure, and cannot be visible from the outside of the part. This can lead to stress concentrations in the finger. Another flaw with the 3D printed method is the loss of adhesion of the grip pads as well as the flexure joint. This could be alleviated with additional epoxy adhesive, however, the potential pulling out of a flexure could be a

TABLE II: FINGER WEIGHTS

Finger Composition	Weight (g)
Sparse Printed ABS	13.2
Solid Printed ABS	14.5
PB 400 Expanding Epoxy Foam	8.5
Carbon and PB400 Laminate	8.6
6061 Aluminum (Solid)	31.6

significant failure while attempting to maintain a grasp. We found the task of embedding a flexure in an anthropomorphic finger difficult. Attempts to split the finger or have a removable insert and adhering the flexure in place caused severe lateral weakness in the fingers.

The main advantage of machined aluminum is the strength of the material. However, complex 3D geometries are difficult to machine with CNC Mills and require multiple readjustments.

The main advantage to the carbon fingers was the durability of the finger with respect to weight. We saw that it was also relatively easy to manufacture as the carbon shell and grip pad could be made at the same time. Then, without removing from its respective molds, the two parts making up the outer layers could be sealed together with foam. The carbon shell presented additional advantages such as abrasive resistance as well as a clean surface finish that can be an issue with 3D printed parts and fingers made completely from expanding foams. Errors associated with foam fingers included internal voids and a soft outer surface that was easily damaged. First, a common flaw with intentionally porous expanding foams is that gas pockets or “voids” can form that are bigger than expected. As seen in Fig.8, these voids can cause severe weaknesses in the part or surface blemishes. The addition of a carbon fiber shell allows the finger to have a better durability, however, does not aid in preventing internal voids in the finger.

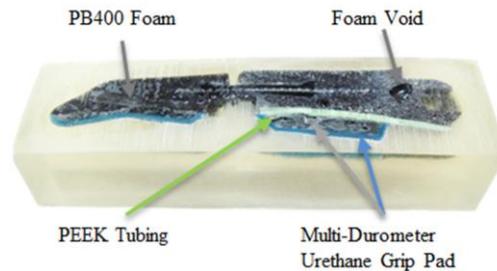


Figure 8. A foam finger was cut in half to evaluate internal defects in the part. In this model we could see voids, or gas pockets in the foam core, a common inconsistency seen in expanding foams.

V. DISCUSSION

In this study, we found that our manufacturing method created a durable and lightweight prosthetic finger, properties that are very important for the area [17]. A full hand made out of carbon laminate using our proposed method could potentially be one half the weight of a 3D printed hand and one quarter the weight of a machined aluminum hand. For amputees the prosthetic hand is an extension of their body, reducing weight of the prosthetic can not only help prevent fatigue but can also aid grasping by allowing for easier and quicker movements.

The ability to work in parallel when curing the grip pad urethane and carbon fiber resin allows the process to be simplified to four steps; creating molds, casting urethanes and laying carbon fiber, creating foam core, and removing final finger from molds. The downtime associated with letting resins cure is shared during the production of the carbon fiber and gripping surfaces. This allows the

manufacturer to create any necessary inserts for the mold and the finger, such as a urethane flexure joint, while the first two parts are curing. This efficiency is one of the advantages of our composite finger manufacturing process.

If weight, customizability, and cost were not important factors, a machined aluminum finger would be the primary option due its superior strength and durability. The use of composites in prosthetics fingers provides a significant stiffness to weight profile over that of aluminum and solid ABS plastics. At low strains, we saw that the Grablab composite finger was almost 8 times stiffer than solid and sparse printed ABS plastic. A more durable finger for a given weight allows the user to have the same sturdiness with less fatigue or force required to maneuver the finger.

The current manufacturing process only allows us to produce individual fingers in parallel and would like to eventually extend the use of this method into the fabrication of a palm. As additive manufacturing becomes more available, we believe that this manufacturing method can reach out of prostheses into broader categories like custom lightweight robotics. Rapid prototyping with additive manufacturing allows the user to visualize the size and geometry of a part, however, a current downside of this is the user's inability to use that prototype for the actual application. As a prototyping technique, our manufacturing method can provide the fabricator with a useable and rapidly alterable prototype that can simulate the durability of the final product. The rapid manufacturing of molds to create composites can impact many industries where a durable lightweight replacement part is needed quickly or where access to heavy machinery or casting equipment is limited.

VI. CONCLUSION

We presented a multi-step manufacturing technique for fabricating composite prostheses using molds created through additive manufacturing. This method combines the rapid prototyping capabilities of additive manufacturing techniques with the part strength and durability of the professional prosthetics market. Through a three point bending test, weight, and manufacturing analysis we determined that our composite fingers are a viable option for use in prosthetic hands. In the future, we expect to further refine and utilize this manufacturing method for the production of a full prosthetic. We believe this method could be extended to other fields where custom, lightweight, and durable parts are essential.

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