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Development Of 3D Printable Prosthetic Arm For Amputees Using Computer Aided Design And Fused Deposition Modelling

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Abstract

In this paper, a 3D printable upper limb prosthetics was designed, printed and assembled. The arm model was created using computer-aided design software (SOLIDWORKS). Stress simulation programs were used to analyse the various arm parts before they were printed in 3D using Fused Deposition Modelling (FDM) process. Structural analysis and cost comparison with other commercial prosthetics were also carried out. From result of the structural analysis, it is shown that the 3D printed arm can withstand external impact of about 250 N from its user in the event of a fall. Also, reliable and effective embedded electronics like Microcontrollers, Sensors, DC servo motors and a solar battery charger module were integrated into the design. The overall prototype arm weighs about 2.2kg, including the motors, major electronics and control system. And its cost of production is approximately 300 dollars, which is low when compared to the weight and cost of most commercial prosthetics. It also mimics the functions of the human upper arm as best as possible, controlled to some extent by muscular contractions and runs continuously without battery run-out, as a result of the solar battery charging technique. Finally, this paper sheds light on the specifics of 3D prosthetics design using FDM and may serve as a guide for those intending to produce a similar prosthetic device.

Keywords: *3D Printing, Computer Aided Design, Fused Deposition Modelling, SOLIDWORKS*

1. Introduction

According to a ten years' retrospective review in Nigeria, about 25 per cent of limb amputation is done on the upper limb (Dada, et al., 2010). This limb amputation is a veritable way of saving lives of patients with severe injuries like diabetics, tumor or other diseases, and it can be a life-changing event with physical, social, psychological, and economic consequences for an amputee. In order to mitigate these consequences and assist an amputee return to a state of normalcy, prostheses are used. Prosthetics like the upper arm prosthetics is a device that substitute a defective part of the upper limb and it assists an amputee in carrying out daily life activities. Prosthetic Upper arm vary in type and method of control and are designed or customized around a patient's specific needs. Some of them are non-functional, serving only cosmetic purposes. Another type of prosthetic upper arm is the body powered prostheses that have mechanical hooks and is controlled by cables or harness powered by body motions (biomed, 2003). More conventional types are the myoelectric prosthesis, which are controlled by nerve signals generated in muscles around a user's residual limb either through; use of surface Electromyography electrodes or by TMR (Targeted Muscle Reinnervation) and powered through electronics like batteries, microcontrollers and DC motors (Scheme, et al., 2011). For decades, innovations and advancement in technology have vastly improved the performance and use of these prostheses, they have also affected both the cost of manufacturing and the cost of using these prosthetic devices. Therefore, state of the art

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prosthetics especially those with multiple degrees of freedom, myoelectric control, biofeedback and neuro-control are extremely expensive. Apart from cost, other critical factors like weight, power source, and insufficient degrees of freedom also limits the use and development of these devices.

Biswarup, et al., (2011) and Humaid, et al., (2016) saw the need to address these limitations in a cost-effective manner by proposing the use of myoelectric control. But their works were limited to the use of woods, heavy materials and constructed plastics for the development of test prototypes. The use of heavy materials, woods and constructed plastics in their work failed to satisfy some of the important factors like human-like appearance in terms of size and weight which are considered when developing a prosthesis. Also, sufficient autonomy of energy source to allow the prostheses work all day were not considered. Fahad, et al., (2013) made use of limit switches for actuation which made their developed prototypes less cosmetically appealing. Also, responses with switches were very slow when compared with servo motors which are faster and offer more degrees of freedom.

With the innovation of 3D printing, an addictive manufacturing process, 3D printable prosthetics are now developed, and used as inexpensive alternatives. They are light in terms of weight, customizable and can provide considerable hand mobility at affordable prices. In this paper, the development of a 3D printable upper arm prosthetics is explored, a model of the hand was created with computer-aided design software and simulation express programs were used to analyse the different arm parts and then 3D printed. Also, reliable and effective embedded electronics like; a Myoware muscle sensor with electrodes, an Arduino microcontroller, a solar battery charge controller with a mini solar panel, servo motors and ultrasonic sensors, are then integrated into the 3D printed arm. This paper, also highlights the production process and design specifics of the various parts which can serve as a guide for further development of stronger and more durable prostheses.

2. Literature Review

Biswarup, et al., (2011) in their paper presented a hardware design technique of a prosthetic arm using gear motor control. The architectural design of the prosthetic arm featured a constructed hand gripper from hard wood which is lighter in weight when compared with existing metallic arms. Its prosthetic arm control movement was based on microcontroller processing of signals from tact sensor switches placed on selected muscle area. These signals were used to control low power gear motor which produced high torque enhancing the power of hand gripping and opening. Some of the limitations of this work includes; limited dexterity since only one degree of freedom i.e. hand opening and closing was considered, the use of wood makes the design less cosmetically appealing, and finally switch control was slow in response.

Humaid, et al., (2016) presented a technique to design an electromyography-based prototype prosthetic arm using artificial intelligence, in such a way that the prototype arm can imitate the actions of a real human arm. The design featured five individually actuated fingers with a movable wrist design. A microprocessor was used to interpret and analyse signals from muscles using surface electromyography electrodes (SEMGs). The analysed and interpreted sensory signals are used by the microprocessor to control the servo motor actuators in the fingers and wrist, thus control was regulated by the extension and contractions of muscles connected to electrodes. A major limitation to this work is that, heavy materials were used for developing its prototype and it lacks autonomy of power source for continuous operation.

Omarkulov, et al., (2015) in their paper titled “Design and analysis of an underactuated anthropomorphic finger for upper-limb prosthetics” presented the design of a linkage-based finger mechanism with extended range of gripping motions. The finger design was done using a path-point generation method based on geometrical dimensions and motion of a typical index human finger. Using a 3D printed prototype, the design description, kinematics analysis and experimental evaluation of the finger gripping performance was carried out in this paper. Under-actuation of the finger was achieved with mechanical linkage system, consisting of two crossed four-bar linkage mechanisms. The presented finger design can be used as a blueprint to design a five-fingered anthropomorphic hand in an upper-limb prostheses development.

2.1. Amputation and Use of Prosthesis

The use of prosthetics especially those of the upper limb depends on the level of user's amputation. As a result of these levels of amputations, upper limb prosthetics can further be classified into various kinds and they work according to the amputee's specific needs. Therefore, the more distal an amputation is from the shoulder, the more precise the motion can be. For instance, patients with amputated wrist or whose amputation is below the elbow make use of wrist powered prosthetic device or a transradial prosthesis, powered by the movement of the elbow joint. An amputation above the elbow that leaves only the shoulder joint require a transhumeral prosthesis with multiple degrees of freedom or movement (Cordella, et al., 2016). Figure. 1 depicts the various levels of amputation at the upper extremity or areas of prosthetic application.

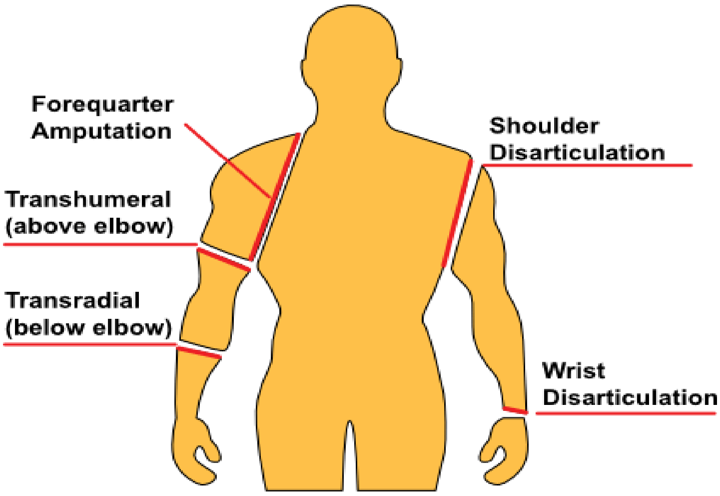

Figure 1: Various levels of amputation at the upper extremity (nova scotia health, 2018)

2.2. 3D Printing, and Printing Materials

Three dimensional (3D) printing or addictive manufacturing is simply a process of making three dimensional solid objects from a digital file. it is a method of producing a 3D object by creating successive layers of material, with each layer being a cross-section of the object at a certain point (PrintSpace 3D, 2016). A review of 3D printed hand prostheses shows that the 3 most common technologies used are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Selective Stereolithography Apparatus (SLA).

FDM or Fused filament fabrication is chosen as the preferred printing technology in this work, because of its low price and ease of use. It consists of a fused plastic filament deposition, or the extrusion of a molten thermoplastic material from a nozzle or extruder as shown in Figure 2. The plastic solidifies after leaving the nozzle, forming a single layer. Objects are gradually printed layer by layer. Varying the layer heights and fill percentages can affect the strength and integrity of the print material.

In FDM printing, models are built from bottom up and it only allows to print simple shape objects. In case of a complex geometry, support materials are needed (Moreo, 2016). Also, FDM printers are the cheapest printers and they are meant to be used by single costumers. An example is the MakerBot printer. It has an adjustable base which provides support to horizontal planes during printing. It has its own development environment and an LCD screen. With the LCD screen, several features such as print speed, layer resolution, and extrusion temperature can be set, and fine tuning of other printer options can be done in order to produce high quality printed components.

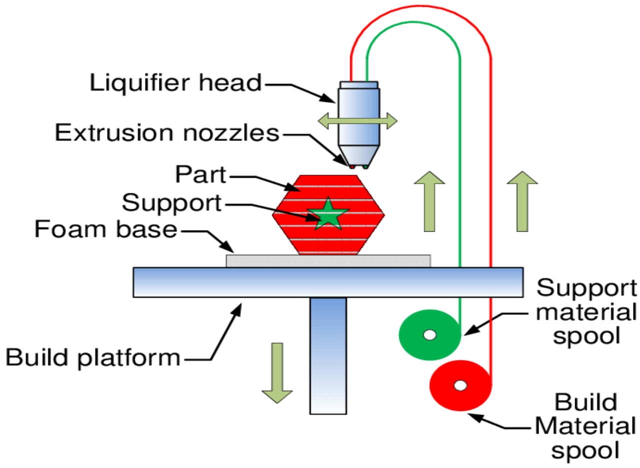

Figure 2: Fused Deposition Modeling Process (Ning, et al., 2015).

Several different materials can be used in 3D printing, including plastics, metals, and organic cells. Two of the most common materials are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Both are thermoplastics, but ABS is stronger and more resistant to wear and heat deformation [10]. PLA was chosen in this work because it is lustrous, sweet-smelling, and biodegradable. PLA does not produce toxic fumes during the printing process or release toxic chemicals as it wears down over time. Also, PLAs come in two thicknesses of 1.75mm and 2.85mm (or 3.00mm) respectively, they have optimal printing temperature range from 185oC to 205oC.

2.3 Computer Aided Design

Computer-aided design (CAD) is the use of software to construct designs. Several types of CAD software exist, each with different features. Examples are SOLIDWORKS, Blender, AutoCAD Inventor and Fusion 360. SOLIDWORKS is a 3D modeling CAD software where a user typically begins the modeling process by creating a two-dimensional sketch before extruding it into three dimensions. Then, the piece can be molded or cut into virtually any design. Parts can then be assembled into a larger structure (Wijk, et al., 2015). SOLIDWORKS is a convenient platform on which to design a customized 3Dprintable prosthesis, because of its intuitive interface, ease of use, and Simulation Xpress program, which can simulate force against each part of the prosthesis to evaluate its performance.

3. Methodology

The design method of the entire 3D printable upper arm can be grouped into three; that is structural design, electronic and control system design and software design but the focus of this paper is on the structural design and its analysis. In the electronic and control system design, modular design approach was adopted were by flexible and robust components like myoware sensor, ultrasonic sensor module, BQ24650 module, DC servo motors, arduino microcontroller and other components which were already fabricated were selected and integrated into the system. The aim of designing in this manner is to build a system with easily replaceable parts that have standardized interfaces. Likewise, structured programming was adopted for the software design. The choice of using structured programming is because three control structures of this method; sequence, selection and iteration, help create programs that are easy to read, understand, modify and debug. C language is the chosen programming language for the software design. It is relatively easier to work with and moreover, the arduino microcontroller integrated development environment (IDE) uses C language as its default programing language.

The structural design and its analysis were done using CAD tool; SolidWorks. SolidWorks is a convenient platform to carry out this design process, because of its intuitive interface, ease of use and simulation Xpress program which can simulate force against each designed parts of the prosthetics in other to evaluate its performance. SolidWorks was used in the modelling process to create a two-dimensional sketch before extruding it into three dimensions, then the parts were molded or cut into virtually any design and later assembled into a larger structure. It was also used for visualization and scaling of the CAD files. It provided parametric tools that aided in editing components of the design as specifications changes without starting all over from scratch.

Below is a detailed description of the fingers and thumb design, palm design, elbow and fore arm design.

A. Finger and Thumb Design

Each finger consists of three individual printable components (which represent the distal phalanx, proximal phalanx and metacarpals of the human finger) that is linked together with a NinjaFlex 85A TPU (thermoplastic polyurethane) flexible filaments. Loops or holes are created at the inside tip of the finger, as well as locking points. Artificial tendons run through this holes inside the fingers, to form enclosed loops that terminate at the locking points. So that when the tendons are pulled, rotational forces are applied to all the joints and the fingers curls up. The flexible filaments form joint linkages to hold the finger components into their locking positions. Figure. 4 shows the CAD design of printable finger plates.

The thumb is also designed in a similar fashion like the fingers shown in Figure 3. it is designed to provide at least two degrees of freedom, which allows for open/close as well as adduction/abduction which is similar to the movements in a normal human thumb. The metacarpal section of the thumb is designed to house a small dc servo in order to aid this movement.

Figure 3: Fingers and Thumb Plates

B. Palm Design

Each finger is designed to connect to the palm by NinjaFlex flexible filament. The palm is also designed to house small servos i.e. actuators that allows for finger movements. The open positions in the palm area shown in Figure 4 is the servo housing. The bottom of the palm incorporates part of the wrist rotation mechanism.

Figure 4: Palm Design

C. Wrist Design

The wrist is designed to house a small but high torque servo, this servo is a continuous rotation servo which rotates indefinitely. However, continuous rotation servos have no angular position feedback and the hand needs to be rotated to specific position like in a normal hand. To solve this problem, mechanical blocks as shown in Figure 5 were designed. Servo horn attachments were also designed with a hole to allow the palm to fit directly into the forearm.

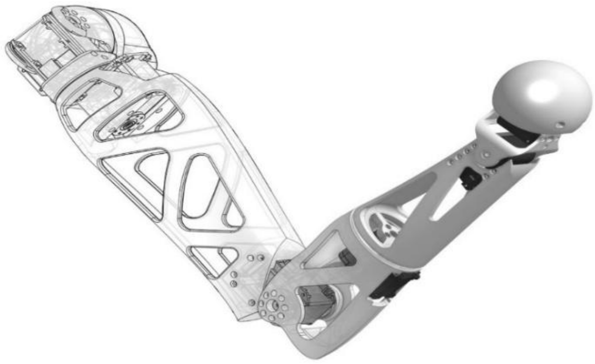

Figure 5: Part of the wrist and forearm design with mechanical blocks in the servo housing

D. Forearm Design

The design of the forearm is somewhat challenging as it is required to house servo motors and some electronics, and also allow the attachment of the elbow joint. It is part of the largest section of the entire arm. Its design consists of a base, an upper section and a lower section with servo housings and horn attachments. To minimize the chance of a crack occurring during assembling the forearm parts, guided holes for screws have been incorporated into the design plus enough materials to firmly support the screw.

E. Elbow Design

The elbow joint is designed in such a way that it houses a servo and must be able to move the weight of the entire forearm on top of any additional load. Based on weight measurement and few mathematically analysis, the minimum required torque to lift the forearm with no load was found to be roughly 13.5kg-cm. Therefore, for operation similar to that of a normal human arm, a light weight motor with a torque of approximately 20kg-cm can be incorporated into the elbow joint.

F. Upper Arm Design

This is the largest section of the entire arm. Since this design is just a prototype and not for real life application, the upperarm is designed to house a servo which serves as the shoulder joint as shown in Figure 6.

Figure 6: Assembled View of Entire Arm System showing elbow joint and upperarm

3.1 Printing and Assembling

After completion of virtual mechanical simulations, the prototype upper arm was ready for manufacture. The method of manufacture used was rapid prototyping on a Fused Deposition Modelling (FDM) 3D printer. Here a thread of molten plastic is used to trace out a layer of a part in the X-Y-Z plane, and once an entire layer is traced, the print platform is lowered and the next layer is printed.

Firstly, the prototype hand model was converted into stereolithography (STL) files. These STL files were loaded into the printer's software, arranged for printing, and converted to G code. G code is the control code that provides the printer with instructions regarding the velocity of the print head, extruder temperature and the filament extrusion velocity.

At each printing, a spool of the PLA is loaded into the printer, once the nozzle reaches the set temperature in the G-code, the filament is fed to the extrusion head and in the nozzle where it melts. The extrusion head was attached to a 3-axis support system that allows it to move in X, Y, and Z directions. The melted material was extruded in thin strands and deposited layer by layer in predetermined locations, where it cools and solidifies. To fill an area, multiple passes were performed. When a layer is finished, the build platform moves down and a new layer is deposited. This process is done repeatedly until the part is complete.

The entire hand parts were printed in 23 hours in a MakerBot Replicator 2X 3D printer. The set fill percentage was 30%, and the plastic used was 1.75mm and 2.85mm (or 3 mm) light blue PLA filament. The prototype arm consisted of 30 individually printed 3D parts, the forearm took the longest amount of time to print. Figure. 7 shows the various parts before assembling.

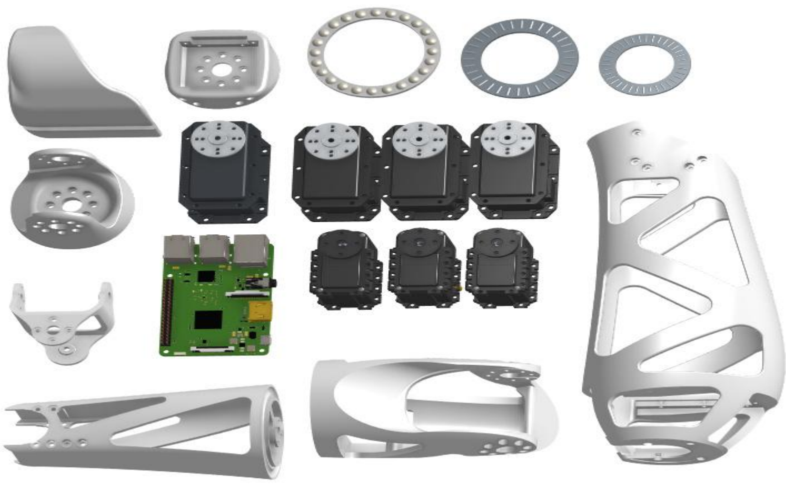

Figure 7: 3D Printed Arm Parts

During assembly, each finger has 3 printed components which represents the distal, proximal and metacarpal phalanx of the human finger, and they are joined together using 3mm NinjaFlex 85A TPU filaments which forms the finger joints. A long length of braided line (about 60cm) is looped through the fingertip holes at least twice and then a drop of super glue is applied to the locking point to firmly anchor the braided lines which serves as artificial tendons. This is to make sure the tendons firmly lock at the tip of each finger and do not slip when tensioned. Servos are carefully placed into their housing in the palm with their wires passing through created holes in the lower palm section. The artificial tendons which runs from each finger are carefully attached and glued on each of the custom servo horns. Each of these tendons passes through the holes in the servo horn and tied in order to give tension in the tendon lines. The custom servo horns are then press fitted onto the servo shafts. Through the guided holes created during design, the palm sections are screwed together and the palm is connected to the wrist socket. A servo is placed in its housing in the forearm, then the two large forearm sections are carefully aligned and glued together. The base of the forearm is designed to be attached directly to the elbow, which is designed to house another servo for elbow movement. Figure 8 is the assembled prototype 3D upper arm prosthetics.

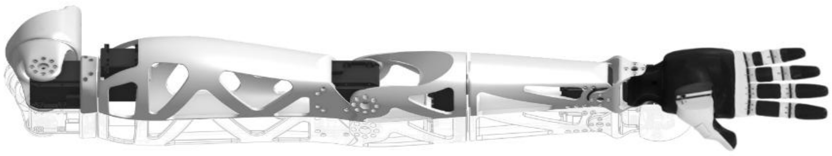

Figure 8: SOLIDWORKS Assembled 3D Upperarm Prosthesis

3.2 Structural Analysis and Testing

Structural analysis of the fully assembled arm design was done in SOLIDWORKS using its stress Simulation Xpress program. This was done in order to determine the strength of the PLA material, its ability to avoid fractures, and, to ensure that each individual part was constructed firmly enough to withstand impact from a fall by a user of the prosthetics. In the test, each load-bearing part of the arm, received a simulated force of 250 newtons, and it resulted in a factor of safety. A factor of safety is a number that indicates if the design will fail. A factor of safety that is less than one indicates that the design cannot withstand simulated force. A factor of safety that equals one indicates that the design is close to failure. A factor of safety that is greater than one indicates that the design can successfully withstand the force. Most of the tests run on various parts of the prosthesis resulted in factors of safety that were greater than one as shown in Table 1.

Table 1: Result of Solidworks Stress Analysis

Parts	Factor of Safety
Finger Plates	1.25-1.6
Palm Design	20.3
Wrist Design	15.3
Upper forearm	9.3
Lower forearm	10.5
Elbow joint housing	16.2
Upperarm Design	36.9

3.3 Cost Analysis

The total sum for producing this prototype is ninety thousand naira, which is approximately $300. From the cost comparison presented in Table 2, it can be observed that the developed prototype cost less than most conventional prosthesis. Making 3D printed prosthesis a promising solution to the problem of existing expensive prosthesis.

Table 2: Cost Comparison with Existing Commercial Prosthesis

Type of Prosthesis	Cost ($)
3D Printed Arm	300
Cosmetic Prosthesis	5,000
Split Hook Prosthesis	10,000
Myoelectric	100,000

4. Result and Discussion

It was necessary to ensure that the designed arm has the capability to withstand forces applied on it from any angle, especially in the event of a fall with a user. The fill percentage of the printer was set to 30% which is the optimum option and the PLA print material has a thickness of 2.85mm. The result from the analysis and testing as shown in Table 1 made it clear that several parts of the printed arm can

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withstand large amount of forces. Only the finger plates failed the simulation when a force was exerted on them. All other parts of the hand passed the stress test. However, it can be inferred that once the hand is assembled, the weight of any impact on the hand would be distributed across the entire arm, decreasing the magnitude of force that each individual part would receive. This means that the complete hand would be able to successfully withstand heavy impacts from its users.

Also, minimizing weight is crucial and was part of the objectives of this design, since the entire weight of a prosthetic arm acts on a relatively small area of the skin at the socket connection. This makes amputees feel the weight of a prosthetic arm more than their biological arm. The full importance of this weight reduction by making use of PLA can be addressed if a socket connection is implemented in future designs. The final arm system weighs about 2.2 kg including the motors, major electronics and control system. Which is relatively low compared to the average human arm (2.5kg according to body size) and the weights of most commercial prosthetics. Hence, this work is an improvement to the ones carried out in [3], [4] and [5].

CONCLUSION

The overall objective of this design which is developing a 3D printed Upperarm prosthetics using CAD software was achieved. SOLIDWORKS was used to design the various arm parts before assembling it in SOLIDWORKS. With its simulation Xpress program, force against each designed parts of the prosthetics arm were simulated in order to evaluate its performance. It was also used in the scaling and conversion of the CAD files into stereolithography (STL) files before printed. The entire arm parts were printed with a Fused Deposition Modeling printer and later assembled.

The test result from structural analysis carried out in SOLIDWORKS showed that the arm is capable of withstanding external impact of about 250 Newtons in the event of a fall, if used by a patient. The overall prototype arm weighs about 2.2kg and its cost of production is approximately 300 dollars, which is low when compared to the weight and cost of most commercial prosthetics.

Finally, the application of 3D printing in the manufacturing of prosthetic devices can lower the cost of these devices by high orders of magnitude, making them available to patients with low socioeconomic status. Also, the work in this paper sheds light on the specifics of 3D prosthetics design using FDM and may serve as a guide for those intending to produce a similar prosthetic device.

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