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PAPER

Development of Customized Passive Arm Prosthetics by Integrating 3D Printing and Scanning Technology

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ABSTRACT

Severe hand injuries resulting from accidents can lead to the traumatic loss of an upper limb. The provision of an assistive device, such as an arm prosthesis, can help patients regain their courage and motivation to engage with the public. This project aimed to integrate 3D scanning and printing technology to develop a customized passive arm prosthesis for individuals who have experienced shoulder disarticulation due to a traumatic accident. The fabrication of the arm prosthesis was specifically designed and tailored to meet each patient's unique needs and preferences. The prosthesis design was created based on 3D scan files obtained from the patients. Finite element analysis was employed to analyze the design and determine the optimal materials to use, as well as to optimize the overall design. The finalized model was then converted into STL file format and G-code for the 3D printing process. To ensure ease of use, the entire arm prosthesis and a harness system were assembled, and multiple tests and fittings were conducted on the patient. Several prototypes of the arm prosthesis were fabricated to achieve the best fit for each individual patient.

KEYWORDS

shoulder disarticulation, passive arm prosthesis, medical engineering design, 3D printing, 3D scanning

1 INTRODUCTION

Upper extremity amputations are common in various circumstances, such as infection, trauma, cancer, disease progression, and congenital malformations. The degree of a patient's limb amputation significantly affects the patient's outcomes and the quality of care that medical professionals are required to offer [1]. The patient must first undergo physical therapy to increase strength and range of motion and occupational therapy to learn how to adapt to everyday activities without a prosthesis before being fitted for one. Additionally, this permits the incision to mend and the swelling to go down, enabling the prosthetic to fit appropriately [2]. Trauma-related

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upper limb amputations occur at a rate of 3.8 per 100,000, with finger amputations being the most common (2.8 per 100,000). Hand amputations due to trauma happen at a rate of 0.02 per 100,000 people. Amputations of the forearm and humerus due to trauma are the most frequent upper limb amputations, excluding finger amputations [3].

Upper-limb prosthetics are wearable devices that restore the lost exercise function and look of upper limbs. Shoulder disarticulation prosthesis is the name given to the prosthetic that corresponds to a shoulder defect [4]. The extensive selection of prosthetics for hand replacement may be categorized into active and passive prosthetics. The force to operate the gripping mechanism of an active prosthesis is applied using an electronic actuator or a cable driven by the body. In passive prosthetics, the force required to modify the gripping mechanism is delivered outside, such as by the excellent hand [5]. The purpose of arm prosthetics is to restore natural function to the greatest extent possible. Appearance is also an essential factor. Therefore, when wearing clothing, it is desired to restore a uniform appearance [6].

Severe hand injuries can be particularly damaging, given that virtually all our daily chores rely on hand manipulation. In addition, such accidents may cause long-term disabilities, mental and social issues, and difficulty in reintegration into society [7, 8]. Since it was discovered centuries ago how traumatic losing an upper limb can be, the concept of prosthetic replacement has gained popularity. How snugly the socket fits and how skillfully the prosthesis is mainly made affect how long a person wears a prosthesis. Inadequate prosthesis fitting can cause a restricted range of motion, discomfort, and generally subpar performance, leading to the device being abandoned [7]. In general, active prosthetics outperform passive ones in terms of functionality. Because of this, active prosthetics are usually seen as the better choice for people with upper limb impairments. Contrarily, these prosthetics are more challenging to manage. Therefore, young children or recent amputees have usually been prescribed a passive prosthetic hand since it is relatively simple to use [9–11].

Therefore, this project aims to (i) Create a passive arm prosthetic that best fits the patient's amputated limb, ensuring that the shoulder fits tightly and that the anchoring mechanism is robust, durable, and straightforward; (ii) Perform finite element analysis on critical components of the arm prosthesis that simulate real-life scenarios; (iii) Fabricate (3D-Print) all components of the arm prosthesis, and perform multiple testing and fittings onto the patient to acquire feedback on design improvement. The primary function of a passive arm prosthetic is to provide cosmetic symmetry and balance to the wearer. It helps individuals with upper limb amputations achieve a more natural appearance and feel more comfortable in social situations. Passive prosthetics do not have the ability to grasp or manipulate objects, as they lack the mechanical or electronic mechanisms required for functional movement. Instead, they are used primarily for aesthetics and psychological well-being.

2 METHODOLOGY

The arm prosthesis was developed using the engineering design process, which was used to identify, investigate, conceive, make a prototype, test it (for analysis), and enhance it.

2.1 Patient consultation

During the visit, there was a collaboration with two other institutions to meet the patient at the hospital. First, a brief explanation of the patient's condition and the background of the patient's surgery was explained in the initial meeting. Then, an industrial collaborator (3D Gens Sdn. Bhd.) offered their service to 3D scan the patient's body using their most recent scanner. Then, the patient's medical history and biographical data were thoroughly compiled. Also, the patient's left arm was physically measured with rulers and a measuring tape to get the detailed dimensions and measurements. Figure 1 shows the patient's consultation and 3D scanning process to obtain the digital images. Table 1 shows the criteria to be fulfilled in designing the arm prosthetics based on consultation with the patient. The process encouraged technical development by integrating arts into the design and innovation process [12]. 3D scanning with laser scanning method was used to capture the left arm. Higher accuracy equipment was required with a controlled environment and consistent lighting to minimize shadows and reflection, which further contribute to better output.

Fig. 1. 3D scanning and measurement process of the patient's left arm

Table 1. Criteria in designing the arm prosthesis

Criteria Item	Description
Aesthetics (Human-like)	The component's design is human-like and does not appear strange.
Weight	The item's weight is preferably not too hefty.
Surface Finish	The component has a smooth surface finish with no sharp edges or corners.
Complex Geometry	The component does not contain excessively complicated forms, geometry, surface, or any other detailed design that might compromise the 3D print quality.

The 3D scan files of the patient were converted to STL format. Five 3D scan files were obtained, which covered the patient's upper body, including her torso, as illustrated in Figure 2a.

2.2 Data processing (design)

Fully utilizing the 3D scan files received, each component of the arm prosthesis was designed and contoured around the patient's 3D body scan to acquire the most human-like, exact, and identical shape of the patient's body. The most critical part of the prosthesis is the shoulders, where the amputation was done. Due to shoulder disarticulation, the patient has no shoulder to the extent of having half of her right clavicle removed. Therefore, the design of the shoulder must mimic the geometry of her other shoulder, ensuring the design looks proportionate to the patient's body. Other parts of the arm prosthesis were also designed using the 3D scanned files received. Figure 2b illustrates the design method and process of creating a shoulder wrap/pad.

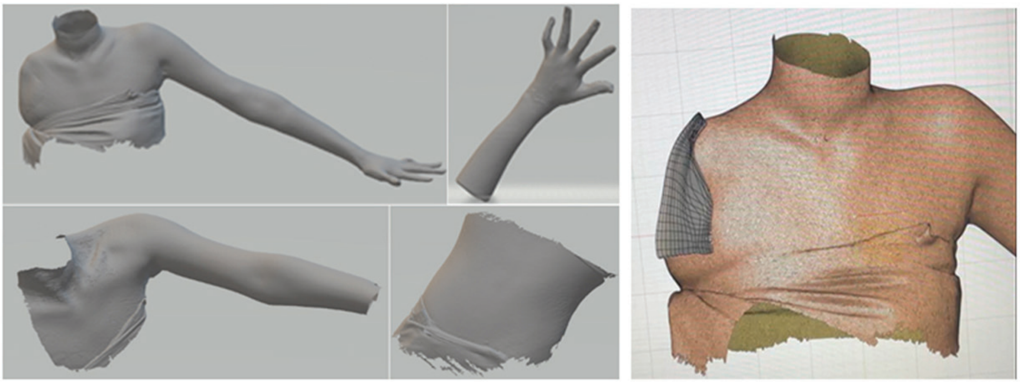


Fig. 2. a) 3D scanned images of the patient (from top left: upper body, hand, arm and body), b) Designing the shoulder part of the prosthesis using 3D scanned data

2.3 Finite element analysis

Finite Element Analysis (FEA) is indeed a powerful computational tool widely used in various fields, including biomedical engineering, to predict and evaluate the performance of products, components, or structures [13, 14]. In this study, a static stress analysis was performed on the shoulder component of the arm prosthesis to observe the force-loading effects in the slot area of the shoulder. First, the boundary condition (constraints) was set on the four-hole slots on the shoulder's corners (labeled red line) where the harness strap is tied, as described in Figure 3. Next, a 9 N structural load/force was applied to the inner area of the shoulder where the weight of the whole arm would be hanging. The influence of gravity was present in this simulation. This analysis tested two different types of materials: PLA (Polylactic Acid) and ABS (Acrylonitrile butadiene styrene), to study the effect of different materials under similar loading and determine which material was most suitable. PLA is known for its relatively high stiffness and rigidity, which makes it a suitable choice for applications where structural integrity and precision are essential. Its tensile strength typically ranges from 50 to 60 MPa. In contrast, ABS is valued for its exceptional toughness and impact resistance. It has a higher tensile strength, usually falling in the range of 30 to 45 MPa. Resulting von-Mises stress, displacement, and safety factors were the key emphasis in this simulation to determine the validity of the design under real-life circumstances.

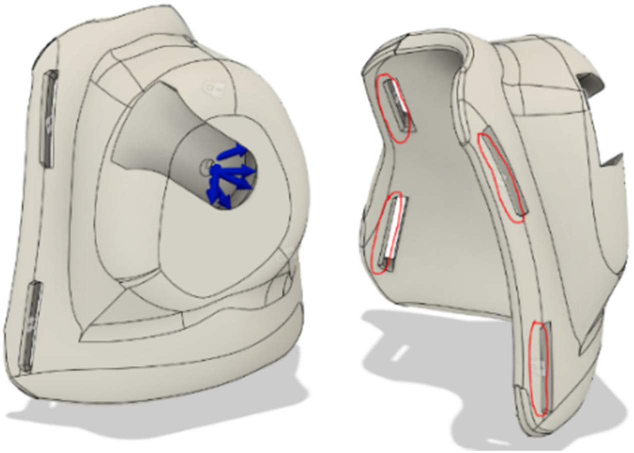
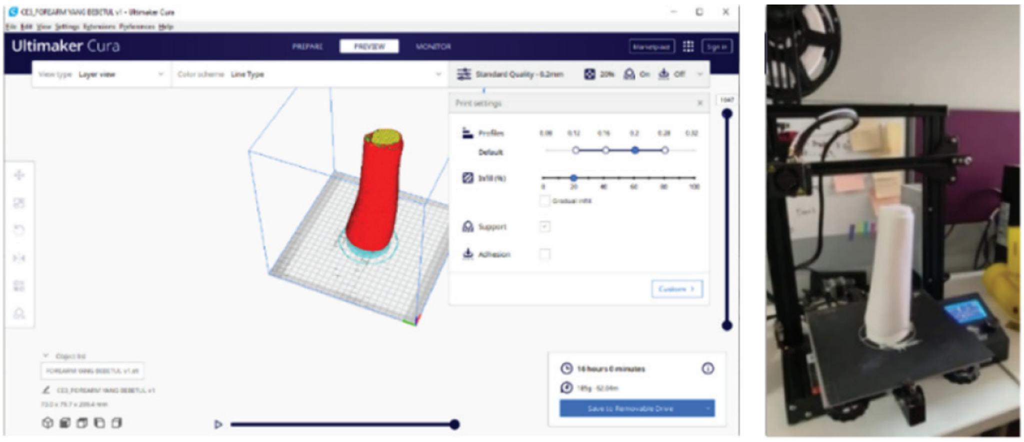


Fig. 3. Loading (left) and boundary conditions (right) of the shoulder part model

2.4 3D printing

Each prototype was rendered using Ultimaker Cura software before proceeding to 3D printing. First, parameters such as infill percentage, wall thickness, supports, or adhesion to the printed model must be considered. Next, previewing the printing process will allow the estimation of product weight and printing duration. Next, calibration of the 3D printer ensures quality prints and prevents mess-ups. Figure 4 shows a model of the forearm of prototype 1, which was rendered first in Ultimaker Cura before being 3D printed.



a) b)

Fig. 4. a) Rendering process in Ultimaker Cura software and b) 3D printing process

2.5 Product assembly and creation of harness mechanism

All that was left to do was to join all the 3D printed parts of the arm prosthesis into a single passive arm prosthetic connected by ball and socket joints. Next, the harness mechanism of the arm prosthesis was built using straps that wrap around the patient's arm and body which can be locked and unlocked with a buckle.

The components of the harness were 3D printed as well. The harness system allows for adjustable straps, which can be tightened and loosened according to the patient's preference, as illustrated in Figure 5.

a) **b)** **c)**

Fig. 5. a) The 3D printed prototype, b) harness mechanism, c) Assembled arm prosthesis

3 METHODOLOGY

3.1 Effects of PLA and ABS materials on the prototypes

Four variables were considered for evaluating and determining which material is best used as the arm prosthesis, as presented in Figure 6. The stress state represented by the von Mises stress is the one that is greater than the yield stress determined by a uniaxial tensile test. Results of the FEA showcased that the maximum von Mises stress of PLA is higher than ABS, indicating a higher tolerance of stress induced on the material's strength. Computing the displacement field within a solid subject to external forces is the primary goal of the displacement-based finite element approach. The maximum displacement experienced by PLA is lower than that of ABS, 0.001125mm and 0.001715mm, respectively.

Therefore, lower displacement under the same loading is more favorable. An opposing force to an action force is referred to as a reaction force. The activities of applied forces typically produce response forces and reaction moments. Structure failure, which can result in fracture and corrosion, can happen when reaction forces are more significant than action forces. Comparing both materials, PLA resulted in higher maximum reaction forces than ABS, suggesting that PLA opposes more force towards the applied force from the detachable arm prosthesis, which is also influenced by gravity force. The ratio between a measurement of the maximum load that won't cause the stated type of failure and a comparable measurement of the maximum load that is anticipated to be applied is the most frequent way to express a safety factor. Both materials have a safety factor of 15. Because this is relatively high and much over 1, it indicates that neither of these materials will fail under the conditions that have been shown. As a result, the use of PLA material, rather than ABS material, is recommended as the appropriate material for fabricating this arm prosthetic. The safety factor of both materials is the same at the value of 15, which is relatively high and well above 1, meaning both materials will not experience failure in the given circumstances. Therefore, PLA material is preferable over ABS as the suitable material for fabricating this arm prosthetic.

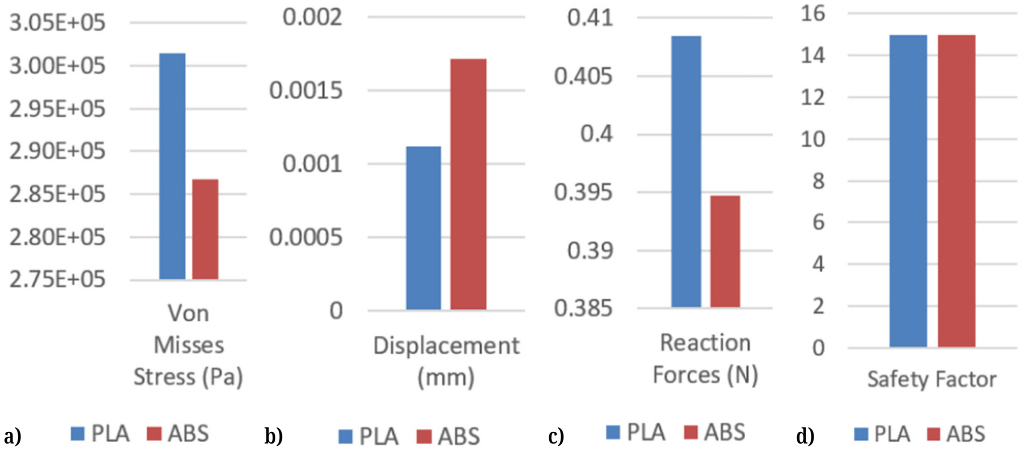


Fig. 6. Comparison between PLA and ABS materials, a) von-Mises stress, b) displacement, c) reaction force, and d) safety factor

3.2 Fabrication of the prototypes

Procedures in the engineering design process include problem-solving techniques, such as choosing goals and limitations, prototyping, testing, and assessment. With every prototype 3D printed, enhancements, improvisation, and improvements are made after each testing and fitting session. Feedback and observation from the patient are most important to obtain the best quality of the 3D printed arm prosthetic. Table 2 explains the enhancement of the model after testing and fitting with the dedicated patient. It was continuously conducted to meet the patient's request and comfort.

In total, four prototypes of the arm prosthesis were designed. The fabrication of multiple prototypes was due to the prosthetics' fitting, dimensions, and weight. The issues faced by the patient while wearing or putting on the arm prosthesis were;

i. the device was quite heavy and short in length,
ii. the shoulder part of the arm prosthetic was too bulky, resulting in overall body structure imbalance,
iii. putting on or taking off the device was time-consuming every time,
iv. another person was required to assist in wearing the device, and
v. the harness was loose fitting.

Those were the concerns that each new prototype design was trying to tackle. The 4th prototype was able to get rid of these shortcomings and proved to have the best design. The overall weight of the latest prototype is considerably lighter than its predecessors, which were heavier, which made the patient uncomfortable. In addition, the overall length of the arm prosthesis was modified to reference the left arm more accurately. In contrast, previous prototypes were short in length resulting in a disproportionate appearance due to arm length difference.

Meanwhile, the shoulder part of the prosthetic has been reduced in size. Previous prototypes had either an incomplete/improper design or were too bulky, which led to the patient wearing the device appearing disproportionate because of the protruding shoulder. The shoulder of the latest prototype no longer bulges and is designed with minimal additions to rid of the bulkiness. The shoulder and the whole arm have been designed to be detachable using a slot-in mechanism and the harness system's fitting has become more secure, as shown in Figure 7.

Table 2. Enhancement of the prosthesis arm model after progress meeting with the patient

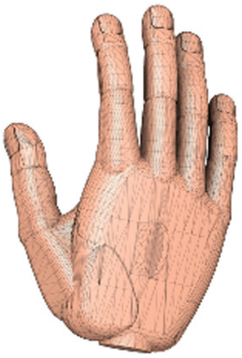
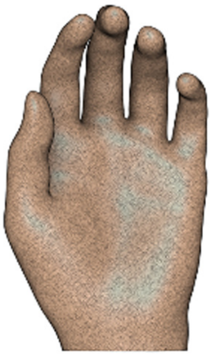
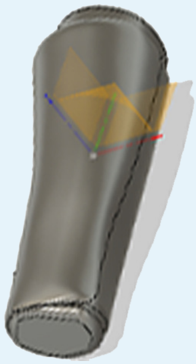
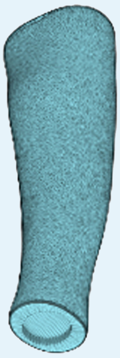
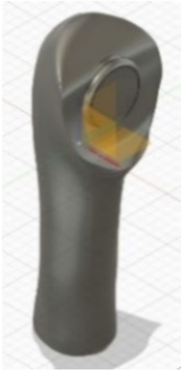
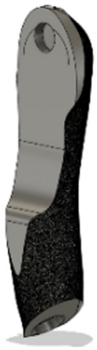
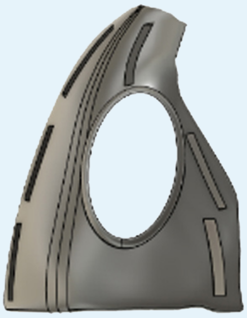
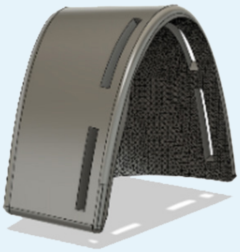
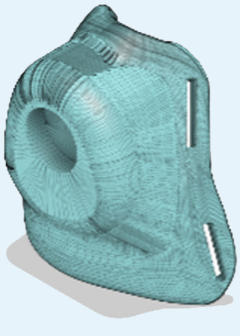
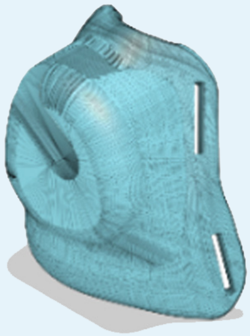
Model	1	2	3	4
Hand				
Forearm				
Upper arm				
Shoulder				

Fig. 7. Patient wearing the arm prosthesis using the slot-in mechanism

The feedback from the patient was very encouraging regarding the fourth attempt of the prototype. Issues such as weight, arm length, and shoulder imbalance were successfully resolved. The passive arm has been delivered to the patient for daily use, and further suggestions and comments will be gathered for future development and improvement. Although the device is a passive product, it has increased the patient's motivation and spirit for daily routine activities.

4 CONCLUSION

The development of customized arm prosthetics was successful by integrating 3D scanning and 3D printing technology. The patient-specific device was designed to suit the patient's passive condition, mirroring the right hand based on the scanning process of the left arm. Computational analysis suggested that using PLA material for the device was sufficient and more convenient compared to ABS material. During the fitting process, the challenges of ensuring the device's lightweight, comfort, strength, and ease of wear by a single person were addressed. The integration of a harness increased the device's tightness and proper fit for the patient. This project contributes to and paves the way for future improvements in 3D-printed prosthetics with minimal expense, time, and manpower. Obtaining feedback and comments from the patient was crucial in achieving these enhancements through multiple fitting sessions and prosthetic fabrication, ultimately leading to the success of the study. One of the most significant limitations is that findings from a single patient cannot be generalized to a broader population. Individual patient characteristics, medical history, genetics, and responses to treatment can vary widely, and a single case may not be representative of the typical outcomes or responses observed in a larger, more diverse group.

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