QATAR UNIVERSITY

COLLEGE OF ENGINEERING

DESIGN AND FABRICATION OF A PARAMETRIC 3D-PRINTED PASSIVE PROSTEHTIC HAND BASED ON ANTHROPOMETRIC FEATURES

BY

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ABSTRACT

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Title: Design and Fabrication of a Parametric 3D-Printed Passive Prosthetic Hand Based on Anthropometric Features.

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People with upper-limb reductions or amputations need prosthetic replacements throughout their lives as they grow and change. The standard method of prosthetic development takes a lot of time for fabrication by technicians and requires expert designers for patient-specific customizations. This can cause significant hardships for patients living in remote regions. Furthermore, many high-functional electric-powered prostheses are expensive and beyond the affordability of a large segment of users. Additionally, they require experts for maintenance whose availability maybe limited.

To address these issues, a parametric 3D-printed passive upper-limb prosthesis design is proposed in this thesis. The parameters are based on few anthropometric features from the healthy hand that can be easily measured. Since polymer-based 3D printing has become popular and affordable, low-cost rapid fabrication of custom designs is no longer challenging. The prosthetic hand model is made using state-of-the-art 3D parametric modeling software. Seven anthropometric features are used as input for the generation of the custom model: palm length, wrist diameter and circumference, middle finger length and circumference, and metacarpal circumference and diameter. The fabricated passive prosthetic hand can perform up to 31 grasps.

DEDICATION

I dedicate this thesis to my parents.

ACKNOWLEDGMENTS

I begin in the Name of Allah the Almighty and express my gratitude to Him for giving me the strength and fortitude to complete this thesis.

I would not have been able to finish this thesis, especially during this pandemic, without the help of many people to whom I am profoundly thankful. I am indebted to my parents, Mr. Mozammel Hoque and Mrs. Mosammat Kohinur Aktar Shirin, who sacrifices, and prayers have allowed me to reach thus far. I am grateful to them for all the privileges and opportunities that they have provided me with. I am extremely grateful to my thesis supervisor Dr. John-John Cabibihan for his extensive support, guidance, and mentorship that he has provided me during my master's program. He has allowed me to explore various ideas and equipped me with valuable skills that I have obtained by working on different projects with him. I thank my colleague Eng. Aya Gaballa from whose works, collaborations, and advice I have greatly benefited. I am grateful to my siblings Dr. Mohammed Mohsin and Mr. Mohammed Golam Mostafa for their support and encouragement. I especially thank my friend Eng. Mohammad Houkan, who has provided with valuable insights, constructive feedback, and assisted me in overcoming technical challenges in various stages of this project. I extend my thanks to all my friends for their kind support during this journey. I would like to acknowledge the Department of Mechanical and Industrial Engineering, all my respected instructors, and colleagues for their support and kindness. I am sincerely grateful to you all. Thank you.

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CHAPTER 1: INTRODUCTION

Our hands are prehensile organs through which not only can we sense our reality but also create, reshape, and live it. The loss of these significant limbs can be very traumatic for the victims regardless of whether it occurs due to accidents, diseases, or wars. Amputations and upper limb reductions not only prevent the patient from performing activities of daily living, socialization, and work, it can also cause social stigma, associated mental health problems, and loss of other socio-economic opportunities. Many children are also born without limbs due to congenital defects. They need special care to accommodate them and support their education and development through alternative means. Furthermore, due to long-lasting wars in many parts of the world, people are losing their limbs. Many of these amputees suffer from trauma in addition to their physical disability. Prosthetic users, especially children, and adolescents need frequent adjustments as they grow. Adults need prosthetics with functionality that allow them to live with dignity and enable them to return to work.

To help these groups of people live fulfilling lives, affordable and functional prosthetic designs are needed. With the increased availability and popularity of low-cost additive manufacturing (also known as 3D printing), it is now possible to rapidly fabricate complex designs without requiring laborious processes from standard manufacturing such as casting and machining. Parametric prosthetic designs are especially suitable for patients who need frequent adjustments or replacements as in the case of children and adolescents. It can be also beneficial to patients living in remote regions where there might be a lack of expert designers or machining facilities. Thus, through this thesis, I propose a parametric 3D-printed passive prosthetic hand based on anthropometric features. The primary advantage of the parametric design is that it will require the end-user to measure a few anthropometric features from the healthy hand and enter them into a program through a user-friendly graphical user interface (GUI). Thereupon, the program will automatically create the custom prosthetic design that can be sent to a 3D printer for fabrication. The ease, low-cost, and customized nature of this method methods that 3D printed prosthetic will be widely available and meet the need of individuals more accurately than what typical prosthesis development methods offer.

Upper-Limb Protheses

Upper-limb prostheses can be sorted into two categories based on their actuation: active and passive (Maat, Smit, Plettenburg, & Breedveld, 2018). The active actuation prostheses are powered either electrically or by the body (Carey, Lura, & Jason Highsmith, 2015). In contrast, passive prosthetics are usually used for cosmetic reasons; however, they can include mechanism that give them some functionality for grasping – making the dynamic passive as opposed to static passive prosthesis. Figures

Figure 1 and Figure 2 are examples of commercially available active prosthesis, and Figure Figure 3 shows an anthropomorphic passive prosthetic hand. Electric-powered (EP) prostheses can offer many grasping features and functionalities but are often prohibitively expensive to buy and remain out of reach of many patients. Currently, many open-source 3D-printed body-powered (BP) prostheses are available in the market; however, they offer limited functionality and have poor grasping performance. Life-life passive prosthetics are worn by many users as they are affordable and can reduce social stigma (Truijen et al., 2019).

Figure 1. The electric-powered Bebionic prosthetic hand (© Ottobock, Germany)

Figure 2. Anthropomorphic body-powered Raptor Reloaded prosthetic hand (© 2015 Walter Hsiao)

Figure 3. Biomimetic passive prosthetic hand (© SPS)

Prosthetics can also be classified based on functionality. Although many of the prosthetics are designed to be anthropomorphic, some prostheses are designed to serve special functions without adopting anthropomorphism. For example, the hook-type prosthesis shown in Figure Figure 4 do not look anthropomorphic, yet it can grasp and manipulate objects. Some prosthetics are designed to be used as specialized tools like forks, knives, or spoons. These can be categorized as statics prosthetic tools.

Other types of prosthetics can be adjustable depending on the tasks. All these static, dynamic, anthropomorphic, and non-anthropomorphic prosthetic devices and tools come under the broad umbrella of assistive technologies.

Figure 4. An upper-limb non-anthropomorphic body-powered prosthesis with a hook (© Ottobock, Germany)

Due to its dexterity and sophistication, the human hand can perform both precision and power grasps. Based on literature review, the human hand grasps are categorized into 33 distinct types (Feix, Romero, Schmiedmayer, Dollar, & Kragic, 2016). However, most commercially available prosthetics including electric and body-powered ones can only perform a limited number of grasps. It would be ideal to have a prosthetic hand that can perform all 33 grasps. Different approaches are taken to design anthropomorphic prostheses that may perform some selected grasps. For instance, the human hand grasps can be grouped on activities of daily living such as eating, or cleaning. They can also be combined based on a specific routine like studying that requires activities such as typing or writing.

Just like clothing, prosthetics need to fit the wearer to be comfortable and be usable. Poor-fitting can cause discomfort, chafing, and pain and discourage the user from continuing to use the prosthetic. Additionally, the material of the prosthetics needs to be carefully chosen to have maximum comfort. For example, a metallic prosthesis in a desert climate would heat up rather quickly and cause injury to the wearer. A plastic prosthetic could wear out rapidly and require frequent replacements. Such and other issues present practical problems to widespread prosthetic usage despite the abundance of research on prosthetic designs.

3D printing revolutionized and paved the way for small-scale localized production as opposed to large scale centralized production from the era of the industrial revolution. It also paved the way for low-cost rapid fabrication of complex models. It is now possible to print entire structures as one assembly – simplifying the development and reach of the prosthetic hands in remote areas.

Parametric modeling of the hand can simplify the prosthetic hand fabrication process by using pre-designed models. For instance, if a child in a remote region needs a prosthetic hand, they can approach a local nongovernmental organizational (NGO) or a hospital. For non-parametric designs, the NGO can do a fast 3D scan of the healthy hand of the child and send it over to a designer via the Internet. The designer can create a custom prosthetic hand model based on patient data. they will send it back to the NGO, and it will print it through their on-site 3D printer. However, the NGOs do not need to send the data back to the designer by switching to parametric designs. They can just input the hand parameters in a program that can output a model customized for the patient. This can potentially reduce the waiting time to receive a prosthetic hand. it can even allow the patients to choose their preferred prosthesis design from a database of prosthetic models. Furthermore, patients may even print it at their homes if they have some familiarity with 3D printing.

Motivation

A survey of literature revealed that although there is a lot of research for upper-limb prostheses, not a lot of attention has been paid to parametric designs. The problem with non-parametric designs is that they are hard to modify once finalized. The flexibility in fine-tuning to suit individual patients is very limited. Generally, scaling them up or down often results in the poor fitting. Through parametric design, the prosthetic hand can be fine-tuned based on a predetermined set of features. This can result in a better fit when scaling up or down and adjusting for different patients. Furthermore, parametric designs can consider other factors into accounts such as gender, race, age, or other relevant features. With parametric modeling, a pre-designed database of models can be used whereby the user only needs to give in the input parameters and immediately get a custom model as output and ready for 3D printing.

In typical 3D modeling, the design engineer works with dimensions. However, in parametric modeling, the emphasis is more on the relations between different geometric features. For example, instead of just asking what the length of a hand is, the designer should ask what the relation is between the length of the hand and the length of the fingers. While this introduces some complexity in the initial design, subsequent modifications become easier and quicker. Without parametric relations between the hand features, the designer needs to modify the 3D model substantially for a different size of hand. However, using parametric relations the process of creating another with different size comes to modifying a few dimensions which are mathematically linked to other geometric features of the hand. Parametric modeling allows the designer to explore the design space much more thoroughly as well as modify the 3D model in a non-linear fashion. Without established relations between the geometric features, the 3D model will only allow linear modifications and the exploration of the design space will be much more limited.

Aim and Objectives

The primary goal of this thesis is to demonstrate the feasibility of designing and fabricating a 3D printed parametric prosthetic hand based on anthropometric features.

The objectives that are required to meet the aim include the following:

i. To design a parametric prosthetic hand model using anthropometric features.
ii. To fabricate the prosthetic hand using 3D printing.

Scope and Deliverables

The scope of this thesis includes the design and fabrication of the 3D printed prosthetic hand. The parametric model is developed for a passive prosthetic hand. The fabrication includes 3D printing. Testing for grasps is included within the scope. The scope for the program for the 3D model is limited to scripts that run on independent 3D modeling software. Obtaining the anthropometric features using a 3D scanner is included in the scope.

Not included within the scope of this project are the active prosthetics such as body-powered or electric-powered prosthetics. The design and fabrication of the cosmetic glove that should be worn over the prosthetic hand are not considered. The connection of the prosthetic hand to the forearm is not considered within the parametric model. Fitting the fabricated prosthetic hand on the patient is not included in the scope.

Statement of Contribution

There are three main contributions of this thesis in terms of novelty, innovation, and methodology. Firstly, I have innovated on the familiar ball-and-socket joint and incorporated it into my design of a 3D prosthetic hand model. Secondly, I have demonstrated a parametric approach to designing passive prosthetic hand by using anthropometric features. Finally, I have produced a prosthetic hand by using 3D printing that can perform 31 grasps that is not reported elsewhere in the literature. Additionally, I have developed a script that can quickly generate this passive prosthetic hand model customized for each patient based on the given anthropometric features. I have innovated on the cosmetic passive prosthesis and made it dynamic and functional.

Organization of Chapters

This thesis is organized into several chapters. In this introductory chapter, the overview of the thesis has been laid out. This includes the motivation behind this study as well as brief discussions of the key ideas that will be expanded in later chapters. Chapter 2 includes a comprehensive literature review on prostheses developments and similar work on parametric 3D printed prosthetics. Additionally, it provides a comprehensive look at the human hand covering its anatomical description and various attempts at modeling it. Chapter 3 includes the methodology detailing the parametric design approach based on anthropometric data and the 3D fabrication process. Chapter 4 provides the results and discussion including the metrics of performance and evaluation. Finally, Chapter 5 concludes this seminal work and guides future research.

CHAPTER 2: BACKGROUND AND RELATED WORKS

In Chapter 2, we present a comprehensive and relevant survey of literature related to 3D-printed parametric prosthetic hand developments. The anatomical features and taxonomy of the hand are presented along with the various classifications of the grasps in Anatomy of the Human Hand. A comprehensive review on advances in upper-limb prostheses is presented in Review on Upper-Limb Prostheses Developments covering EP and BP prostheses. The modeling of the human hand including kinematics and simulations is presented in Modeling of the Human Hand. 3D Scanning and 3D Printing presents the developments in additive manufacturing and 3D printing technologies. Finally, parametric designs based on anthropometric features are reviewed in Parametric Designs of Prostheses.

Anatomy of the Human Hand

The human hand is dexterous, adaptive, and flexible enough to perform various tasks, maneuvers, and manipulations. Its remarkable flexibility can be observed by watching jugglers, acrobats, and magicians perform their trades by the ultimate mastery of their hands. The hands, on the other hand, can be trained for strength like those of heavy-weight lifters, or the agility of a boxing fighter, or delicate manipulations of a surgeon. The hands can enable people to communicate such as those who use sign languages and can convey many other emotive meanings between people. In the design of prostheses, we endeavor to mimic the anthropomorphism of the hand as it is not only the best possible design, we know of but also one that makes us human.

Musculoskeletal Structure

The human hand is a complex prehensile organ that consists of bones, joints, ligaments, muscles, arteries, nerves, tendons, and skin as depicted in Figure Figure 5. The skin gives the hand sensory abilities such as feeling warmth, texture, and pressure, and so on. The muscles, tendons, and bones enable the hand to perform grasps and manipulation. Both sensory and motor functions complement each other to make the hands very agile, sensitive, and responsive organs.

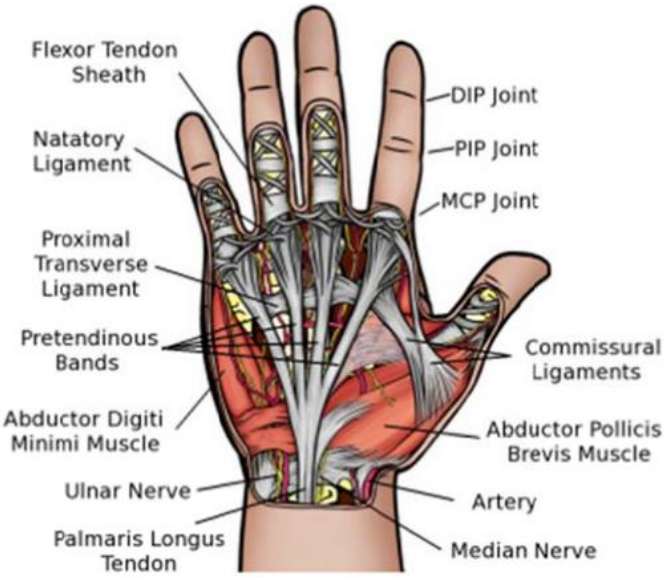

Figure 5. Musculoskeletal structure of the right hand (© 2015 IEEE)

The hand has 27 bones. Of these 27 bones, 8 are located in the wrist, 4 in the metacarpal, 3 in the thumb, and the remaining 12 make up the phalanxes of the other fingers as shown in Figure Figure 6. The bones are connected through different types of joints allowing a diverse range of motions (Peña-Pitarch, Falguera, & Yang, 2014a).

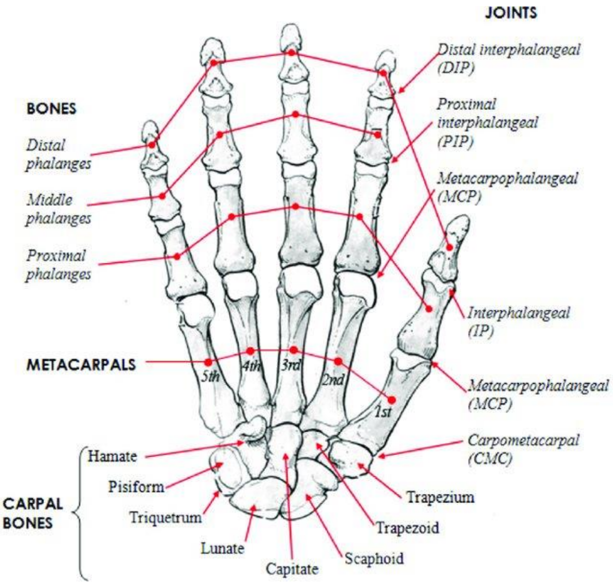

Figure 6. Bones and joints of the human hand (Source: Nanayakkara et al., 2017)

The fingers can have different types of motion such as flexion, extension, adduction, or abduction. Figure Figure 7 shows the various types of motions of the thumb and fingers.

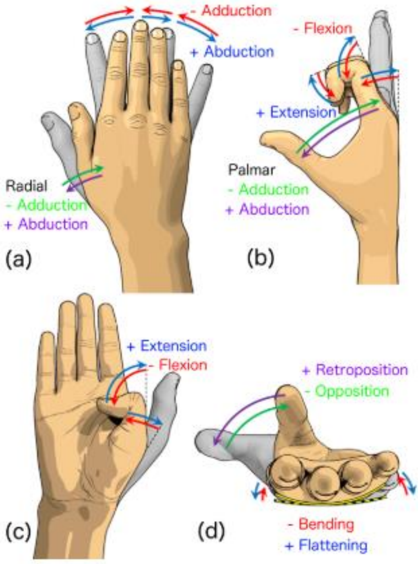

Figure 7. The fingers can be in various positions such as in adduction, abduction, flexion, extension, retroposition, or opposition. a) Shows the radial adduction/ abduction positions for all fingers. b) Shows the palmar adduction/abductions where the fingers can be in flexion or extension. c) Shows the a different type of flexion/extension of the thumb. d) Shows the retroposition/opposition of the thumb

and bending/flattening of the fingers II-V (Source: (J.-J. Cabibihan, Alkhatib, Mudassir, Lambert, Al-Kwifi, et al., 2020))

Grasp Taxonomy

Our hands can perform many different types of grasps. Feix et al. provides a list of 33 types of grasp classifications (Feix et al., 2016). The definition of a grasp is as follows:

> "A grasp is every static hand posture with which an object can be held securely with one hand, irrespective of the hand orientation."

The grasps can be broadly categorized into power, precision, and intermediate grasps as shown in Figure Figure 8. These grasps are sorted in two separate columns based on whether the thumb is abducted or adducted. They are further sorted based on what part of the hand is in an opposing position while performing the grasp. Furthermore, the paper uses the concept of virtual fingers to illustrate the number of fingers that are applying opposite forces during the grasp.

Unsurprisingly, neither prehensile abilities nor the hands are unique to us. For example, primates have hands similar to ours and perform some of the same grasps (Pouydebat, Laurin, Gorce, & Bels, 2008). Other animals such as the sea horses, octopuses, or elephants can grasp objects using their tails, tentacles, or trunks, respectively. Some researchers have investigated biomimetic designs and the relative advantages they provide for grasping. Porter et al. found that the square-tail of the seahorse allows a higher degree of deformation and enable the tail to return to its original shape as well as give it increased strength and prehensile abilities (Porter, Adriaens, Hatton, Meyers, & McKittrick, 2015). These nature-inspired designs can be further investigated for developing biomimetic prostheses.

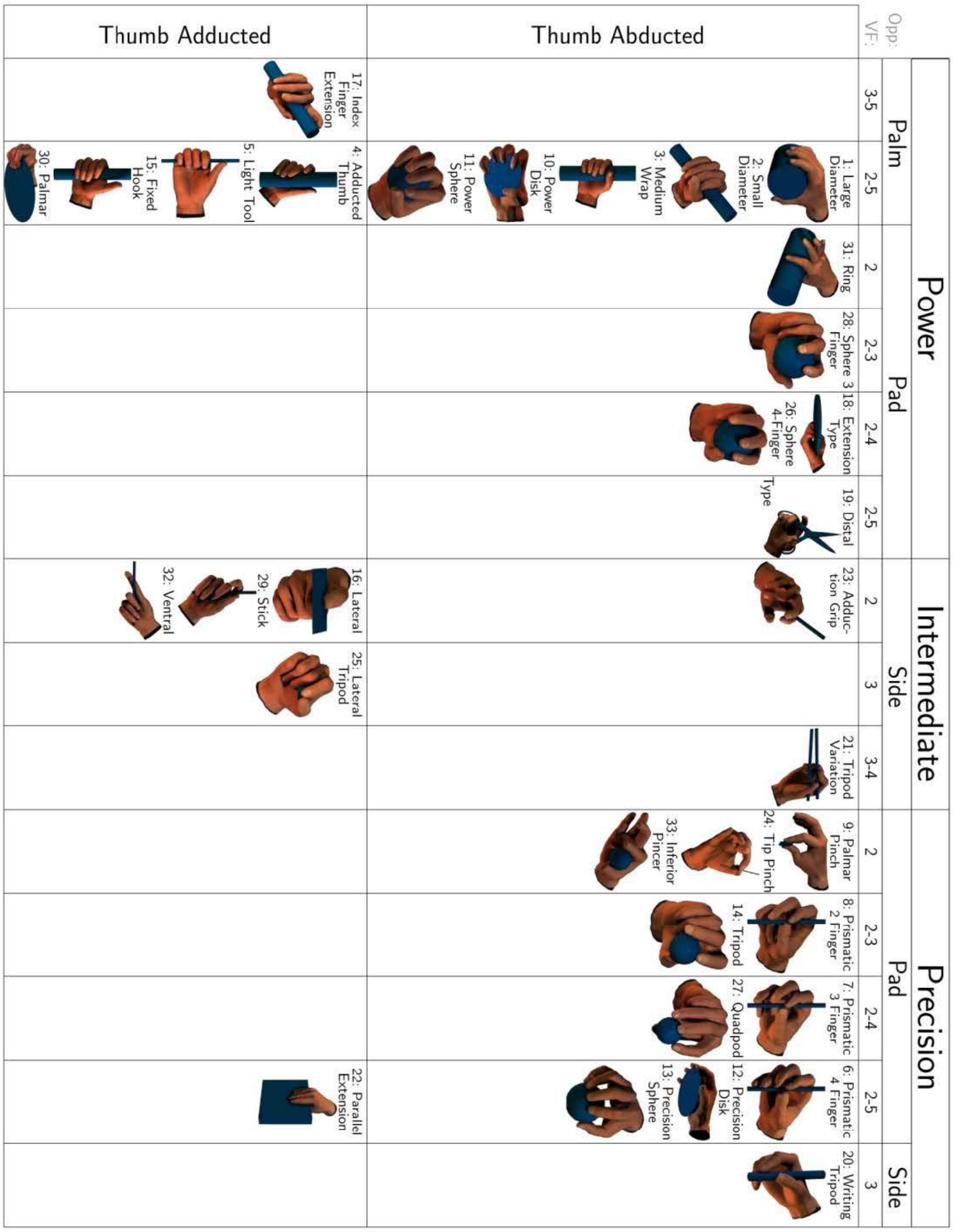

Figure 8. The grasp taxonomy includes 33 types of grasps sorted into two columns. based on thumb adduction or abduction. They can be broadly classed as power, intermediate or precision grasps (© 2016 IEEE)

Review on Upper-Limb Protheses Developments

This section provides an overview on the recent developments on the upper-limb prostheses. This includes a brief description the nature of upper-limb amputations, advances in electric and body-powered prostheses, and discussion on control, comfort, affordability, and aesthetics of these assistive technologies.

Upper-Limb Amputation

The upper-limb prostheses can be designed to address different levels or type of upper-limb amputation shown in Figure Figure 9. For finger amputations, either one or more fingers could be missing, or part of a finger such as segments could be missing. Amputation could also be below (transradial) or above the (transhumeral) elbow, it could be at the shoulder including the shoulder blade (forequarter) or starting from the shoulder-arm joint (shoulder disarticulation). The wrist disarticulation implies that the hand is missing completely. In some cases, the wrist joint can be present while the remaining of the hand is amputated (Hussain, Shams, & Jawaid Khan, 2019).

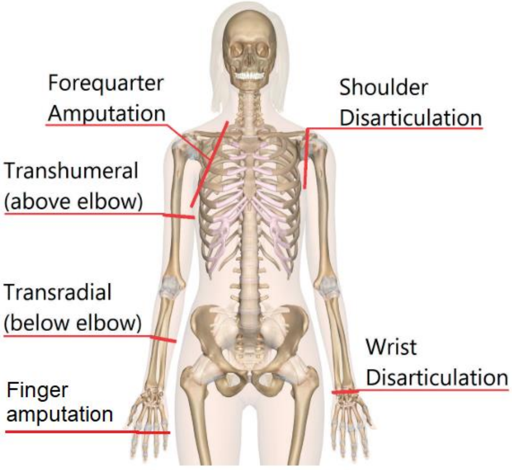

Figure 9. The severity of the upper-limb amputation can vary such as missing fingers, transradial amputation, transhumeral amputation, forequarter amputation, shoulder disarticulation, or wrist disarticulation (Source: Hussain et al., 2019)

EP and BP Prostheses

Despite the popularity of electric-powered hands in the market, they are unaffordable, hard to maintain and control, and still lack many grasping functions. Andrianesis's hand has 11 DOFs, can be controlled by EMG, and can achieve 6 types of grasps including power, hook, precision, lateral, tripod, and spherical (Andrianesis & Tzes, 2015). Table Table 1 summarizes some of the commercial EP prostheses, their DOFs, type of control, and the number of grasps (ten Kate, Smit, & Breedveld, 2017). The prosthetic types are forearm (F), hand (H), and upper arm (U). the control types are electroencephalogram (EEG), electromyography (EMG), and voice activation.

Table 1. A sample of electric powered hands available in the market and/or the literature.

Prosthesis	Type	DOF	Control	Grasps
Youbionic	F	11	EMG	6
Tact	F	11	EMG	6
Robot hand	F	15	EMG	2
Nu hand	F	19	EMG	6
Muscle robot hand	F	5	EMG	2
Latest bionic arm	F	15	EMG	6
InMoov 2 hand	F	15	EMG	3
Handiii Coyote	F	15	EMG	6
Handiii	F	15	EMG	6
HACKberry	F	10	EMG	3
Andrianesis' hand	F	15	EMG	6
Bebionic	F+H	6	EMG	5
Michelangelo	H	2	EMG	3
SensorHand	H	1	EMG	1
Vincent hand	H	6	EMG	5
Roboarm	U+F+H	14	EEG	6
Mind-controlled robotic hand	U+F+H	16	EEG	6
Limbitless arm	U+F+H	14	EMG	4
DIY prosthesis	F+H	16	Voice	6
Dextrus EMG	F	15	EMG	6
Bionico hand	F	16	EMG	6
Simone's hand	F	15	EMG	2
O'Neill's hand	F	15	EMG	3
Gretsch's hand	F	10	EMG	3
Bahari's hand	F	14	EMG	3
iLimb	H	6	EMG	5

Many 3D-printed open-source prosthetic hand models are inexpensive and widely available. Several of them are body-powered. However, they offer a limited range of grasps and functionality. Table Table 2 summarizes some commonly used BP prosthesis available in the market. They are usually operated with elastic cords for extension and non-elastic cords for flexion. They require active exertion of force to perform the grasp. Often body-powered prostheses users require training of specific muscle groups to use the prostheses after amputation. The prostheses can be either forearm with hand (F) or just hand alone (H). They are controlled by shoulder harness (SH), wrist (W), or elbow (E).

Table 2. Body-powered prosthetics available in the market

Prosthesis	Type	DOF	Control	Grasps
Gosselin's hand	F	15	SH	3
Groenewegen’s	F	15	W	2
Adjustable thumb	H	11	W	3
Cyborg arm	F	10	E	2
Falcon hand V1	H	13	W	2
Cyborg beast	H	10	W	2
Falcon hand V2	H	11	W	3
Flexy arm	F	11	E	2
Hollies hand	H	10	W	2
K-1	H	14	W	2
Galileo hand	F	11	SH	3
Flexy hand	F	14	W	4
Not impossible	F	10	E	2
Talon hand	H	10	W	2
Tenim hand	F	15	SH	6
Odysseus hand	H	6	W	2
Victory hand	H	14	W	3
Talon flextensor	H	10	W	2
Raptor Reloaded	H	10	W	2
Raptor hand	H	10	W	2

Many users prefer passive prosthetic hands for affordability and cosmetics that can reduce social stigma. Hoover, they do usually do not offer many DOFs. They can be hard to control and have very few grasps poses.

Control, Comfort, Aesthetics, and Affordability

There are different ways of controlling the BP, EP, and passive (adjustable) prosthetics. The prosthetics can have different levels of comfort based on the materials and control types.

The BP prosthetics are controlled by muscle flexion and extension. The forces from these flexion and extension motions are transferred to the prosthesis by cables or linkages. For example, in the hook-type prosthesis shown in Figure Figure 4 on page 4, the wearer can grasp an object using the terminal device by pulling the control and release it by letting go of the cable. This may cause some discomfort to the wearer as the forces have to exerted continuously using muscles in the arm or shoulder. There could be problems such as slippage and lack of tactile feedback that can make the grasping process harder. 3D-printed BP prosthesis shown in Figure Figure 2 on page 3 can grasp an object by bending the wrist joint. The forces are transferred through the cables (elastic and non-elastic) that pass through the fingers.

The EP prosthetics offer mainly 3 different types of control: EMG, ENG, and remote. Firstly, EMG-based prostheses do not offer tactile feedback; however, they can pick up electrical signals produced due to muscle contraction/extension from the surface of the skin and use that to control the prosthetic movement. This can be prone to noise and error. However, researchers have improved control using signal processing techniques and machine learning models. Secondly, ENG-based prosthesis offers tactile feedback as it is connected to the PNS through an interface. The problem with this approach is that this method is required invasive surgery to attach to the patient. However, in terms of control, this can be the most intuitive and natural method as it uses the same neural path the body normally uses to send messages to the limbs. Lastly, the remote control does not use either EMG or ENG but rather uses external radio frequency identification (RFID) chips or applications to control the prosthetic hand.

While many passive prostheses are static (non-adjustable), some of them may have joints that allow them to be adjusted. The wearer can adjust them using a healthy hand. In terms of control, there can be a passive locking mechanism that enables grasps. Otherwise, it is just changing poses with the help of a healthy hand. Anthropomorphic passive prostheses mainly serve to improve the cosmesis of the hand without offering a lot of functional grasps. It may be comfortable to wear if the material is suitable such as absorbing sweat and heat. However, most of the time it helps the wearer feel better by enabling them to live their lives without their disability being visible in social settings. This can reduce social stigma and improve their mental health.

Modeling of the Human Hand

Kinematic modeling of the human hand is necessary for designing prosthetics with grasping capabilities. Kinematic models are also necessary to create any simulations to study the behavior of a designed prosthetic hand.

Kinematics

Kinematics is the study of motion or movement. Kinematics analysis is done without consideration of the forces that may be responsible for the motion. Within the context of prosthetic hand designs, kinematic analysis is necessary for understanding and modeling the spatial relations of the bones and joints and their range of motions considering the rotational and transnational transformations. To develop a kinematic model of the hand, we need to consider the degrees of freedom (DOF) of the joints.

Pitarch et al. developed a kinematic model of the hand based with 25 DOFs. In their model, they considered the range of motion of the joints, workspace of the fingers, and the Denavit-Hartenberg parameters to describe the joint relations. They aimed to develop a comprehensive framework for the simulation of the hand for grasping and manipulating objects. They modeled the arching of the palm by considering 4 DOFs in the carpometacarpal (CMC) joints of the ring and little fingers - totaling 6 DOFs for each of these fingers. The thumb has 5 DOFs, and the index and middle fingers have 4 DOFs each (Peña-Pitarch, Falguera, & Yang, 2014b).

ElKoura and Singh proposed a 27 DOFs kinematic model for the hand. They considered the thumb to have 5 DOFs, each of the other four fingers to have 4 DOFs, and the wrist to have 6 DOFs for translation and rotation (ElKoura & Singh, 2003).

Simulations

With advances in computer graphics and processing capabilities, much prosthetic research and development can be done using simulation environments that can reduce the cost of development. For example, simulation software can provide a realistic environment by mimicking the effects of gravity, collision mechanics, friction, material properties, surface texture, sensors, and so on. This can allow designers to change their concepts without resorting to fabrication for minor changes.

Developing and testing EP prosthesis can be expensive and pose different types of risks to the patients. Hauschild et al. developed a virtual reality (VR) environment for testing and fitting neural prosthetic limbs (Hauschild, Davoodi, & Loeb, 2007). Through their environment, patients can use virtual limbs to manipulate virtual objects as depicted in Figure Figure 10. It includes realistic modeling of the musculoskeletal and mechatronic systems that allow developers to build and test prosthetics before letting users try it out.

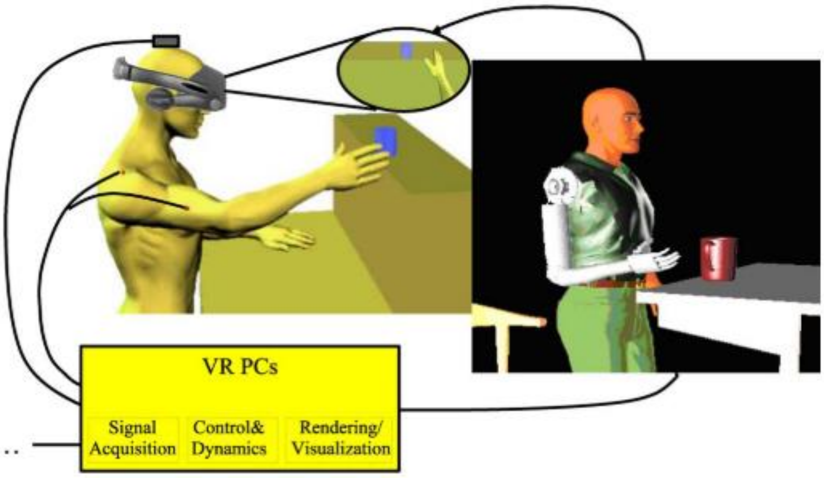

Figure 10. VR environment allows quick development and testing of EP prosthetics as well as enables users to train on the prosthetics before using the real product (© 2007 IEEE)

One of the challenges in designing robotic arms and to some extension in using simulations to design EP prostheses is finding accurate and anthropomorphic grasps. Especially for a complex design like the human hand with many DOFs, the solutions for forward and inverse kinematics can be time-consuming. And many of the grasps from these solutions will not be anthropomorphic. Additionally, researchers have to program for each different concept manually. To ease the development of robotic arm and corresponding kinematic solutions, Diankov developed a program for automated construction of robotic arm (Diankov, 2010). The proposed open-source library, which is called OpenRAVE[1], allows automatic generation of the required databases, kinematic solutions, and executables that enable the robotic arms to perform the specified tasks.

There are many other simulation frameworks and libraries that are used to grasp simulations. Miller and Allen developed a grasping simulator for robotic hand

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[1] www.openrave.org

(Miller & Allen, 2004). They developed Graspit![2], which is an open-source GUI-based application that allows the user to see the robots maneuvering around obstacles and performing their tasks in VR. It includes a library of robotic hand models, allows calculation of grasp quality metrics, grasp planning, interaction with sensors and prosthetic hands among and many other functionalities. Leon et al. developed OpenGRASP[3] as a holistic solution for motion and grasp planning for mobile robots including development and testing of new algorithms, modeling of the environments and robots, the modeling of actuators, sensors, and collision or contact. The modular architecture allows easy integration of new functions, features as well as existing standards and technologies (León et al., 2010).

3D Scanning and 3D Printing

3D scanning is necessary in the field of rehabilitation and assistive technologies to create custom prostheses and orthoses. Imaging techniques such as magnetic resonance imaging (MRI), computer tomography (CT) scans, or X-rays can be time-consuming and relatively expensive in some regions. They may also not be available everywhere such as in remote regions, refugee camps, or rural areas. The devices are bulky and require radiologists to be present onsite. Low-cost 3D scanners and scanning methods can make the custom fabrication process quicker and more available. To that end, many researchers are investigating the usage of 3D scanning methods and commercial 3D scanners for use in clinical settings.

Volonghi et al. evaluated two commercial 3D scanners, Cronos 3D Dual and Insight3, for acquiring static and real-time 3D scans from healthy and mobility-impaired patients (Volonghi, Baronio, & Signoroni, 2018). Cronos 3D Dual is a

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[2] graspit-simulator.github.io
[3] opengrasp.sourceforge.net

commercial static structured-light (SL) scanner that can be mounted on a tripod to capture an image of the hand from different views. Figure

Figure 11 shows the working mechanism of typical 3D scanners. The images can be aligned and stitched together using image processing software. After cleaning the background and other artifacts, a 3D mesh of the hand can be created. The Cronos 3D Dual offers image accuracy in the range of ± 30 to 60 μm with a resolution of 2 megapixels. The scanning can be completed within 3 minutes, and the 3D mesh can be generated within 7.5 minutes that includes aligning the images, removing backgrounds, generating the mesh, and cleaning any artifacts. As a real-time structured light scanner, the Insight3 can complete the scanning process within 1.5 minutes. It offers a resolution of 1.31 megapixels and an accuracy in the range of ± 0.25 to 0.5 mm. The post-processing can be completed within 8 to 10 minutes. The Insight3 does not require aligning the images manually. Using either of these 3D scanners, the whole process of capturing 3D scans and generating a hand mesh can be completed within 20 minutes. This is significantly faster and convenient than traditional imaging methods like MRI, CT scans, and X-rays.

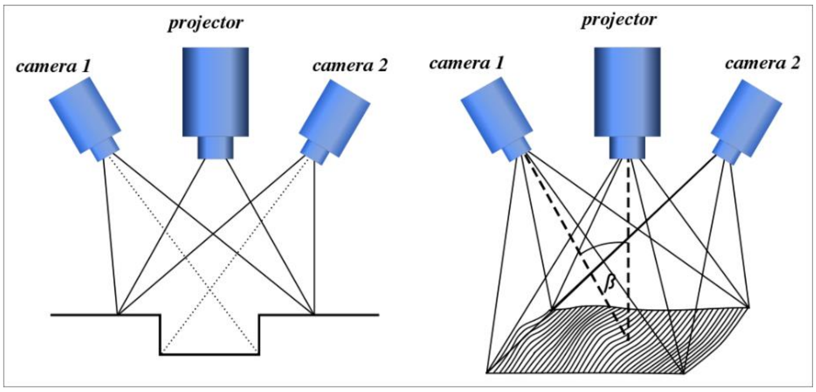

Figure 11. Structured-light scanner works by projecting a narrow range of electromagnetic beam (e.g. infrared) at a surface. The cameras at the sides positioned at angles receive the topological image different from the projector at the center. The combined images from these 3 different angles allow recreating surface texture (© CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=4502990)

Yu et al. evaluated the accuracy, reliability, and reproducibility of CT scans, Gemini SL 3D scanning, and direct measurement methods for reconstructing models of hands (Yu, Zeng, Pan, Sui, & Tang, 2020). According to them, the Gemini SL 3D scanner was able to capture and recreate a complete and smooth 3D model of the hand within 2.42 minutes. The CT scans could capture a complete image of the hand in 8.9 seconds, however, took 6.5 minutes for the reconstruction of the hand model. The authors suggested, based on statistical analysis, that either the SL scanner or the CT scanner should be used instead of the direct measurement method which had significant deviations from both of the other methods in terms of accuracy, reproducibility, and reliability.

Haleem and Javaid have provided an extensive review on the applications of 3D scanning in the medical field (Haleem & Javaid, 2019). According to them, 3D scanning technology is complementary to 3D printing technology. It is necessary for anthropometric studies and has the potential to reduce costs, time, and improve methods of obtaining data. It also integrates with other rehabilitation and assistive technologies like prosthetics and orthotics, craniofacial surgery, capturing accurate information of body size, shape, and skin surface. It is flexible, portable, accurate, and has a low operational loss. It also makes the transfer and storage of anthropometric data quite easy as the data is already digital. It can be used extensively in dental applications for fabricating prosthetic teeth, braces, retainers, and so on. It is also an excellent tool for replicating body parts for studying where using biological organs may not be readily available.

Cabibihan and Gaballa proposed a method for measuring the anthropometric hand features after collecting the 3D scans using commercially available SL scanners (J. Cabibihan & Gaballa, 2020). They propose a pose-invariant approach to measuring the hand features based on natural landmarks and the joint-centers method. Through the pose-invariant approach, the anthropometric features can be extracted from the hand regardless of the pose of the hand during scans. This is particularly helpful for settings where commercial SL 3D scanners are used.

Furthermore, they have used 4 commercial SL scanners and compared them against the CT scans. The SL scanner is Creaform, Structure, Kinect, and Sense. They offer 0.1, 0.5, 5, and 1 mm precision, respectively. They cost $20,000, $400, $300, $300, respectively. Based on their results, scanning with Structure took the shortest duration of 36.46 ± 2.11 seconds, followed by Sense with 39.70 ± 1.87 seconds, Kinect with 38.80 ± 1.30 seconds, and Creaform with 310.33 ± 41.90 seconds. Although the Creaform took the longest time, it was also the most accurate in terms of comparison to the CT scans. Table Table 3 shows commercial 3D scanners with different technologies and prices ranging from a few hundred dollars up to $ 37,000. The technology includes laser triangulation (LR), structured light (SL), simultaneous localization and mapping (SLAM), and white light (WL).

Table 3. Commercial 3D scanners and their prices

Scanner	Technology	Price $
Ciclop	LT	200
Murobo Atlas	LT	240
Microsoft Kinect	ST	300
Occipital Structure ST01	ST	400
Occipital Structure Sensor (Mark II)	ST	530
HP Z 3D Camera	SLAM	600
Scan Dimension Sol	LT	600
3D Systems Sense 2nd Gen	LT	700
Matter and Form 3D Scanner V2	LT	750
Shining 3D EinScan SE	ST	1400
HP Structured Light Scanner Pro S3	ST	3900
Shining 3D EinScan Pro/Pro+	WL	3900
Open Technologies Scan in a Box-FX	SL	5000
Peel 3D Peel 1	SL	5990

Scanner	Technology	Price $
Metron E 3D Scanner	SL	5990
Shining 3D EinScan Pro 2X	SL	5500
Peel 3D Peel 2	SL	7490
Artec Eva Lite	SL	9800
Artec Eva	SL	14685
Creaform Go!Scan20	SL	20000
Artec Space Spider	SL	24800
Artec Leo	SL	25800
Creaform Go!Scan Spark	WL	37000

3D printing is a fabrication technology based on the layered deposition of materials that can print 3D objects. Due to the layered deposition technique, some also call it additive manufacturing. It is the opposite of subtractive manufacturing where the product is fabricated by removing materials from a solid block. Subtractive manufacturing uses machining processes like drilling, milling, sawing, and so on. Over the last 20 years, 3D printing has matured as an alternative manufacturing technology. It is a cost-efficient method for fabricating 3D objects. It is possible to fabricate precise designs using 3D printing. Lowering manufacturing costs is important in competitive markets. With 3D people can lower the cost of fabrication as this technology reduces material wastage and allows for material recycling (Deshmukh, Houkan, AlMaadeed, & Sadasivuni, 2020).

Parametric Designs of Prostheses

Guevara et al. developed a GUI-based software using Python and Tkinter library that can take hand parameters as inputs from the user. After the required relational calculations are performed automatically in the background, the software sends the dimensions to OpenSCAD, which generates a pre-designed 3D hand model with the received dimensions and exports it in STL format that is ready to be 3D-printed. The impact of this work is that it only uses open-source software and libraries which can cut-down costs and make it widely accessible (Guevara-L et al., 2020).

Furthermore, Phung and Perez used Grasshopper with Rhinoceros 3D and Solidworks to design a parametric model for a 3D-printed prosthetic forearm considering the portion from elbow to the wrist. Users can input custom hand parameters using Grasshopper and quickly get a 3D model of the forearm that can then be fabricated using a 3D printer (Phung & Pérez, 2020).

Bustamante et al. developed a parametric 3D-printed body-powered prosthetic hand using Rhinoceros and Autodesk Inventor (Bustamante, Vega-Centeno, Sánchez, & Mio, 2018).

Moreo developed a generalized parametric 3D-printed BP prosthetic hand for children in developing countries using Solidworks. They approached the problem from a product design perspective by starting with several different concepts and eliminating them based on different criteria such as comfort, cosmetics, controls, and functionality (Moreo, 2016).

Li and Tanaka demonstrated through a feasibility study the suitability of using parametric designs for 3D-printed orthosis for fracture immobilization targeting upper limbs. They used Grasshopper with Rhinoceros 3D for modeling the orthosis. 5 nurses participated in a short training program where they learned to use the parametric program and were able to design 4 orthoses without any help within 20 minutes (Li & Tanaka, 2018).

CHAPTER 3: METHODOLOGY

To design and fabricate a 3D printed parametric passive prosthesis using anthropometric features, several steps have been taken. Firstly, interviews with patients were conducted to understand their needs. It helped in determining whether the passive prosthetic hands meet their requirements. Secondly, the data from the healthy hands of patients were collected using a low-cost rapid scanning technique using 3D scanners. The scans were post-processed and the anthropometric hand features have been extracted. A parametric 3D prosthetic hand model is developed. The 3D model is generated using a script written in Python programming language. The anthropometric features measured from the patient's hand are then entered into the parametric 3D model generator program. Upon receiving the input dimensions, it can generate a custom prosthetic hand model in real-time. It outputs an STL file that is sent to a 3D printer for rapid prototyping. Figure Figure 12 shows an overview of the methodology.

Figure 12. Overview of design and fabrication of a 3D printed parametric passive prosthetic hand

Interview with Patients

Several interviews were conducted with five patients in a refugee camp in Jordan in 2019. Their ages were between 8 to 22 years. Four of them were born with congenital upper limb reductions while the fifth one lost their hand and leg in the war.

A patient named Nadia (not real name) said that she goes to school and wanted a prosthetic that could help her with lightweight activities such as holding a phone, mirror, or makeup box. She could then use her healthy hand to operate the phone or apply the makeup. She also said that she wants a prosthetic that looks realistic to facilitate social interactions without her disability or prosthesis bringing unwanted attention. She admitted that a cosmetic prosthetic would improve her self-esteem and body-image and help her feel better about herself and her body. Figure \ref{fig:nadia} shows Nadia's silicone-based passive cosmetic prosthetic hand.

Nadia's story was inspiring, and the other patients shared similar sentiment about their prostheses. Her story inspired me to explore and innovate on the passive prosthesis and complete this design as part of my thesis.

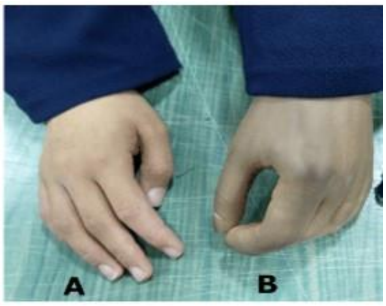

Figure 13. Nadia's hands: (a) healthy (b) passive cosmetic (Source: J.-J. Cabibihan, Alkhatib, Mudassir, Lambert, Al-kwifi, et al., 2020)

Anthropometric Data Collection

As the goal of a parametric prosthetic design is to make the prosthesis more attuned to the patient's hand features, the process begins by 3D scanning of the healthy hand of the patient. The 3D scanning is usually done with a structured light sensors camera - some of which are mentioned in Table Table 3 on page 24. Alternatively, if X-rays or

CT scans are used, then 3D imaging software such as Slicer 3D[4] can be used to reconstruct a 3D model. Moreover, a ruler and a measuring tape can also be used for taking anthropometric measurements. However, the measurements will be less accurate than those obtained from 3D scans.

Scanning

A depth camera was used for taking scans from the patients. The scanner was mounted on a tripod. The patient was seated during the scanning and rested their healthy hand on a stool. The healthy hand was oriented at an upright pose. The tripod was moved around the healthy hand covering 270° as shown in Figure Figure 14. The tripod was fastened with a 1 m long cable to the stool to have a consistent distance from the hand during scanning.

The 3D scanner captures the image of the hand as cloud points. There is several paid and free 3D cloud point scanning software available in the market. We used the 3D Scan[5] software from Microsoft. A supported graphical processing unit (GPU) is required for scanning with this software. The cloud points were converted to mesh using a mesh editing program - MeshLab[6]. After cleaning up the meshes, the model was exported as an STL file.

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[4] www.slicer.org
[5] www.microsoft.com/en-us/p/3d-scan/9nblggh68pmc
[6] www.meshlab.net

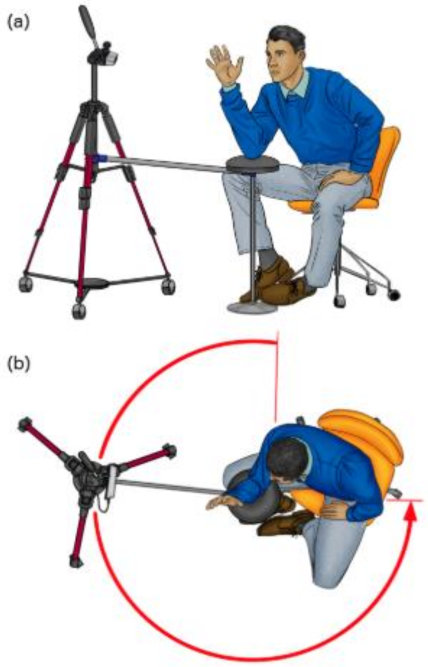

Figure 14. Using commercially available depth scanners, the hands of the patients can be scanned in a very short time. a) Shows the front view of a seated person resting their arm on a stool and facing a camera that is mounted on a tripod. b) Shows the top-view of (a) with the red arc indicating the angular distance required to fully capture the hand (Source: J. Cabibihan & Gaballa, 2020)

Table Table 4 shows data from two patients obtained from 3D scans that is shown in Figure Figure 15.

Table 4. Patient data from 3D scans

Hand Features	Patient 1	Patient 2
Middle finger length [mm]	61.84	57.69
Middle finger circumference [mm]	59.40	41.42
Metacarpal circumference [mm]	170.52	127.65
Metacarpal diameter [mm]	73.95	55.12
Wrist diameter [mm]	56.99	40.44
Wrist circumference [mm]	161.33	110.15
Palm length [mm]	136.73	131.48

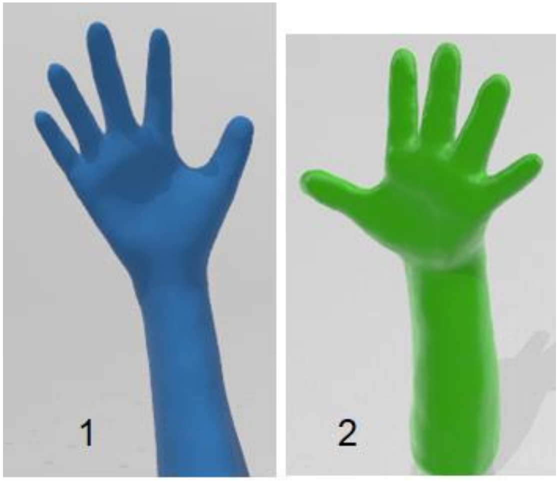

Figure 15. 3D hand scans of Patient 1 and Patient 2

Parameterization

There are seven hand parameters extracted from the scans as shown in Figure Figure 16. Features extracted from the hand and listed as follows:

1. Middle finger length: the sum of the lengths of proximal, middle, and distal phalanges
2. Middle finger circumference: assumed to be a circle and measured about the proximal joint
3. Metacarpal circumference: considering the four metacarpal bones of the four fingers and excluding the thumb; palm circumference
4. Metacarpal diameter: palm width excluding the thumb
5. Wrist diameter: the wrist is assumed to be an ellipse and the diameter is the major axis
6. Wrist circumference: the circumference of the wrist can be measured using the major and minor axes
7. Palm length: measured from the center of the wrist to the end of the metacarpal bone of the middle finger

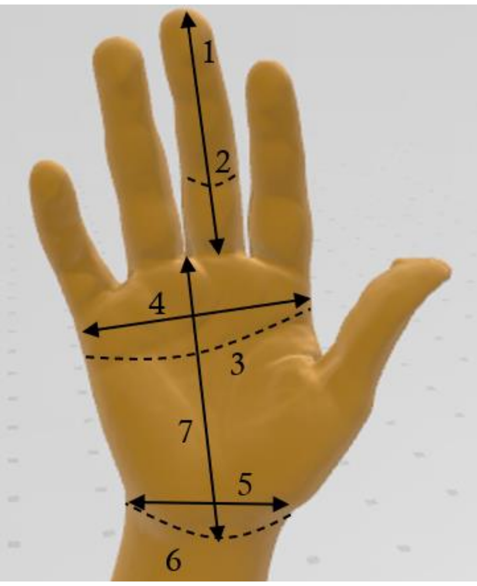

Figure 16. Features extracted from the hand

The anthropometric relations between the fingers are obtained from (Peña-Pitarch et al., 2014b). They developed the relations between hand length and hand width with the length of the metacarpal and phalangeal bones. The hand length is defined as the sum of the length of the palms and middle finger. The hand width is the width of the metacarpal bones excluding the thumb.

Parametric Modeling

The parametric modeling includes developing mathematical relations between the different anthropometric features of the hand as well as programming them in a way that enables creation of 3D models efficiently and exporting to STL format for 3D printing.

Assumptions

Some of the assumptions used for this passive prosthetic hand design include the following:

i. The patient has a healthy hand that they can use for operating the prosthetic hand.
ii. The prosthetic hand will be used for lightweight activities and social interactions.
iii. A prosthetic glove would be worn over the passive prosthetic hand to increase the aesthetics.

Programming in Grasshopper 3D

Rhinoceros 3D[7] (Rhino) is a commercial 3D modeling software developed by Robert McNeel & Associates. It runs on Windows (PC) and Macintosh (macOS) operating systems. The program supports parametric modeling using either polygonal meshes or splines. It supports non-uniform rational B-splines (NURBS) that can render mathematically accurate models. In other words, the polygonal mesh method would use tiny polygons to approximate the model whereas NURBS would render a model that is exactly defined mathematically. Mesh-based modeling and rendering are quite popular as it requires less computational resources. NURBS-based modeling and rendering are preferred where accurate representation is important.

Grasshopper 3D[8] is a built-in plugin for Rhino that allows visual block-based programming for parametric designs. It can create novel shapes and patterns using generative algorithms with parametric relations. Generative algorithms are useful for designing shapes that can evolve in complexity, produce novel patterns, and are not hard coded for a selected range of values (Khabazi, n.d.). Their evolution is guided by parameters instead of being restricted by them. This modeling approach suitable for

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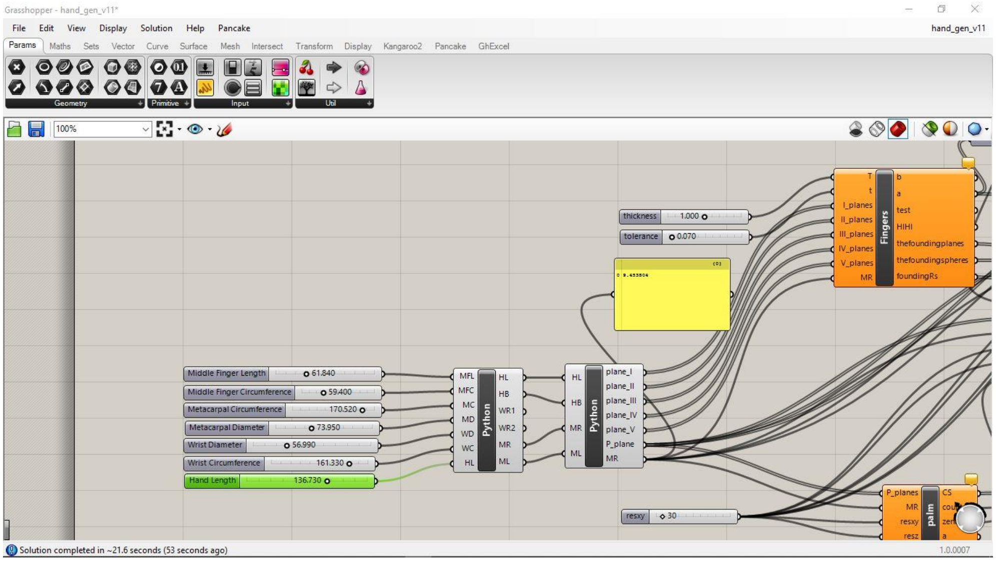
[7] www.rhino3d.com
[8] www.grasshopper3d.com

designing a prosthetic hand as demonstrated by (Li & Tanaka, 2018) and (Bustamante et al., 2018). Figure Figure 17 shows the Grasshopper interface with functional blocks.



Grasshopper - hand_gen_v11*

thickness 1.000

tolerance 0.070

Middle Finger Length 61.840

Middle Finger Circumference 59.400

Metacarpal Circumference 170.520

Metacarpal Diameter 73.950

Wrist Diameter 56.990

Wrist Circumference 161.330

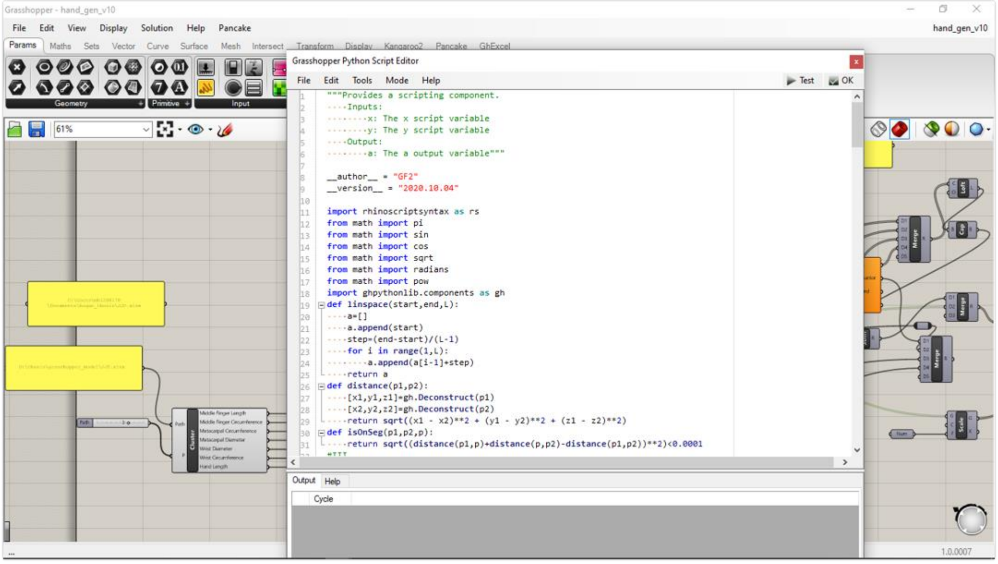
Hand Length 136.730

resxy 30

Solution completed in ~21.6 seconds (53 seconds ago)

Figure 17. Grasshopper offers a a GUI-based visual programming interface that offers powerful parametric design tools

Grasshopper also supports Python 2.7 which allows for scripting and generating 3D models using the python libraries and APIs. Figure Figure 18 shows the Python code within Grasshopper block.

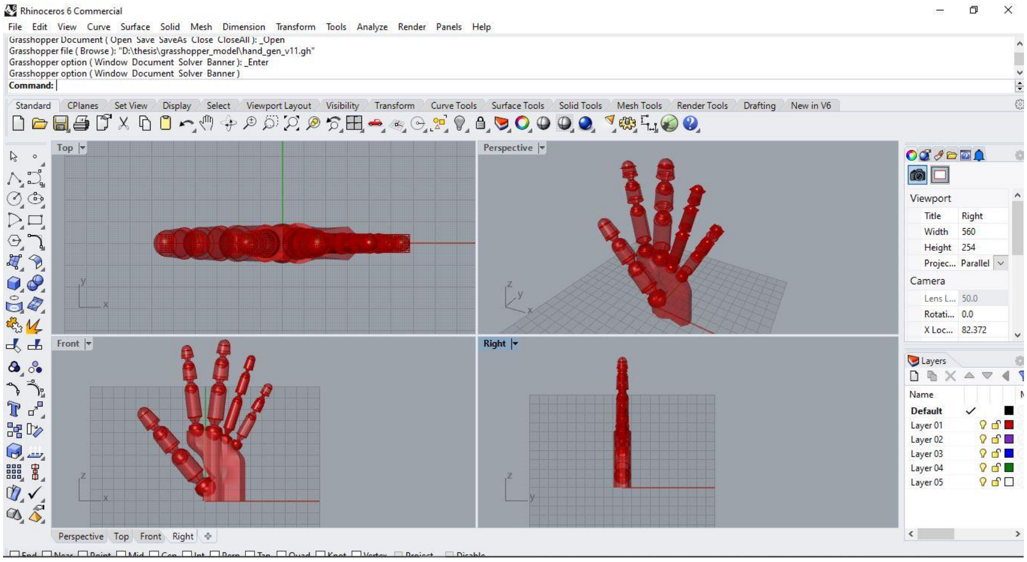


```
"""Provides a scripting component.
    Inputs:
        x: The x script variable
        y: The y script variable
    Output:
        a: The a output variable"""

__author__ = "GF2"
__version__ = "2020.10.04"

import rhinoscriptsyntax as rs
from math import pi
from math import sin
from math import cos
from math import sqrt
from math import radians
from math import pow
import ghpythonlib.components as gh
def linspace(start,end,L):
    a=[]
    a.append(start)
    step=(end-start)/(L-1)
    for i in range(1,L):
        a.append(a[i-1]+step)
    return a
def distance(p1,p2):
    [x1,y1,z1]=gh.Deconstruct(p1)
    [x2,y2,z2]=gh.Deconstruct(p2)
    return sqrt((x1 - x2)**2 + (y1 - y2)**2 + (z1 - z2)**2)
def isOnSeg(p1,p2,p):
    return sqrt((distance(p1,p)+distance(p,p2)-distance(p1,p2))**2)<0.0001
```

Figure 18. Python functional programming used within Grasshopper blocks

3D Model

The 3D model of the parametric prosthetic hand is generated by the Python script. Figure Figure 19 shows the four views of the prosthetic hand model from Rhino. Figure Figure 20 shows the rendering of the hand. Ball and socket joints have been used for all the joints of the fingers and metacarpals. The ball and socket joints allow rotations along x, y, and z axes. Figure Figure 21 shows the rendering of the palm along with a finger segment.



```
Grasshopper Document ( Open  Save  SaveAs  Close  CloseAll ): _Open
Grasshopper file ( Browse ): "D:\thesis\grasshopper_model\hand_gen_v11.gh"
Grasshopper option ( Window  Document  Solver  Banner ): _Enter
Grasshopper option ( Window  Document  Solver  Banner )
Command:
```

Viewport
Title Right
Width 560
Height 254
Projec... Parallel
Camera
Lens L... 50.0
Rotati... 0.0
X Loc... 82.372

Layers

Name			
Default	✓		■
Layer 01			🟥
Layer 02			■
Layer 03			■
Layer 04			🟩
Layer 05			□

Figure 19. The four views show the parametric 3D model of the hand in Rhino 3D

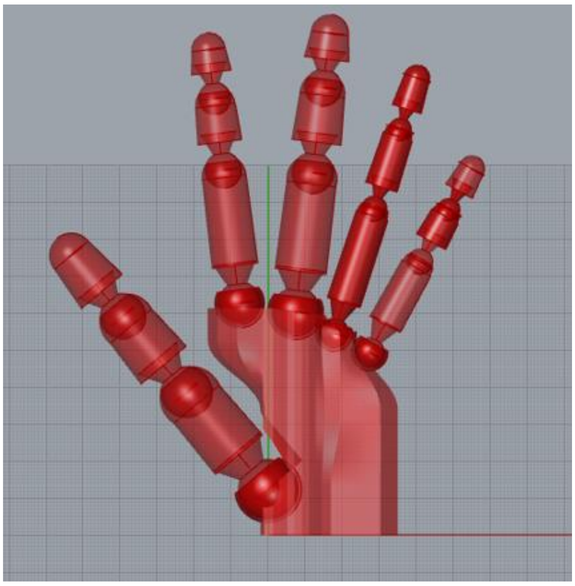


Figure 20. 3D model of the passive prosthetic hand

Figure 21. The palm and proximal little finger segment

3D Printing

The material properties of ABS and PLA polymers are shown in Table Table 5. The properties are obtained from experiments performed by Alkhatib et al. (Alkhatib, Cabibihan, & Mahdi, 2019).

Table 5. Material properties of 3D printed ABS and PLA

Material	Density [g/cm^3]	Young’s Modulus [GPa]	Ultimate Tensile Stress [MPa]	Failure Strain %
ABS	1.10	1.40	32	1.05
PLA	1.30	3.90	54	2.20

After generating the prosthetic hand model on Rhino with Grasshopper, the model is exported as a standard tessellation language (STL) file. The STL file is prepared for 3D printing using the open-source slicing software Cura[9]. Cura creates a

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[9] github.com/Ultimaker/Cura

G-code containing the instructions for printing based on the STL file. The G-code is a computer numerical control (CNC) programming language that is widely used in computer-aided manufacturing (CAM) for automated controlling of fabrication machines. The prosthetic hand is prototyped using a low-budget entry-level 3D printer, Duplicator i3 Mini[10]. A sample print is made using the settings mentioned in Table Table 6.

Table 6. Print settings used for printing a sample prosthetic hand

Print Parameter	Setting
Profile	0.15 mm
Wall thickness	0.8 mm
Wall line count	2
Top/bottom thickness	0.8 mm
Top layers	8
Bottom thickness	0.8 mm
Bottom layers	8
Infill density	30%
Infill pattern	Concentric
Printing temperature	210° C

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[10] all3dp.com/1/wanhao-duplicator-i3-mini-3d-printer-review.

CHAPTER 4: RESULTS AND DISCUSSION

The 3D printed parametric passive prosthesis is a novel approach to designing and fabricating prosthetics that are patient-specific and offer some gasp functionality. Consequently, it will be evaluated mainly on these criteria: modeling patient hands, fabrication of prosthetic hand, number of grasps.

3D Model

The parametric model is versatile. Using the Python script in Grasshopper, the design can be quickly changed or adjusted for different patients. Figure Figure 22 shows the 3D model based on the data from the two patients. Notice that although the design looks similar, the joints, finger segments, palm, and overall features are different.

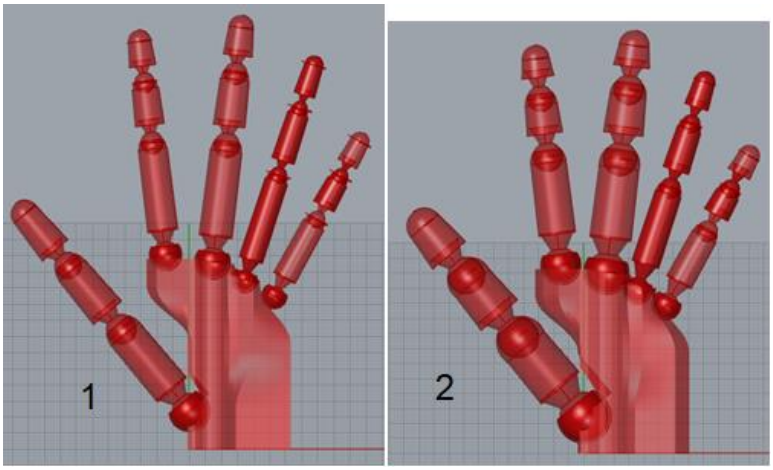

Figure 22. Patient hand models generated using the script

Furthermore, some randomly generated hands are shown in Figure Figure 23. These demonstrate how easily the hand can be tuned without requiring any effort from the designer.

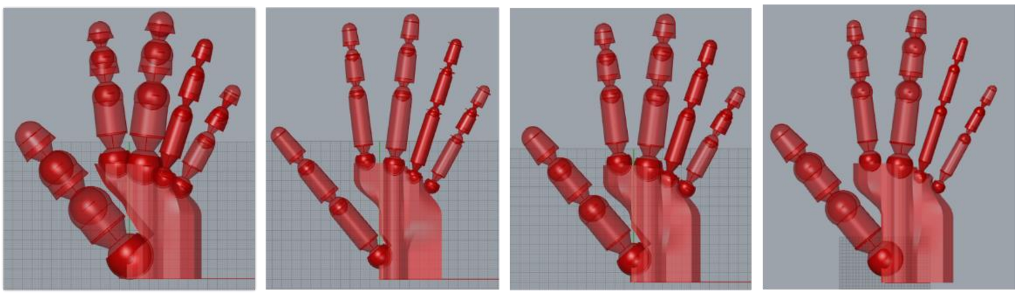

Figure 23. Randomly generated prosthetic hands

Fabrication

The 3D printed hand is shown in Figure Figure 24. This is based on the hand dimensions of Patient 2. The palm and finger segments are printed separately. The ball is inserted into the socket by force. A low-tolerance (0.07mm) value is used for the ball and socket joint so that there are a tight fit and enough friction to avoid the ball from slipping. Some of the limitations related to material include the use of PLA and ABS. PLA deforms easily in the presence of heat, which can be a problem when using this prosthesis outside in the sunlight.

Figure 24. 3D printed passive prosthetic hand

Grasps

The grasp results are shown in Figure Figure 26. The passive prosthetic hand can perform 31 out of the 33 grasps. The failed grasps include the distal type and tripod variation which are like holding a pair of scissors and a pair of chopsticks, respectively. This is the largest number of grasps reported in the literature.

Furthermore, the hand can perform gestures that are encountered during social interactions such as a handshake or making a victory sign shown in Figure Figure 25. This has been a requested feature by some of the prosthetic users that were interviewed.

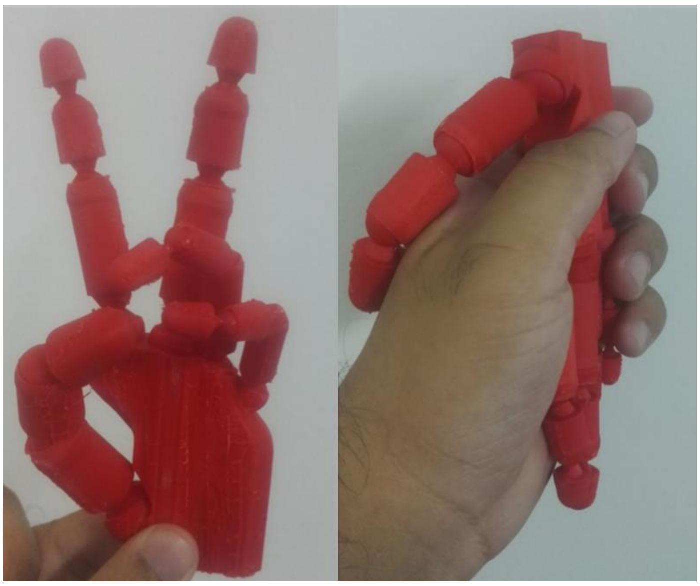

Figure 25. Social gestures that the passive prosthetic hand can be used to participate

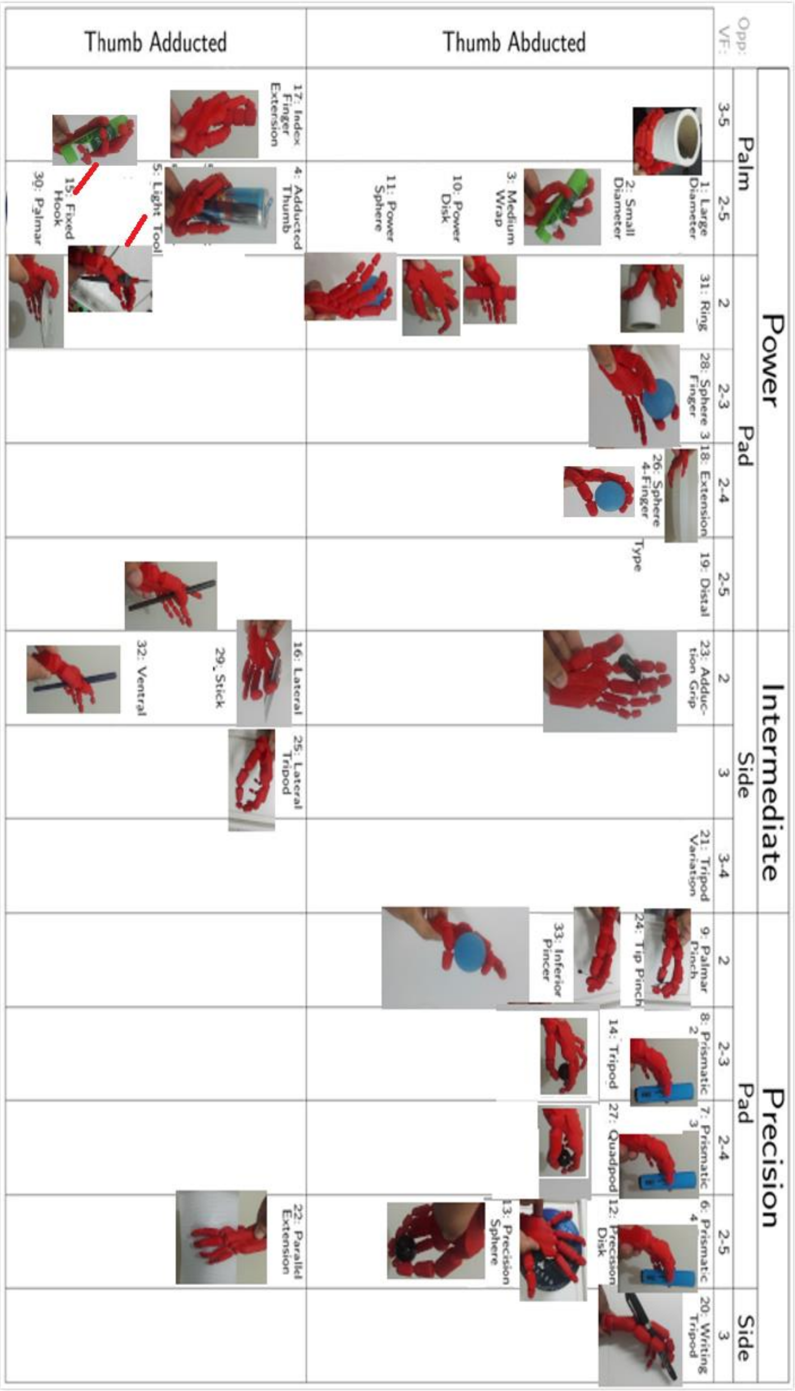

Figure 26. 31 grasps performed by the 3D printed parametric passive prosthetic hand

Discussion

In this thesis, we have successfully designed a passive parametric 3D printed prosthetic model that can be fabricated based on patient-specific dimensions and can perform 31 grasps. This is the first reported passive prosthetic hand that can perform such many grasps.

One of the main issues with this model is that the kinematics of the hand changes based on the hand features of the patients. For example, a hand with thicker finger segments and joints will affect the mobility and degree of freedom of the fingers. A thin finger segment will lead to increased mobility; however, it also increases the stresses at the neck of the finger segments leading to premature failure of the finger segments. Additionally, thinner segments caused excessive stress at the necks during the insertion of the ball into sockets.

Another challenge in using this model is that the quality of the hand depends on the printer and material. To mitigate this problem, I have devised a test to calibrate the printer settings to get an optimal print. For material variability, I made a baseline tolerance that works with mismatched materials. For example, if a component wears out and needs to be replaced, it can be easily replaced with another printed component made of a different material. The Python scripted model is suitable for the mass production of hands where it can produce a list of hands that can be provided via an Excel sheet. The hand can be switched by mirroring with a simple click of a toggle switch in Grasshopper. This will help solve the problem of the lack of available dimensions in either kind of amputees (left or right-handed).

Although a rigorous cost model for this design has not been developed, the cost of a prosthetic hand weighing about 40 grams and printed using PLA would be about 1 USD. The price would vary depending on the size of the hand and as well as other associated costs like labor cost, energy cost, 3D printer cost, and so on.

CHAPTER 5: CONCLUSION

In conclusion, this thesis addresses some of the problems that prosthetic users face in developing regions such as the lack of affordable prostheses, a passive cosmetic prosthesis for lightweight activities, and social interactions. The objectives of this thesis have been met by demonstrating the feasibility of a parametric 3D prosthetic hand model developed using anthropometric features and fabricated using 3D printing. Furthermore, using a Python script the 3D model can be generated efficiently based on the features extracted from the patient hand scans. The fabricated prosthetic hand is tested for grasps. It has been able to perform 31 grasps out of the 33 that the human hand can do. This is the greatest number of grasps reported for any upper limb prostheses in the literature.

In the future, the parametric modeling approach can be extended to include the forearm and the arm by determining the relations between the hand, forearm, and arm. Furthermore, this design approach can be extended to the body-powered and electric-powered prosthesis. Different materials can also be explored that have more desirable properties than PLA or ABS. Different designs and types of joints can be explored to increase the grasp forces and mobility of the design.

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