Faculty of Mechanical Technology and Engineering

PARAMETER OPTIMIZATION OF FUSED DEPOSITION MODELING PROCESS FOR 3D PRINTED PROSTHETIC SOCKET USING PCR-TOPSIS METHOD

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DECLARATION

I declare that this thesis entitled "Parameter Optimization of Fused Deposition Modeling Process for 3D Printed Prosthetic Socket Using PCR-TOPSIS Method" is the result of my own research except as cited in the references. The thesis has not been accepted for any Master of Science and is not concurrently submitted in candidature of any other Master of Science.

Signature : ....

Name : LIM GUO DONG

Date : 5th December 2023

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : ....

Supervisor Name : PROF. MADYA DR. MOHD JUZAILA BIN ABD LATIF

Date : 5^{th} December 2023

DEDICATION

I dedicate this thesis to my cherished parents and family for their never-ending love and support. This is also dedicated to my honorable supervisor for his mentorship throughout my study, as well as to the examiners, lecturers, and all my friends for their constant support over the years.

ABSTRACT

Prosthetic devices play a crucial role in the rehabilitation process of amputees while socket serves as the most critical component to ensure their success. However, the conventional fabrication process of prosthetic sockets is a labour-intensive and time-consuming process. The advancement of additive manufacturing (AM) in rapid development and its ability to create free-form geometry have posed the potential in revolutionizing traditional manufacturing industries. Fused deposition modeling (FDM) has been the most popular technique in AM technology used in socket fabrication. However, the strength of FDM products is influenced by a series of FDM printing parameters. Therefore, this study aims to investigate the optimum combination of FDM printing parameters in the development of transtibial prosthetic sockets. The study was initiated with the material selection while three FDM materials were investigated and their strength is compared to the conventional socket material, polypropylene (PP). Polylactic acid (PLA) was identified to be the most suitable material due to its highest performance index of 79.74 and has been employed for the subsequent parameter optimization study. A three-dimensional (3D) scanner was utilized to capture the digitized data of the amputee's stump and convert it into a stereolithography (STL) mesh model. The 3D model of the prosthetic socket was then constructed using the computer-aided-design (CAD) software and tested at different socket thicknesses to determine the appropriate thickness of the socket wall. Subsequently, the samples of the prosthetic sockets were prepared with an FDM printing machine and examined for their structural strength according to the ISO 10328 standard. Experimental data obtained were evaluated and the optimum printing parameter combination was determined through PCR-TOPSIS analysis. The optimum condition to fabricate the 3D printed socket was found to be the combination of 1.0 mm nozzle diameter, 0.48 mm layer thickness, and 30% infill percentage. Additionally, infill percentage is identified to be the most significant printing parameter followed by layer thickness and nozzle diameter.

PENGOPTIMUMAN PARAMETER PROSES PERMODELAN PENGENDAPAN TERLAKUR UNTUK SOKET PROSTETIK CETAKAN 3D MENGGUNAKAN KAEDAH PCR-TOPSIS

ABSTRAK

Peranti prostetik memainkan peranan penting dalam proses pemulihan orang yang diamputasi manakala soket berfungsi sebagai komponen paling kritikal untuk memastikan kejayaan mereka. Walau bagaimanapun, proses fabrikasi konvensional soket prostetik adalah proses yang intensif buruh dan memerlukan tempoh yang panjang. Kemajuan pembuatan bahan tambahan (AM) dalam pembangunan pesat dan keupayaannya untuk mencipta geometri bentuk bebas telah menunjukkan potensi dalam merevolusikan industri pembuatan tradisional. Permodelan pengendapan terlakur (FDM) telah menjadi teknik paling popular dalam teknologi AM yang digunakan dalam fabrikasi soket. Walau bagaimanapun, kekuatan produk FDM dipengaruhi oleh banyak parameter percetakan FDM. Oleh itu, kajian ini bertujuan untuk menyiasat kombinasi optimum parameter pencetakan FDM dalam penghasilan soket prostetik transtibial. Kajian ini dimulakan dengan pemilihan bahan manakala tiga bahan FDM telah dikaji dan kekuatannya dibandingkan dengan bahan soket konvensional, PP. PLA dikenal pasti sebagai bahan yang paling sesuai kerana indeks prestasi tertingginya iaitu 79.74 dan telah digunakan untuk kajian pengoptimuman parameter seterusnya. Pengimbas 3D telah digunakan untuk menangkap data digital tunggul amputasi dan menukarnya kepada model STL. Model soket prostetik seterusnya telah dibina menggunakan perisian CAD dan diuji pada ketebalan soket yang berbeza untuk menentukan ketebalan dinding soket yang sesuai. Selepas itu, soket prostetik telah dihasilkan menggunakan mesin pencetak FDM dan diperiksa kekuatan strukturnya mengikut piawaian ISO 10328. Data eksperimen yang diperolehi telah dinilai dan kombinasi parameter cetakan optimum telah ditentukan melalui analisis PCR-TOPSIS. Paratmeter optimum untuk membuat soket cetakan 3D didapati adalah gabungan diameter muncung 1.0 mm, ketebalan lapisan 0.48 mm, dan peratusan isian 30%. Selain itu, peratusan isian dikenal pasti sebagai parameter pencetakan paling pengaruhi diikuti oleh ketebalan lapisan dan diameter muncung.

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LIST OF ABBREVIATIONS

3D	-	Three Dimensional
ABS	-	Acrylonitrile Butadiene Styrene
AHP	-	Analytic Hierarchy Process
AM	-	Additive Manufacturing
ANN	-	Artificial Neural Networks
CAD	-	Computer-Aided Design
CAM	-	Computer-Aided Manufacturing
CF	-	Carbon Fiber
CNC	-	Computer Numerical Control
ELECTRE	-	Elimination and Choice Expressing the Reality
FDM	-	Fused Deposition Modeling
HST	-	Hydrostatic Design
ISO	-	International Organization for Standardization
LLA	-	Lower Limb Amputation
LMICs	-	Low and Middle-Income Countries
MCDM	-	Multiple Criteria Decision Making
PA	-	Polyamide
PE	-	Polyethylene
PCR	-	Process Capability Ratio

PETG	-	Polyethylene Terephthalate Glycol
PLA	-	Polylactic Acid
POP	-	Plaster of Paris
PTB	-	Patellar Tendon Bearing
PVA	-	Polyvinyl Alcohol
PVC	-	Polyvinyl Chloride
RSM	-	Response Surface Method
RSMM	-	Rapid Socket Manufacturing Machine
SMART	-	Simple Multi-Attribute Rating Technique
SNR	-	Signal Noise Ratio
STL	-	Stereolithography
TOPSIS	-	Technique for Order Preference by Similarity to Ideal Solution
TSB	-	Total Surface Weight Bearing
VIKOR	-	Multicriteria Optimization and Compromise Solution
WHO	-	World Health Organization
WPIM	-	Weighted Property Index Method

LIST OF PUBLICATIONS

1. **Lim, G. D.**, Abd Latif, M. J., Alkahari, M. R., Yob, M. S., Thapliyal, S., and Threemurty, L. R., 2020. Optimization of Tensile Strength and Processing Time Using PCR-Topsis Method for FDM Process. *Journal of Advanced Manufacturing Technology* (JAMT), 14(3), pp. 67-80.

2. **Lim, G. D.**, Abd Latif, M. J., Alkahari, M. R., Yob, M. S., Musa, M., Rahman, M. N., and Theemurty, L. R., 2022. Parameter Optimization of Fused Deposition Modeling Process for 3D Printed Prosthetic Socket using PCR-TOPSIS Method. *International Journal of Nanoelectronics & Materials*, 15, pp. 247-258.

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CHAPTER 1

INTRODUCTION

1.1 Background

Amputation may result in negative impacts on the general health, vitality, social function, and physical role performance of amputees compared to the general population (Mahdi et al., 2016). World Health Organization (WHO) estimates that 0.5% of the population of a developing country is suffering from a certain form of disability which may require a prosthetic or orthotic device and related rehabilitation services. Recently, there is only five to fifteen percent of people with amputations have access to rehabilitation technology, especially in low and middle-income countries (LMICs) (Arifin et al., 2017). Amputation can be categorized into two main divisions which are upper limb and lower limb amputation (LLA). However, LLA occupied the highest prevalence which accounts for 84% (Rahman, 2017).

Following amputations, rehabilitation is carried out to recover the daily life activities of amputees by regaining their functional mobility and reducing their dependency on others (Ülger et al., 2018). An individual with LLA is prescribed a prosthesis during the rehabilitation process to regain mobility. It is acknowledged that a successful rehabilitation outcome requires the provision of high-quality and efficient prosthetics services. A well-working prosthesis may increase a user's quality of life, satisfaction, chances for education and employment, and social acceptance (Arifin et al., 2017).

The prosthetic is part of the bio-mechatronics field which is the science of using mechanical devices with human muscle, skeleton, and nervous systems to assist or enhance motor control. Technically, a lower limb prosthetic device consists of but is not limited to a socket, pylon, and artificial foot as shown in Figure 1.1 (Jawaid et al., 2017; Nurhanisah et al., 2019). The socket is considered the most important component of the lower limb prosthetic device, which constitutes the critical interface between the amputee’s stump and prosthesis (Laing et al., 2011, 2017). Nevertheless, the prosthetic socket fabrication process is customized to fit the individual shape of the amputee’s residual limb (Yusof et al., 2019).

Figure 1.1: Components of a lower limb prosthesis (Nurhanisah et al., 2019)

Prosthetics have been used for at least 3500 years, but prosthetic technology remained relatively stagnant until the nineteenth century (Keszler et al., 2019). The conventional procedure for creating a prosthetic socket involves either placing layers of woven materials combined with acrylic resins over the positive mold or draping a heated thermoplastic sheet over the positive mold. It typically requires two to three days to complete this labor-intensive process for one socket (Ng et al., 2002). Advancement in the area of prosthetics has greatly accelerated during the past few decades due to the introduction of new technology such as additive manufacturing (AM) (Keszler et al., 2019).

AM is a technique where objects are made by fusing or depositing materials in layers. The AM process has a wide range of applications such as 3D printed prostheses, developing medical devices, transplantation of tissues and organs, surgical planning models, and surgical guides for dental implants (Fadhil et al., 2017; Kate et al., 2017; Tunchel et al., 2016; Werz et al., 2018; Zuniga et al., 2015). Among all AM techniques available, fused deposition modeling (FDM) is the most widely applied AM technique in prosthetic socket fabrication due to its simplicity of the process, low cost, and customization ability (Neethan et al., 2019). FDM provides a great opportunity to improve efficiency and simplify the conventional prosthetic manufacturing process. The labor and costs involved may be greatly reduced, while amputees may acquire their prosthetic devices in a shorter period. This can especially be a significant benefit for amputees who need to change their prostheses quite often due to their growth (Kate et al., 2017).

Much research has investigated the application of FDM in the fabrication of lower limb prosthetic sockets to focus on the strength and safety of the socket. Nevertheless, the strength of the FDM product is not only influenced by the material but also the parameter setting of the FDM process (Górski et al., 2021; Nickel et al., 2020; Owen and Desjardins, 2020; Stewart, 2020). There is a lot of FDM parameter setting which may affect the FDM product strength which included nozzle diameter, infill percentage, layer thickness, and other as shown in Figure 1.2 (Dey et al., 2019; Pandzic et al., 2019). These parameters not only affect the strength of the FDM product but also the processing time. Thus, optimization of the FDM parameters is crucial to achieving maximum efficiency.

Figure 1.2: Parameters that influence on strength of FDM fabricated product (Pandzic et al., 2019)

AM technology has been recently explored by researchers in the fabrication of prosthetic devices, especially prosthetic sockets (Górski et al., 2021; Owen and Desjardins, 2020; Stewart, 2020; van der Stelt et al., 2022). The conventional prosthetic socket fabrication method involves several independent steps and the total process is time-consuming and labor-intensive. Moreover, all processes have to be repeated if socket fit is inappropriate and a lot of material required for fitting and production process is eventually discarded. Even with the utilization of computer aided design (CAD) and computer-aided manufacturing (CAM) techniques, the positive mold of the amputee stump is either thrown away or may require additional space to be stored at a central fabrication facility (Owen and Desjardins, 2020). The application of AM technology may greatly reduce these problems as little waste is generated since positive mold does not have to be created and the amputee stump information was stored in digital data. Nevertheless, the reliability and sustainability of 3D printed prostheses are the main concern prior to their application on amputees.

1.2 Problem Statement

The prevalence of LLA is high across the globe and continues to be a major threat to morbidity and mortality. According to scientific research, diabetes mellitus is a major risk factor for LLA (Hoffstad et al., 2015; Hussain et al., 2019; Yusof et al., 2019). In fact, in 2005, it was estimated that a lower limb was amputated due to diabetes every 30 seconds somewhere in the globe (Arifin et al., 2017). The rehabilitation of amputees following LLA poses a growing socioeconomic challenge and the provision of affordable and high-quality prosthetic service is critical for their rehabilitation process (Arifin et al., 2017; Dickinson et al., 2017). However, facilities to fabricate prostheses are generally far from the recipients' places and the selling price of a prosthesis is too expensive, especially for those from lower-income families (van der Stelt et al., 2021). According to the International Society for Prosthetics and Orthotics, the clinical community intended to improve evidence-based practice, and there is a need for new technology in prosthetic limb componentry and its provision (Dickinson et al., 2017).

From the vantage point of lower limb amputees, the socket is the most important component of the prosthesis, and its primary mechanical function is to support the load bearing from the residual limb (Stewart, 2020). Generally, the prosthetic socket is fabricated manually from a positive plaster cast of the amputee's residual limb. This process has some disadvantages such as being labor-intensive, time-consuming, and highly dependent on the skills and experience of the prosthetist involved (van der Stelt et al., 2021, 2022; Wang et al., 2020). Besides, both the wrap cast and mold are destroyed during the process which makes the process unrepeatable and results in material wastage (van der Stelt et al., 2022; Wang et al., 2020).

AM technology showed great potential to provide substantial benefits over the conventional prosthetic socket fabrication process. AM technology requires minimum human intervention and operator skills, which is curial in the medical profession. Also, the AM product is precisely consistent and the overall process generally takes less processing time. AM is a perfect technique for automated socket fabrication due to its ability to produce free-form surfaces and hidden features (Ng et al., 2002).

AM has the potential to provide substantial benefits compared to conventional socket production. AM inherently reduces the overall processing time and ensures precise consistency. It requires minimal operator skill and human intervention, making it particularly crucial in the medical field. The ability to create free-form surfaces and hidden features makes AM an ideal technology for automated socket fabrication (Ng et al., 2002). FDM is an effective AM method to produce 3D printed prosthetic sockets because it provides promising possibilities to produce complex geometries and personalized designs combined with the ease of manufacturing. However, FDM is a time-consuming production process and the strength of FDM-printed prosthetic sockets is still in doubt (Kate et al., 2017). Hence, the strength of 3D printed prosthetic sockets using FDM must be improved, and the manufacturing time must be significantly reduced (Ng et al., 2002).

Several factors including filament properties, extruder path planning, STL file resolution, and process parameters are responsible for FDM part quality degradation (Dey et al., 2019). The FDM process is manipulated by a series of process parameters such as infill percentage, layer thickness, and nozzle diameter, while each parameter influence on the strength and fabrication time of FDM products. As such, achieving an optimal combination of process parameters is very challenging due to the nature of the FDM process and the interplay among various parameters (Dey et al., 2019). Furthermore, FDM involves