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Optimization of Manufacturing Parameters for Below Knee Prosthetic Sockets Based on 3D Printing Using the Taguchi Method

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Abstract

Fused Deposition Modeling (FDM) technology is widely applied in the fabrication of transtibial prosthetic sockets due to its operational simplicity and high design flexibility. However, prolonged printing time remains a major constraint in improving production efficiency for clinical and industrial applications. This study aims to optimize the printing time of transtibial prosthetic sockets by adjusting three process parameters: socket wall thickness (1, 2, and 3 mm), thermoplastic filament type (PLA, ABS, and PP), and nozzle diameter (0.4 mm, 0.6 mm, and 0.8 mm). The Taguchi method with an L9 orthogonal array was employed as the experimental design. All specimens were fabricated using a Flashforge Guider II Series printer, and the printing time was evaluated using the Signal to Noise (S/N) ratio with the "smaller is better" criterion and analysis of variance (ANOVA) at a significance level of α = 0.05. The results indicate that nozzle diameter has the most significant effect on printing time, contributing 55.40%, followed by wall thickness at 39.51%, while material type contributes only 1.24% and is not statistically significant. The optimal parameter combination 1 mm wall thickness, PLA filament, and a 0.8 mm nozzle diameter reduced the average printing time by 24%, with a coefficient of variation below 5%. Confirmation tests yielded a validation S/N ratio of −64.58 dB, confirming the stability of the printing process. These findings provide practical guidance for accelerating the production rate of FDM based prosthetic sockets and suggest further research focusing on mechanical performance evaluation, infill pattern variation, and multi objective optimization.

Keywords: *FDM; molding time optimization; orthogonal array; prosthetic socket; taguchi*

Abstrak

Teknologi *Fused Deposition Modeling* (FDM) merupakan salah satu metode manufaktur aditif yang banyak digunakan dalam pembuatan soket prostetik transtibial karena kemudahan operasional serta fleksibilitas desain yang tinggi. Namun demikian, waktu pencetakan yang relatif lama masih menjadi kendala utama dalam peningkatan efisiensi produksi, khususnya untuk aplikasi klinis dan industri. Penelitian ini bertujuan untuk mengoptimalkan waktu pencetakan soket prostetik transtibial melalui pengaturan tiga parameter proses, yaitu ketebalan dinding soket (1, 2, dan 3 mm), jenis filamen termoplastik (PLA, ABS, dan PP), serta diameter nosel (0,4 mm, 0,6 mm, dan 0,8 mm). Metode Taguchi dengan susunan ortogonal L9 digunakan sebagai desain eksperimen. Seluruh spesimen dicetak menggunakan printer *Flashforge Guider* II *Series*, kemudian waktu pencetakan dianalisis menggunakan rasio *Signal to Noise* (S/N) dengan kriteria "lebih kecil lebih baik" serta analisis varians (ANOVA) pada tingkat signifikansi α = 0,05. Hasil analisis menunjukkan bahwa diameter nosel memberikan pengaruh paling dominan terhadap waktu pencetakan dengan kontribusi sebesar 55,40%, diikuti oleh ketebalan dinding sebesar 39,51%, sedangkan jenis material hanya memberikan kontribusi sebesar 1,24% dan tidak signifikan secara statistik. Kombinasi parameter optimal, yaitu ketebalan dinding 1 mm, filamen PLA, dan diameter nosel 0,8 mm, mampu menurunkan waktu pencetakan rata rata sebesar 24% dengan koefisien variasi kurang dari 5%. Uji konfirmasi menghasilkan nilai rasio S/N sebesar −64,58 dB yang mengindikasikan stabilitas proses pencetakan. Temuan ini diharapkan dapat menjadi acuan praktis dalam meningkatkan efisiensi produksi soket prostetik berbasis FDM serta menjadi dasar bagi penelitian lanjutan yang mencakup evaluasi sifat mekanik, variasi pola pengisian, dan optimasi multi objektif.

Keywords: FDM; optimasi waktu cetakan; o*rthogonal array*; soket prostetik; taguchi

1. Introduction

Additive Manufacturing (AM), also referred to as three dimensional (3D) printing, is a manufacturing technique based on a layer by layer fabrication approach that has experienced substantial development over the past two decades [1-2]. In contrast to conventional subtractive manufacturing methods, which involve the removal of material from a solid workpiece, AM fabricates components directly from digital models through the controlled addition of material. This approach not only reduces material waste but also enables the production of complex geometries that are challenging to achieve using traditional manufacturing techniques [3-4]. Among the various AM technologies, Fused Deposition Modeling (FDM) is one of the most widely adopted due to its relatively low equipment cost, broad availability of thermoplastic materials, and ease of operation at laboratory and small to medium industrial scales [5-6]. The FDM process involves heating a thermoplastic filament to a semi molten state and extruding it through a nozzle to deposit successive layers according to computer aided design (CAD) data until the final three dimensional structure is formed [7]. The advantages of FDM include extensive material compatibility, flexible adjustment of process parameters, and the capability to manufacture functional prototypes and end use components with adequate dimensional accuracy and competitive production times [8]. Furthermore, the application of FDM in the medical field, particularly in the fabrication of prosthetic components, has demonstrated significant potential for patient specific customization based on anthropometric data, thereby enhancing device fit, comfort, and mechanical performance.

In the healthcare sector, AM has introduced a transformative paradigm in the customization of medical devices by enabling the precise fabrication of prosthetic sockets tailored to the anatomical characteristics of individual patients. Prosthetic sockets constitute a critical interface that transfers mechanical loads between the residual limb and the prosthetic structure; consequently, their design and manufacturing processes must be based on accurate three dimensional anthropometric data to reduce localized pressure, optimize load distribution, and improve long term user comfort. Ngan et al. [9] reported that the implementation of digital workflows in orthotic and prosthetic practices significantly enhances production efficiency and dimensional accuracy in customized socket fabrication. In this context, the integration of three dimensional scanning technologies with computer aided engineering and manufacturing techniques facilitates improved personalization and repeatability in socket design. Furthermore, Stelt et al. [10] demonstrated that the production of transtibial prosthetic sockets using 3D printing technologies can be achieved at relatively low cost, thereby increasing accessibility, particularly in resource limited settings. This digital and additive approach also enables greater design consistency and geometric precision, which are essential for meeting the individualized functional and biomechanical requirements of prosthetic users.

A systematic investigation of transtibial prosthetic sockets conducted by Kim et al. [11] demonstrated that structural designs optimized through iterative mechanical testing can significantly enhance socket strength. In addition to geometric optimization, post processing techniques such as heat treatment (annealing) and the incorporation of reinforcing fibers have been reported to effectively improve the mechanical performance of materials commonly used in three dimensional printing. These findings emphasize the critical role of process parameter selection in AM applications. In particular, variations in prosthetic socket wall thickness have a direct influence on stress distribution and concentration at load bearing contact regions. Therefore, comprehensive analysis is required to ensure adequate structural integrity while avoiding unnecessary increases in material usage and production time [12].

In a related study, Nickel et al. [13] emonstrated that the application of AM in prosthetic fabrication enables the production of lightweight sockets that are precisely tailored to the geometry of the residual limb, while also facilitating real time monitoring and evaluation of socket performance. These findings are particularly significant, as non uniform pressure distribution at the socket limb interface has been identified as a primary factor contributing to soft tissue damage and the development of pressure related injuries in prosthetic users [14]. Consequently, patient specific customization enabled by AM not only improves socket comfort and fit but also holds substantial potential for enhancing long term user safety and overall health outcomes.

Although numerous studies have investigated the optimization of FDM process parameters including extrusion speed, layer thickness, nozzle temperature, and infill patterns to enhance surface quality, mechanical strength, and dimensional accuracy, research specifically addressing the influence of these parameters on printing time remains relatively limited. Optimization of printing time in the AM domain is of critical importance, as it directly affects production throughput and overall operational cost efficiency. Khan et al (2019) [15] demonstrates that by increasing printing speed, interlayer time can be minimized, enabling better thermal fusion and adhesion between layers. This study emphasizes the importance of proper parameter settings, such as printing speed and layer thickness, to achieve the desired time efficiency. Furthermore, Dev and Srivastava (2020) proposed several strategies to accelerate the FDM printing process through systematic adjustment of process parameters, demonstrating that such modifications can substantially influence both production time and the mechanical performance of the printed components. This approach is especially relevant for mass production oriented applications, such as the fabrication of prosthetic sockets, where efficiency, consistency, and mechanical reliability are essential.

The Design of Experiments (DoE) methodology provides a systematic and efficient framework for evaluating the effects of multiple input factors on one or more response variables while minimizing the number of experimental trials. Among the various DoE techniques, the Taguchi method is widely adopted in manufacturing research due to its use of orthogonal arrays, which enable a substantial reduction in experimental runs while facilitating the analysis of factor effects through the Signal to Noise (S/N) ratio. A preliminary study by Lestari et al. (2024) [17] combined the Taguchi method with Response Surface Methodology (RSM) to reduce the printing time and mass of prosthetic sockets; however, that study primarily focused on multi objective optimization and required more comprehensive investigation of individual factor contributions. To address this research gap, the present study investigates the influence of socket wall thickness, filament material type, and nozzle diameter on the printing time of prosthetic sockets fabricated using FDM. The specific objectives of this study are: (1) to evaluate the effect of socket wall thickness, filament material, and nozzle diameter on printing time; (2) to determine the optimal combination of process parameters using the Taguchi method with an L9 orthogonal array; and (3) to assess the statistical significance of the investigated factors through analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$. The novelty of this research lies in the focused optimization of FDM prosthetic socket printing time, which is specifically tailored to prosthetic socket manufacturing applications.

2. Materials and Methodology

2.1. Design of Prosthetic Sockets

The prosthetic socket was designed using SolidWorks 2020 CAD software. The design process began with the acquisition of geometric data from the residual limb of a transtibial amputee, which were reconstructed into a three dimensional model using photogrammetry. The prosthetic socket geometry used in this study was obtained from this photogrammetric model. The resulting socket design is shown in Figure 1

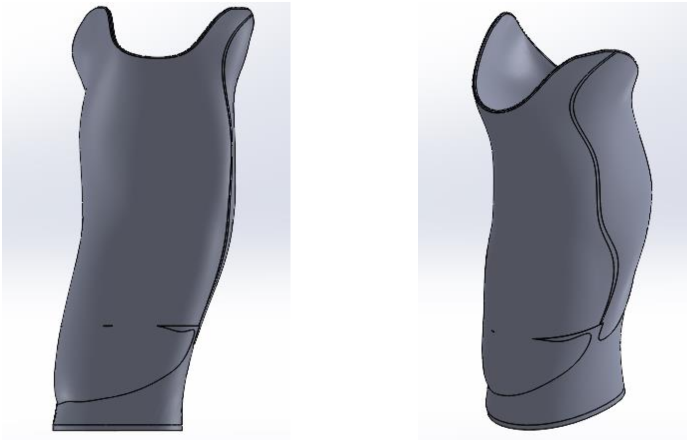

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Figure 1. Design of prosthetic sockets

2.2. Materials and Equipment

Prosthetic socket fabrication was carried out using a Flashforge Guider II FDM printer. Three types of thermoplastic filaments with a diameter of 1.75 mm polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polypropylene (PP) were employed to evaluate and compare printing performance. PLA was selected due to its ease of processing and capability to produce high geometric accuracy. ABS was utilized for its relatively high mechanical strength and impact resistance, which are suitable for functional prosthetic socket applications. PP was chosen for its favorable elasticity and chemical resistance, contributing to improved comfort and durability in regions of direct skin contact. The detailed material properties of the filaments and printer are presented in Tables 1–4, while the printing process parameters are summarized in Table 5.

Table 1. PLA Material Specifications [18]

PLA Material Specifications		
PLA Filament	**Description**	**Value**
	Density	1.2 g/cm3
	Tensile Strength	72 MPa
	Elongation at Break	11.80%
	Flexural strength	90 MPa
	Flexural Modulus	1915 MPa
	IZOD Impact Strength	5.4 kJ/m2

Table 2. ABS Material Specifications [19]

ABS Material Specifications		
ABS Filament	**Description**	**Value**
	Tensile Strenght	43.8 Mpa
	Elastic Limit	38.45 Mpa
	Young Modulus	1.47 Gpa
	Poisson Ratio	0.3
	Elongation at Break in	7.20%
	Stress at Break	29.58 Mpa

Table 3. PP Material Specifications [20]

PP Material Specifications		
PP Filament	**Description**	**Value**
	Density	0.95 g/cm3
	Yield Stress	32 Mpa
	Elongation at Break	70%
	Elongation at Yield	8%
	Tensile Modulus of Elasticity	1300 Mpa

Table 4. 3D Printing Machine Specifications

3D Printing Machine Specifications		
3D Printing Machine	**Description**	***Value***
	Nozzle Diameter	0.4, 0.6, 0.8 mm
	Max Extruder Temperature	300°C
	Max Platform Temperature	120°C
	Print Speed	10-200 mm/s
	Print Volume	280*250*300 mm
	Layer Thickness	0.1 - 0.4 mm
	Print Precision	± 0.2 mm
	Printer Dimension	550*490*570
	Power Supply	100 - 240 VAC, 47 - 63Hz, 24 V, 20.8 A, 500W
	Software	Flashprint
	Working Environment	18 - 30°C
	Noise	50 Db

2.3. Taguchi Experimental Design

This study employed the Taguchi method to evaluate the effects of three factors socket wall thickness, filament material, and nozzle diameter each at three levels, using an L9 (3^3) orthogonal array as shown in Table 6. This approach reduces the number of experiments while ensuring a balanced evaluation of all factor levels, thereby improving time and resource efficiency.

Table 5. Procces Parameters and Levels

Procces Parameters and Levels					
No	**Factors**	**Levels**			**Symbol**
		1	**2**	**3**	
1	Thickness (mm)	1	2	3	A
2	Material	PLA	ABS	PP	B
3	Nozzle diameter (mm)	0.4	0.6	0.8	C

Table 6. Orthogonal Array L_9 3^3 Design Matrix for Testing

Experiment Number	Variable		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 7. Orthogonal Array L_9 3^3 Design Matrix for Testing

Experiment Number	Variable		
	(A) Thickness (mm)	(B) Material	(C) Nozzle Diameter (mm)
1	1	PLA	0.4
2	1	ABS	0.6
3	1	PP	0.8
4	2	PLA	0.6
5	2	ABS	0.8
6	2	PP	0.4
7	3	PLA	0.8
8	3	ABS	0.4
9	3	PP	0.6

2.4. Parameter Optimization Procedure

The optimization process considered three factors socket wall thickness, filament material, and nozzle diameter each at three levels, and employed a Taguchi L9 (3^3) orthogonal array. Prosthetic sockets were printed using a Flashforge Guider II FDM printer, and the printing time was recorded. The results were analyzed using signal to noise (S/N) ratios with the *smaller is better* criterion and ANOVA to identify significant factors. The optimal parameter combination was validated through an additional printing experiment. The overall research procedure is illustrated in Figure 2.

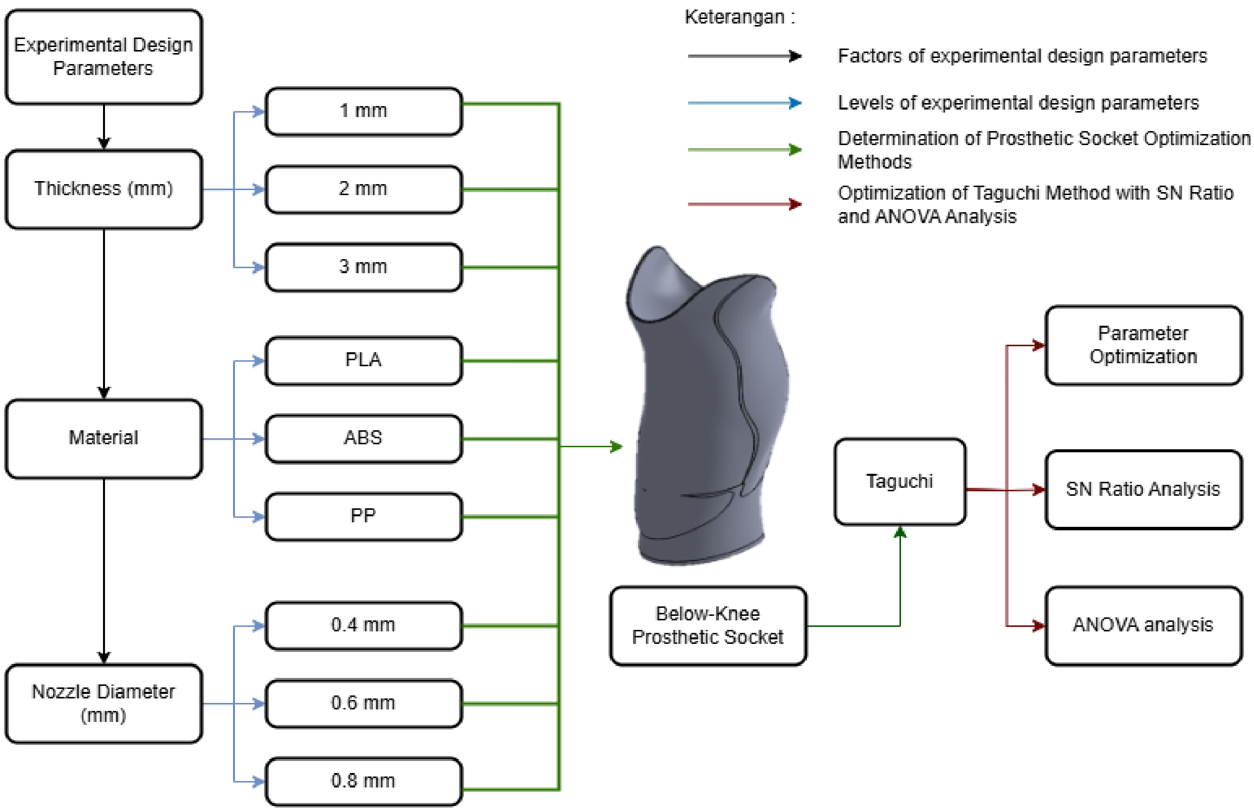

Figure 2. Schematic diagram of manufacturing parameter optimization for sockets

2.5. Data Analysis

2.5.1. Calculation of S/N Ratio Value

During the data analysis stage, the experimental results specifically printing time and prosthetic socket weight were analyzed using Minitab 2019 to calculate the signal to noise (S/N) ratio based on the *smaller is better* criterion. The S/N ratio was used to evaluate process stability against variability, where a lower S/N value indicates better performance. Accordingly, the parameter combination yielding the lowest S/N ratio was identified as the optimal condition. The *smaller is better* S/N ratio is defined in Equation (1).

$$\frac{S}{NR} = -10 \,.\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_1^2\right] \tag{1}$$

Where n is the number of repetitions and yi is the i-th observation (i = 1,2,3……,n)

2.5.2. ANOVA

The S/N ratio results were further evaluated using analysis of variance (ANOVA) at a significance level of α = 0.05 to determine the contribution of socket thickness, filament material, and nozzle diameter to variations in printing time. The S/N ratios are presented in Table 9, while the ANOVA results, including F values, p values, and percentage contributions, are summarized in Table 10. Factor influence was ranked based on delta values (the difference between the highest and lowest S/N ratios). The optimal parameter combination was selected according to the highest ranking and statistical significance and subsequently validated through an additional printing experiment to confirm result consistency.

2.5.3. Calculation of the Predicted Mean of the Optimal S/N Rasio

The average calculation of the predicted SN ratio is performed using Equation (2).

$$\boldsymbol{\mu_{prediction}} = \boldsymbol{y_m} + \sum_{i=1}^{n} (\boldsymbol{y_i} - \boldsymbol{y_m}) \quad (2)$$

Where y(m) is the overall average S/N ratio and y (i) is the average S/N ratio under normal conditions.

2.5.4. Confidence Interval Calculation

Confidence Interval Calculation is used for treatment conditions during experiments. Confidence Interval Calculation for optimal conditions can be calculated using the following Equation (3)-(4) [22-23].

For predictive observation :

$$\boldsymbol{CI_P} = \sqrt{\frac{F_{a:d_{f1}:d_{f2}}\ x\ MS_E}{n_{eff}}} \quad (3)$$

Where $F_{a:d_{f1}:d_{f2}}$ is the F ratio value from the table, α is the risk; confidence level = 1- risk,, d_{f1} s the degree of freedom of the factor, d_{f2} is the degree of freedom of the error, MSE is the mean square error, and neff is the number of effective observations.

$$\boldsymbol{n_{eff}} = \frac{\textbf{Total number of trials}}{\textbf{1+number of degrees of freedom}} \quad (4)$$

$$\mu_{prediction} - CI_k \leq \mu_{confirmation}\ CI_k \leq \mu_K + CI_p$$

3. Result and Discussions

The results of the FDM based prosthetic socket parameter optimization are presented in Table 8. Printing time data from nine experimental runs were analyzed using the signal to noise (S/N) ratio and analysis of variance (ANOVA). The combined results of these analyses were used to identify the optimal parameter settings, which were subsequently validated through repeated experiments to confirm printing time reduction and result consistency.

Table 8. Results of Prosthetic Socket Printing Response Time

Results of Prosthetic Socket Printing Response Time				
No	**Thickness (mm)**	**Material**	**Nozzle Diameter (mm)**	**Time (menit)**
1	1	PLA	0.4	2239
2	1	ABS	0.6	1954
3	1	PP	0.8	1696
4	2	PLA	0.6	2208
5	2	ABS	0.8	1764
6	2	PP	0.4	2542
7	3	PLA	0.8	2131

8	3	ABS	0.4	3221
9	3	PP	0.6	2530

3.1. S/N Ratio Analysis

The signal to noise (S/N) ratio analysis using the *smaller is better* criterion was conducted to evaluate the stability of printing time with respect to variations in each process factor. A larger delta (Δ) value defined as the difference between the maximum and minimum S/N ratios for a given factor indicates a stronger influence on printing time. The S/N ratio results for each factor level are presented in Table 9.

Table 9. Response Table Values for Signal to Noise Ratio for Printing Time

Response Table for Signal to Noise Ratios			
Smaller is better			
Level	**Thickness**	**Material**	**Nozzle Diameter**
1	-65.8	-66.97	-68.42
2	-66.64	-66.82	-66.92
3	-68.26	-66.92	-65.36
Delta	2.46	0.15	3.06
Rank	2	3	1

Based on Table 9, the nozzle diameter exhibits the highest delta (Δ) value of 3.06 dB, indicating that this factor has the most significant influence on reducing printing time. The optimal levels identified were level 1 for socket thickness (1 mm) with an S/N ratio of –65.80 dB, level 2 for filament material with –66.82 dB, and level 3 for nozzle diameter with –65.36 dB. The socket thickness factor ranked second with a Δ value of 2.46 dB, where a thickness of 1 mm provided the best S/N ratio compared to other levels. In contrast, the filament material factor showed a minimal Δ value of 0.15 dB, indicating a negligible effect on printing time within the studied range.

These findings are consistent with the results reported by Fagbolabun [24], who demonstrated that optimal process conditions can be identified through main effect plots of the S/N ratio using the Taguchi method, thereby validating its effectiveness for process parameter optimization. The optimal parameter combination for prosthetic socket printing is illustrated by the mean S/N ratio plot in Figure 4. Based on this plot, the parameters that minimize printing time are socket thickness at level 1 (1 mm), filament material at level 2 (PLA), and nozzle diameter at level 3 (0.8 mm).

The S/N ratio results in Table 9 and the mean S/N ratio plot in Figure 3 consistently demonstrate the relative dominance of the investigated process factors. The nozzle diameter exhibits the highest delta (Δ) value (3.06 dB), followed by socket thickness (2.46 dB), while filament material shows a negligible effect (0.15 dB). This trend is also evident in Figure 4, where the nozzle diameter curve displays the steepest slope, indicating a high sensitivity of printing time to nozzle variation. In contrast, the socket thickness curve shows a more gradual change, and the material curve remains nearly flat. These complementary numerical and graphical results confirm that optimization of printing time should primarily focus on nozzle diameter and socket wall thickness.

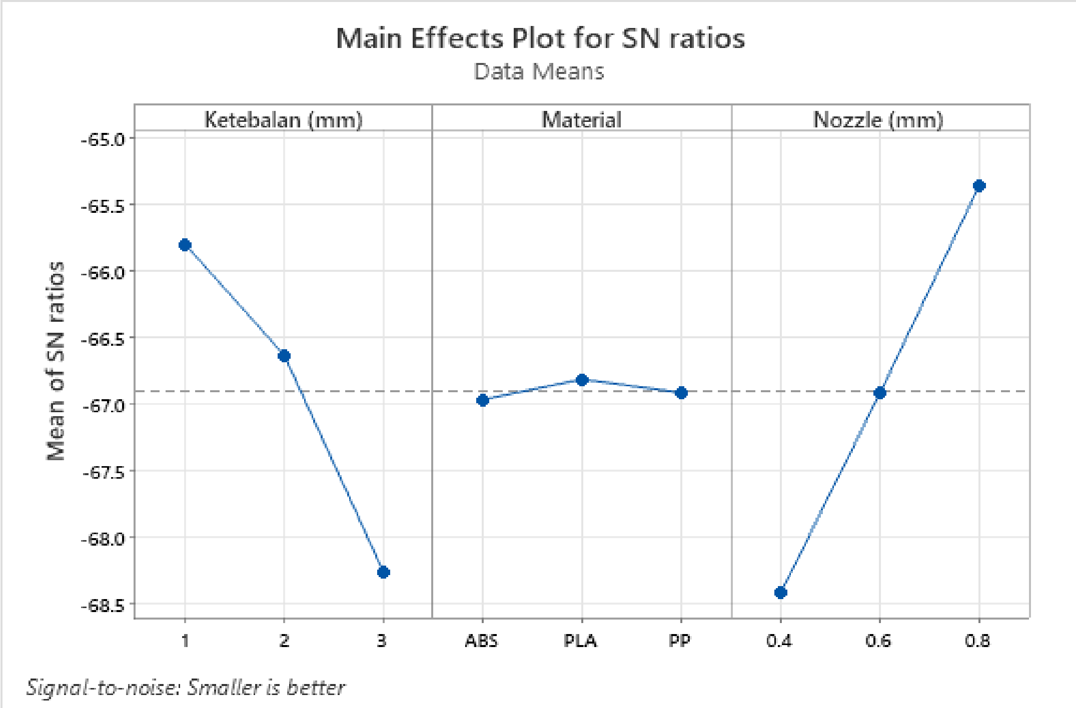

Figure 3. Graph of Mean SN Ratios

3.2. ANOVA Analysis

Analysis of variance (ANOVA) was conducted to quantify the contribution of each factor to variations in printing time, as summarized in Table 10. The results show that nozzle diameter is the dominant factor, contributing 55.40% of the total variation (F = 14.39; p = 0.065), followed by socket wall thickness with a contribution of 39.51% (F = 10.27; p = 0.089). Although the p-values for these factors are slightly above the conventional significance level of α = 0.05, they indicate a strong influence at a more relaxed criterion ($p < 0.10$). In contrast, filament material type contributes only 1.24% of the variation (F = 0.32; p = 0.756), indicating a negligible effect on printing time within the tested material range. The remaining 3.85% is attributed to experimental error. Overall, the ANOVA results confirm that optimization of printing time should primarily focus on adjusting nozzle diameter and socket wall thickness, while material selection may be guided by mechanical performance and user comfort considerations.

Table 10. Results of ANOVA (Analysis of Variance)

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Thickness	2	692678	39.51%	692678	346339	10.27	0.089
Material	2	21740	1.24%	21740	10870	0.32	0.756
Nozzle	2	971247	55.40%	971247	485623	14.39	0.065
Error	2	67478	3.85%	67478	33739		
Total	8	1753143	100.00%				

3.3. Prediction of Optimal Response

$$\mu_{prediction} = y_m + (A_1 - y_m) + (B_2 - y_m) + (C_3 - y_m) \quad (5)$$

$$\mu_{prediction} = (-66.9017164) + ((-65.8) - (66.9017164)) + ((-66.82) - (66.9017164)) + ((-65.36) - (66.9017164))$$

$$\mu_{prediction} = -64.1765$$

The confidence interval of the predicted S/N ratio using 95% CI can be calculated as follows:

$$n_{eff} = \frac{9\ x\ 3}{1 + (2\ x\ 3)} = \frac{27}{7} \quad (6)$$

$$CI_{confirmation} = \sqrt{\frac{19.00\ x\ 6.7478}{\frac{27}{7}}} = 5.7653 \quad (7)$$

So,

$(-64.1765) - 5.7653 \leq \mu_{prediction} \leq (-64.1765) + 5.7653$

$(-69.9418) \leq \mu_{prediction} \leq (-58.4112)$

3.4. Confirmation Experiment

To verify the reliability of the optimal parameters identified through the Taguchi analysis, a confirmation test was conducted by reprinting the prosthetic socket using a 1 mm wall thickness, PP filament, and a 0.8 mm nozzle diameter. Each experiment was repeated three times to record the printing time and calculate the average S/N ratio. The results of the confirmation test are presented in Table 11.

Tabel 11. Parameter Confirmation Experiment

Time Machining Confirmation Experiment				
Thickness (mm)	**Material**	**Nozzle Diameter (mm)**	**Time Machining (Minute)**	**S/N Ratio**
1	PP	0.8	1696	-64.58851696
1	PP	0.8	1696	-64.58851696
1	PP	0.8	1696	-64.58851696
	Mean		1696	-64.58851696

Based on the results of the confirmation experiment, the signal to noise (S/N) ratio was calculated and subsequently used to determine the 95% confidence interval for the mean S/N ratio of the confirmation test, as expressed below:

$$n_{eff} = \frac{9\ x\ 3}{1 + (2\ x\ 3)} = \frac{27}{7}$$

$$CI_{confirmation} = \sqrt{F_{a:d_{f1}:d_{f2}}\ x\ MS_E\ x\ \left[\frac{1}{n_{eff}} + \frac{1}{r}\right]}$$

$$CI_{confirmation} = \sqrt{19.00\ x\ 6.7478\ x\ \left[\frac{1}{\frac{27}{7}} + \frac{1}{3}\right]} = 6.0986$$

So,

$(-64.5885) - 6.0986 \leq \mu_{prediction} \leq (-64.5885) + 6.0986$

$(\mathbf{-70.6871}) \leq \boldsymbol{\mu_{prediction}} \leq (\mathbf{-58.4899})$

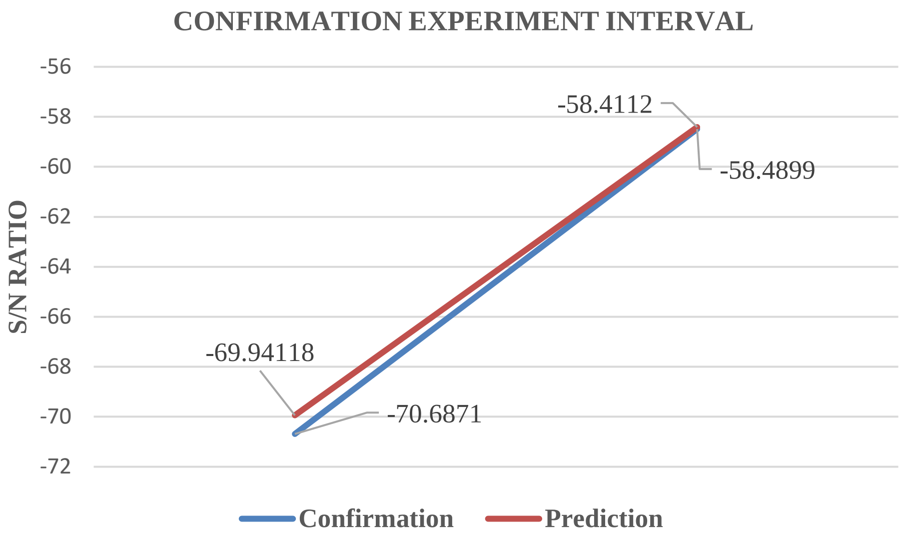

Figure 4. Confirmation experiment interval

4. Conclusion

This study successfully identified and validated the most influential FDM process parameters affecting the printing time of transtibial prosthetic sockets. The Taguchi analysis indicated that nozzle diameter is the dominant factor (55.40% contribution), followed by socket wall thickness (39.51%), while filament material type (PLA, ABS, and PP) has a negligible effect (1.24%). The optimal parameter combination 1 mm wall thickness, 0.8 mm nozzle diameter, and PP filament reduced the average printing time by 24% compared to the reference condition. The resulting S/N ratio (–64.58 dB) and a coefficient of variation below 5% confirm the stability and reliability of the optimized process. Repeated confirmation tests demonstrated that the optimized parameters consistently achieved significant reductions in printing time. These findings provide practical guidance for prosthetic socket manufacturing by improving production efficiency without compromising geometric accuracy or fundamental mechanical performance.

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