Parametric Analysis of 3D Printing Parameters on Stiffness and Hysteresis Characteristics of Paediatric Prosthetic Foot Coupon Samples

Abstract

Background: This research paper presents a comprehensive parametric study that investigates the influence of various 3D printing parameters on the mechanical properties of a paediatric prosthetic keel using coupon samples.

Objective: To analyse how 3D printing parameters impact upon on two crucial mechanical properties: stiffness and hysteresis.

Methods: Key 3D printing parameters including the amount of continuous carbon fibre layers, fibre distribution, and matrix fill pattern, are systematically varied, and mechanically tested through compression to analyse the results.

Results: The results demonstrate the substantial impact that printing parameters have on the mechanical characteristics of 3D printed paediatric prosthetic feet. Notably, the selection of these parameters for the prosthetic keel plays a pivotal role in shaping the overall performance and functionality of the prosthetic foot, emphasising the need for precise parameter optimisation in paediatric prosthetic design, if 3D printing is the manufacturing process.

Conclusion: The findings of this study contribute to a better understanding of the manufacturing process for paediatric prosthetic feet via 3D printing and offer valuable insights for optimising their design. By identifying the ideal combination of 3D printing parameters that yield the desired stiffness and minimise hysteresis, we aim to enhance the performance and comfort of paediatric prosthetic de-vices, ultimately improving the quality of life for young users.

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Keywords

Stiffness; Hysteresis; Composite 3D Printing; 3D Printing Parameters

Background

Paediatric prosthetic devices enhance children's mobility and quality of life [1]. 3D printing could revolutionise the prosthetic industry, offering cost-effective, customised, patient-specific solutions [2 3]. As these technologies advance, it's crucial to investigate how 3D printing parameters affect paediatric prosthetic component mechanics, focusing on stiffness and hysteresis [4]. Understanding these properties' dependence on printing parameters is vital for designing prosthetic feet offering optimal functionality and comfort to young users [5].

This research conducts a parametric study explaining the relationship between 3D printing parameters and the stiffness and hysteresis properties of paediatric prosthetic coupon samples. Hysteresis, a phenomenon where a system's response depends on past states, is a focus [6]. This study addresses the need for a deeper understanding of how printing parameters affect paediatric prosthetic components' performance. Achieving the right balance of stiffness and minimal hysteresis is essential to provide necessary support and energy-efficient mobility for growing children [1 7]. ESR feet store energy when loaded by deforming elastic components and release the energy during late stance, which provides ankle push-off to move the body forward [8].

State-of-the-art 3D printed prosthetic research emphasises customisation, material improvements, and overall comfort [9 10]. A significant gap remains in understanding how 3D printing parameters affect mechanical behaviour, particularly for paediatric users. Existing research mainly concentrate on adult prosthetics, ignoring the unique needs of paediatric users [1], this is due to the limited market size which presents a challenge to the cost of development and production [1].

The primary aim is to identify how each 3D printing parameter impacts stiffness and hysteresis in paediatric prosthetic foot coupon samples. Analysing the influence of individual parameters allows for further investigations to find the optimal parameter combinations. This can be tested in full-scale paediatric prosthetic prototypes to determine if composite 3D printing can produce dynamic response prosthetic feet meeting paediatric users' specific requirements.

Methods

Study Design

The methodology used systematically examines the effects of 3D printing parameters on stiffness and hysteresis properties of coupon samples. Computer-aided design (CAD) modelling, 3D printing, mechanical testing, digital image correlation, and microscopy analysis were combined to understand how specific printing parameters affect paediatric prosthetic components.

Parameter Selection

A literature review identified relevant 3D printing parameters, including walls, infill patterns, and fibre distribution, which could influence stiffness and hysteresis. The review also assessed studies on paediatric prosthetic devices, 3D printing materials, and mechanical testing methods [1 11-13]. The parameters under investigation include:

1. Force applied;
2. Number of fibre layers;
3. Fibre distribution pattern;

4. Fibre fill orientation;
5. Matrix fill pattern;
6. Number of walls.

Force applied directly impacts the coupon sample's mechanical response. The number of fibre layers influences structural integrity and strength. Carbon fibre distribution affects structural reinforcement. Investigating distribution patterns reveals how fibre orientation impacts stiffness and hysteresis, contributing to understanding efficiency and load-bearing behaviour. The arrangement and density of carbon fibre in each layer influence material properties. The distribution and density of the matrix material, influence overall mechanical properties.

Table 1 presents the parameters used for the control sample. Mechanical tests were conducted for each parameter under investigation, with one test per specimen. The printing parameters were varied relating to the specific parameter being studied, while keeping all other parameters the same as the control sample (Table 2). The parameters investigated encompass a range of factors that can influence the stiffness and hysteresis properties of 3D printed paediatric prosthetic feet. The chosen forces follow the ISO 10328 testing procedure for safety levels adapted from adult testing.

[Insert Table 1]

[Insert Table 2]

Data Acquisition and CAD Modeling

An Össur Vari-Flex Junior (Össur, Reykjavík, Iceland), size 19, was measured using an Axiom too (Aberlink Ltd., Gloucestershire, UK) Coordinate Measuring Machine (CMM) (last calibration January 2023). This foot was chosen for the research as it provides comfort, dynamics and good energy response [14], which are the properties this research is trying to achieve through 3D printing as the manufacturing process. Precise measurements of the foot's dimensions, contours, and structural features were imported into SolidWorks (Dassault Systèmes, Massachusetts), CAD software. A detailed CAD model of the foot was created, preserving its geometry and structural characteristics. A specific section of the CAD model representing key components of the foot, including the profile of the arc and the toe height, was chosen for coupon sample generation. This section was isolated and used as the basis for creating coupon samples. Coupon samples were used over the entire prosthetic keel geometry for a more cost-effective, time-efficient, and controlled approach to isolate and study specific material properties and structural characteristics, reducing complexity and resource requirements compared to replicating the entire prosthetic keel. Coupon geometry and test setup can be seen in Figure 1.

[Insert Figure 1]

Slicing and 3D Printing

Eiger software (Markforged Inc., Massachusetts) was used to prepare the printing files geometries. Eiger employs advanced slicing algorithms to convert 3D CAD models into a series of 2D layers (toolpaths) for the 3D printer to follow. The software ensured precise slicing of coupons, allowing control over parameters influencing final mechanical properties. Coupon samples were manufactured using a Markforged Mark Two 3D printer (Markforged Inc., Massachusetts) with Onyx and continuous strand carbon fibre materials. Markforged Onyx material is a micro carbon fibre-filled nylon [15].

Mechanical Testing

Compression tests were undertaken using a Zwick Roell Z030 (ZwickRoell Ltd, Worcestershire, UK) testing machine (last calibration June 2022). The ISO 10328 testing procedure [16] was used and adapted for a paediatric user of 24kg max weight, the maximum weight specified for the Vari-Flex Junior Size 19, category 1. Dantec Dynamic digital image correlation (DIC) (Dantec Dynamics, Denmark) system measured displacement and deformation during compression testing. High-resolution cameras captured images, and DIC software analysed them for displacement data using a speckle pattern. DIC combined with compression testing provided detailed understanding of mechanical behaviours. Force-displacement data from the tests, along with DIC measurements, were used to calculate stiffness (based on Hooke's law) and efficiency (based on hysteresis) properties of each sample. Stiffness (k) and efficiency (e) were defined as:

$$k = \frac{F}{x}$$

$$e = \frac{U_{unloading}}{U_{loading}} \times 100\%$$

Where F is the compressive force measured by the load cell, x is the displacement, and $U_{loading}$ and $U_{unloading}$ are the work done during the loading (compressive) and unloading (rebound) cycles, respectively. The work U between two points 1 and 2 is more generally defined as:

$$U = \int_1^2 F dx$$

$U_{loading}$ and $U_{unloading}$ can be determined from the plot of the force F *vs* the displacement x as the areas under the loading and unloading cycle curves, respectively, using numerical methods, for example, the trapezoidal rule.

Microscopy

Microscopy analysis with a Keyence VHX-5000 digital microscope (Keyence Ltd., Milton Keynes, UK) aimed to investigate the internal structure of the samples. This analysis sought to identify voids, fibre-matrix interface, delamination, and internal defects resulting from the printing process that could influence coupon mechanical behaviour. All samples were consistently sectioned through the curve of the coupon using a surface table, jig, and height gauge to ensure precise slice location.

Results

The outcomes of the investigations on the samples highlight the complex relationship between various 3D printing parameters and the mechanical behaviour of these critical components. The stiffness values are calculated between 0.5 and 2 mm of displacement to ensure results within the materials linear response, consistency, and to remove any errors associated with slippage.

Force/Displacement Curves

Figure 2 presents the force/displacement curves for the variations in the six parameters detailed in Table 2.

[Insert Figure 2]

Stiffness and Efficiency Results

Table 3 presents the resulting stiffness's and efficiencies calculated from the hysteresis values for each coupon sample for the variations in the six parameters detailed in Table 2.

[Insert Table 3]

The results demonstrate the influence of varying force levels on stiffness and hysteresis, providing insights into load-bearing capacity and energy dissipation characteristics. Different fibre layer quantities affect stiffness and hysteresis, guiding fibre reinforcement optimisation. Various fibre fill orientations impact stiffness and hysteresis, informing optimal reinforcement configurations. Examination of matrix fill patterns shows their contribution to stiffness and hysteresis, aiding material selection and component design. Varying walls influence stiffness and hysteresis, guiding build parameter optimisation.

Discussion

Force Applied

The observed reduction in efficiency with increased applied force during compression testing is expected. Despite variations in applied force, the difference in stiffness values among the coupons in this set of testing remained minimal, with less than 5% difference. These findings suggest higher forces lead to more significant deformation in the coupons, causing changes in their internal structure and resulting in lower energy storage properties. Microscopy results, Figure 3, confirm the substantial deformation experienced by samples subjected to higher forces. These samples exhibit features such as increased carbon fibre pull-out, ripping of the internal structure, and larger internal voids, indicating the material's inability to maintain structural integrity under extreme loads. This underscores the importance of optimising design and material properties to enhance mechanical performance and deformation resistance, as well as setting appropriate weight categories for users.

[Insert Figure 3]

Number of Fibre Layers

The number of fibre layers within the coupon emerges as the parameters with the most substantial impact on both efficiency and stiffness. The findings reveal an efficiency range, spanning from 58% for the coupon with no fibre layers to 91% efficiency with

120 fibre layers. This increase in efficiency underscores the pivotal role of fibre layers in optimising the energy storage and return capabilities.

The influence of the number of fibre layers on stiffness is substantial. The coupon with 40 fibre layers exhibited a stiffness of 59.99 N/mm, while the coupon with 120 layers demonstrated considerably higher stiffness at 106.13 N/mm. This increase in stiffness directly correlates with the number of fibre layers, affirming that fibre quantity influences the coupons mechanical properties. These results are consistent with others investigating the influence of fibre volume fraction [17 18].

These observations can be attributed to the reinforcing effect of continuous carbon fibres. As the number of fibre layers' increases, so does the structural integrity of the material, resulting in enhanced stiffness and a more efficient energy storage and release mechanism. This can be attributed to the mechanical characteristics of both the fibre and matrix materials. Carbon fibres, known for their non-viscoelastic properties, exhibit minimal hysteresis, evidenced in the findings presented. As the quantity of fibres is increased, resulting in an increased fractional volume of fibres and a reduced fractional volume of matrix material, hysteresis decreases.

By strategically adjusting the number of fibre layers in the keel's design, it becomes feasible to tailor the prosthetics' mechanical behaviour to meet unique demands of paediatric users. This optimisation process can lead to the development of prosthetic keels offering superior energy return efficiency.

Fibre Distribution Pattern

The arrangement of carbon fibre, specifically the choice between uniform spacing (one fibre layer at a time sandwiched between matrix) and grouped placement (multiple layers of fibre together sandwiched between the matrix), yielded intriguing insights into the efficiency and stiffness of the coupons. Specimens adopting the uniform spacing exhibited improved efficiency and higher stiffness compared to their counterparts with grouped carbon fibre layers.

An explanation for this outcome is the role of layer bonding within the composite material. The uniform spacing promotes distribution of individual fibre layers throughout the specimen, with each layer encapsulated by matrix material on both sides. This arrangement enhances the interlayer bonding between carbon fibres and the matrix, resulting in improved load transmission, efficiency, and energy storage capabilities. Whereas, the grouped placement, exhibits weaker interlayer bonding between adjacent carbon fibre layers, leading to less efficient energy transfer. The microscopy results provide supporting evidence of this superior interlayer bonding. Under examination, it becomes evident that the interfaces between individual carbon fibre layers and the surrounding matrix material exhibit minimal voids, fractures, or delamination, signifying strong adhesion. Whereas, the interfaces between adjacent carbon fibre layers often display signs of discontinuities, such as micro-cracks and separation, indicative of weaker interlayer bonding.

These findings suggest that a design strategy emphasising uniform spacing of individual carbon fibre layers between matrix layers can enhance the performance and efficiency of the prosthetic component.

Fibre Fill Orientation

The orientation of fibre material within the samples, Figure 4, has emerged as a critical factor impacting efficiency and stiffness. Isotropic fill from Markforged routes fibre back and forth in a zig-zag pattern to simulate the individual unidirectional layers of a traditional laminated composite. Subsequent iso-tropic fibre layers rotate the fibres to achieve unidirectional strength within a fibre group [19]. The research findings revealed distinct trends in efficiency, with isotropic fill at 45 degrees showcasing the highest efficiency at 73%, owing to the continuous distribution of carbon fibre layers along the curve of the coupon. In contrast, isotropic fill at 0 degrees displayed the lowest efficiency at 67%, primarily due to the vertical distribution of carbon fibre layers, which stopped prematurely due to spatial constraints.

The concentric pattern, characterised by two loops, the outer of which runs the length of the part with the inner loop running to the middle of the curve, exhibited an efficiency of 69%. Surprisingly, the isotropic fill at 0 degrees and 45 degrees on alternate layers demonstrated an efficiency of 72%, despite the inclusion of layers oriented at 0 degrees, which typically exhibited lower stiffness.

The observed efficiency variations can be attributed to the orientation of carbon fibre layers, influencing the load distribution and energy storage capacity. The continuous distribution of fibres at 45 degrees maximises their utilisation throughout the sample, while the vertical arrangement at 0 degrees results in inefficient energy transmission. Variations in stiffness were minimal across samples, the lower stiffness observed in isotropic fill at 0 degrees aligns with the reduced efficiency, reflecting compromised load-bearing capacity.

These findings underscore the importance of strategically orienting carbon fibre layers to optimise energy storage and transfer. The preference for isotropic fill at 45 degrees due to its higher efficiency suggests its potential application in keel designs.

[Insert Figure 4]

Matrix Fill Pattern

The matrix fill pattern, Figure 5, yielded implications for both efficiency and stiffness. Solid fill offered the highest efficiency at 72% and stiffness at 59.99 N/mm. The rectangular fill pattern followed closely achieving 69% efficiency, and stiffness value of 61.31 N/mm, even though its infill density was less than solid at 92%. This suggests that while solid fill excels in these aspects, alternative patterns like rectangular fill can begin to approach its performance while conserving material, cost, and manufacture time. The solid infill pattern allows for more efficient load transfer throughout the structure. This results in improved load-bearing capacity and energy transmission, leading to higher efficiency. Rectangular fill, while denser than some other patterns, still has gaps or interruptions that hinder load transfer efficiency.

The triangular infill pattern exhibited signs of failure at 8.5 mm of travel and presented the lowest efficiency among all coupons tested, at 58%. Its lower stiffness value of 53.98 N/mm and infill percentage of 55% highlight the challenges in maintaining structural integrity with this pattern. Hexagonal infill, offering efficiency of 69% and stiffness of 55.57 N/mm with a 62% infill percentage, demonstrates its viability as a balance between material usage and mechanical performance. Similarly, the gyroid fill pattern, while exhibiting slightly reduced efficiency at 64% and stiffness at 56.45N/mm, featured a relatively low infill percentage of 52% but required a longer print time.

The ability to achieve high efficiency and stiffness with variations such as solid and rectangular fill patterns while conserving material resources opens avenues for more sustainable and cost-effective designs. Careful consideration should be given to the trade-offs between efficiency, stiffness, and print time.

[Insert Figure 5]

Number of Walls

The number of walls within the samples has unveiled a trend where increased efficiency and higher stiffness are achieved with fewer walls. This finding can be attributed to a notable shift in the distribution of material and load-bearing elements. Samples with fewer walls allow for an expanded infill area at the centre of the coupon, facilitating a more efficient distribution of reinforcing fibre.

In single-wall sample, its one wall layer configuration permits a single loop of fibre reinforcement, accompanied by concentric and 45-degree infill patterns running twothirds of the curve. This configuration exhibits an efficiency of 73% and stiffness of 72.19 N/mm. Conversely, the sample with four wall layers exhibits lower efficiency at 59% and stiffness of 48.76 N/mm. This demonstrates the presence of excessive walls hinders the infill area, limiting the capacity for fibre reinforcement.

The reduction of walls, strategically balanced with the required structural integrity, can lead to more efficient and stiffer prosthetic components. This approach can result in paediatric keels that offer superior energy return for young users. These results demonstrate the significance of material distribution and infill design in tailoring the mechanical properties of paediatric prosthetic components.

Conclusion

This research highlights profound influences of 3D printing parameters on the stiffness, efficiency, and design of paediatric prosthetic components. The systematic investigation of parameters has provided valuable insights into the intricacies of composite 3D printing and its implications for paediatric prosthetic engineering.

The findings underscore the critical importance of parameter optimisation in tailoring mechanical properties of paediatric prosthetic keels. Force applied during testing was revealed to have a direct impact on load-bearing capacity and energy dissipation, offering avenues for precise customisation. The number of fibre layers emerged as a pivotal factor, with uniform spacing enhancing efficiency and stiffness. Additionally, matrix fill patterns played a crucial role, highlighting advantages of solid fill in achieving higher efficiency and stiffness. These discoveries carry implications for the future development and design of paediatric prosthetic keels. The ability to fine-tune parameters during manufacture can lead to the creation of prosthetic components that offer superior energy return, structural integrity, and overall performance. By strategically selecting and adjusting these parameters, it becomes possible to provide young users with tailored prosthetic solutions that optimise their mobility, comfort, and quality of life. In conclusion, this research serves as a foundation for the ongoing evolution of paediatric prosthetic design and manufacturing, emphasising the pivotal role 3D printing can have in shaping the future of paediatric prosthetic engineering.

Future research should leverage the data generated in this study to forecast the optimal parameter configuration for a paediatric prosthetic keel. By employing advanced modelling techniques and data-driven algorithms, the optimum parameters can be extrapolated that maximise performance and efficiency. Future testing will ascertain whether the optimised parameters yield superior results, thus validating the data acquired in this research. Future research will also investigate the structural failure properties of paediatric prosthetics manufactured via 3D printing, to therefore understand their practical applications further.

One limitation is the relatively small sample size used. Although procedures were in place to ensure the accuracy and reliability of the results, a larger sample size could have further strengthened the validity of the findings.

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Figure Legend:

Figure 1	Coupon geometry and test setup

Figure 2	Force/displacement results
Figure 3	Microscopy Analysis
Figure 4	Fibre material orientations
Figure 5	Matrix fill patterns