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Topology Optimization and Structural Analysis of a 3D-Printed PETG Hand Orthosis for Upper Limb Support

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Abstract: *Phocomelia, a congenital condition causing limb malformations, hinders daily tasks. Traditional hand orthoses are heavy and poorly customized, reducing comfort. This study, "Topology Optimization of Hand Orthosis for Phocomelia Patients," develops a lightweight, patient-specific orthosis using topology optimization and finite element analysis (FEA) in SolidWorks 2024. Topology optimization reduced mass by 0% to 50% in 10% increments, producing six sample sets with three models each, 3D-printed in PETG for its strength (tensile strength: 53 MPa). FEA under a 100 N load at a 90-degree angle predicted stresses of 0.017–0.186 MPa, displacements of 0.0155–0.0361 mm, and strains of 0.00044–0.00184, identifying stress concentrations as material decreased. The 20% optimized design (87.5 g) balanced weight reduction with low stress (0.1479 MPa) and displacement (0.0208 mm), ensuring durability and comfort. This design enhances mobility and quality of life for phocomelia patients.*

Keywords: Phocomelia; Topology Optimization; Finite Element Analysis; PETG Material; Hand Orthosis

1. INTRODUCTION

About one in every 150,000 newborns worldwide is affected by phocomelia which causes missing or malformed limbs [1]. Because of this disorder, some people find it very difficult to grip, write or lift things [2]. There are cases where only upper or lower limbs are affected by phocomelia, but if all limbs are impacted, as in tetra-phocomelia, the need for useful solutions is greater. People with phocomelia depend on various assistive devices such as prosthetics and orthoses, to improve how they live and carry out daily activities. Even so, with generic sizes, heavy weight and no customization, traditional orthotics are seldom suitable for patients, resulting in discomfort and little use [3].

The limitations of conventional orthoses are well-documented, with studies indicating that their bulkiness and poor fit contribute to pressure sores, muscle fatigue, and restricted mobility among users. or example, standard hand orthoses, generally produced from stiff materials such as polypropylene or metal, can be quite heavy, posing a problem for people with limited upper limb strength [4]. Such devices can be inflexible when dealing with the different limb structures found in phocomelia patients, so they are not always effective during daily activities [5]. Since there is a pressing demand for better orthotics for patients, researchers are exploring inventive techniques in design and production thanks to additive manufacturing and computational methods. Three-dimensional (3D) printing helps create custom orthoses quickly, highlighting its potential as a good alternative to devices made for people in large batches.

This study leverages advanced computational techniques, specifically topology optimization and finite element analysis (FEA), to develop a lightweight, patient-specific hand orthosis using PETG (Polyethylene Terephthalate Glycol). Topology optimization, which gradually removes unnecessary material from a design, has been proven to make orthoses up to 50% lighter while still maintaining their strength [6].The integration of these techniques with 3D printing enables the creation of orthoses that are not only lighter but also stronger for their weight, addressing the shortcomings of traditional designs. Studies done before have shown that using these methods can reduce the weight of biomedical devices by 15–25%, making them more comfortable for patients and longer lasting [7].

The project focuses on designing a PETG hand orthosis that offers sufficient mechanical strength, a comfortable fit, and reduced weight, validated through computational analysis rather than experimental testing. The methodology employs SolidWorks 2024 to create and optimize the 3D model, targeting a 10% mass reduction per iteration up to 50%, with FEA conducted under a 100 N load to simulate daily use conditions. This approach is built on prior research at Universiti Teknologi MARA (UiTM) Shah Alam, which identified PETG as an optimal material for adaptive devices due to its balance of weight reduction, displacement performance, and mechanical properties [8]. By comparing the results with existing literature, this study aims to contribute to the development of innovative orthotic solutions, potentially leading to improved rehabilitation strategies for individuals with limb deformities. The successful implementation of these techniques could pave the way for cost-effective, ecologically sustainable orthoses, offering significant benefits for phocomelia patients and the broader field of biomedical engineering [9].

2. METHODOLOGY

To develop a lightweight, patient-specific hand orthosis for phocomelia patients, a hybrid approach integrating computational design and material science was employed. Using SolidWorks 2024, a 3D model was created based on upper limb anatomy, optimized through topology optimization to reduce mass while preserving structural integrity. Finite element analysis (FEA) was conducted to evaluate mechanical performance under simulated loads, ensuring the design's suitability for daily use. The methodology, combines 3D printing with PETG and computational analysis to achieve a balance of weight, strength, and comfort, addressing the limitations of traditional orthoses.

2.1 Computational Aided Design Modelling

CAD modelling was utilized to create the foundational 3D model of the hand orthosis, serving as the basis for subsequent topology optimization and finite element analysis (FEA). The CAD modelling involves designing a 3D model of hand orthosis based on the upper limb anatomy of phocomelia patients, specifically focusing on the socket design slot. The model incorporates geometric features such as strap slots and load-bearing surfaces, which are refined to support iterative optimization and FEA analysis of stress, strain, and displacement.

The purpose is to establish a precise, patient-specific digital representation that enables accurate topology optimization and mechanical performance evaluation. A well-designed CAD model ensures the orthosis fits the unique limb structure of phocomelia patients, addressing the discomfort and poor fit of traditional designs, while providing a platform for virtual testing to enhance functionality and comfort. The CAD modelling is performed using SolidWorks 2024, a robust computer-aided design software known for its advanced modelling and simulation capabilities, widely adopted in engineering design for biomedical applications.

The CAD modelling is conducted at the initial stage of the methodology, prior to topology optimization and FEA. This early phase establishes the baseline model, which is then iteratively refined through optimization and analyzed for performance, ensuring a structured design process before 3D printing. The process begins with sketching the orthosis's profile in SolidWorks 2024, based on anatomical data from phocomelia patients. The sketch is extruded into a 3D solid model, with features like strap slots and socket contours added using the software's parametric modelling tools as shown in Figure 1.

Fig. 1. 3D printed hand orthosis for upper limb [8]

2.2 Topology Optimization

Topology optimization was conducted to minimize material usage while maintaining the structural integrity of the hand orthosis, building on prior research at Universiti Teknologi MARA (UiTM) Shah Alam. A 3D model was developed in SolidWorks 2024, based on the upper limb anatomy of phocomelia patients, specifically targeting the socket design slot as described in Mazlan et al. [10]. The optimization process iteratively reduced mass by 10% increments, from 0% to 50%, generating six sample sets, each with three models, totaling 18 samples. PETG was selected as the material due to its optimal balance of weight reduction, displacement performance, and mechanical properties compared to alternatives like PLA and ABS, as demonstrated by Kamaruzzaman et al. [11]. Material properties for PETG, used in the simulation, were sourced from prior studies and are listed in Table 1. Optimized designs were 3D-printed using PETG to create prototypes for analysis, ensuring lightweight functionality for phocomelia patients.

Table 1. Material properties of PETG [12]

Material	PETG
Density	1290 kg/m^3
Young's Modulus	2.2 GPa
Shear Modulus	470Mpa
Poisson Ratio	0.33
Tensile Strength	53 MPa
Compressive Strength	55 MPa
Yield strength	47.9 MPa

The analysis in SolidWorks 2024 focuses on evaluating stress, strain, and displacement to assess the orthosis's mechanical behavior underload. Von Mises stress, a widely accepted measure of material yielding, will be analyzed to predict failure points and ensure the design remains within PETG's yield strength. Strain will quantify material deformation, while displacement will measure physical movement, critical for ensuring comfort and functionality for phocomelia patients. These parameters are analyzed using SolidWorks' simulation module, where the model is meshed into finite elements, and topology optimization is applied via the design insight feature. A fixed geometry constraint is defined at the strap slots, and a reversed force simulating the greatest pull (100 N at 90 degrees) is applied, as shown in Fig. 2, to mimic real-world loading conditions.

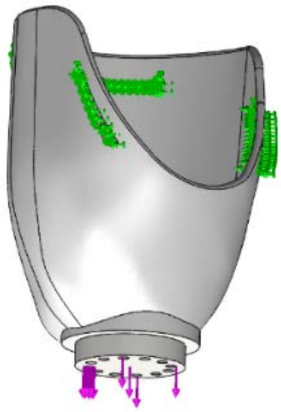


Fig. 2. Fixed geometry applied force on hand orthosis

The purpose of this analysis is to identify the optimal material distribution that minimizes mass while maintaining structural integrity, addressing the bulkiness and discomfort of traditional orthoses. Running the simulation in SolidWorks allows for iterative design refinement, leveraging its computational power to predict performance before 3D printing. The background for this approach lies in the need to reduce material waste and enhance patient-specific customization, with the simulation providing a virtual testing environment to guide the optimization process, ensuring the orthosis supports daily activities effectively [13].

2.3 Finite Element Analysis (FEA)

Finite element analysis (FEA) was employed to assess the mechanical performance of the optimized PETG hand orthosis designs, derived from the CAD model and refined through topology optimization. The FEA will analyze the orthosis's mechanical behavior by computing stress (using the Von Mises stress criterion), strain, and displacement across the six sample sets (0% to 50% mass reduction). Von Mises stress will evaluate material yielding to predict potential failure points, strain will measure deformation under load, and displacement will assess physical movement, ensuring the design supports daily activities for phocomelia patients without compromising comfort or durability.

The analysis is essential to validate the structural integrity and performance of the lightweight orthosis design, addressing the limitations of traditional bulky orthoses. It ensures the design can withstand real-world loads (e.g., 100 N) without excessive stress, strain, or displacement, which could lead to failure or discomfort. FEA provides a virtual testing environment to optimize the design iteratively, reducing the need for physical prototypes and enhancing patient-specific customization [14].

The FEA is conducted within SolidWorks 2024's simulation module, a powerful computational tool renowned for its finite element capabilities. This platform enables precise modelling of the orthosis's complex geometry and material properties, facilitating detailed analysis of stress distribution, deformation, and movement. The FEA is performed after the topology optimization phase, as part of the iterative design process. It occurs during the computational analysis stage, following the creation of the CAD model and its optimization, and before 3D printing. This timing allows for design adjustments based on simulation insights, ensuring the final prototype meets mechanical requirements.

The FEA process begins by importing the optimized 3D models from the CAD and topology optimization phases into SolidWorks 2024's simulation module. PETG material properties are manually input, as they are not predefined in the software, to accurately reflect the material's mechanical behavior. The model is meshed into finite elements, with a global mesh size of approximately 2–3 mm and a finer mesh (1 mm) applied to critical regions such as strap slots and load-bearing surfaces to enhance accuracy [15]. Boundary conditions are defined, including fixed geometry constraints at the strap slots which indicated by a green arrow in Fig. 2 to simulate attachment points, and a 100 N load applied at a 90-degree angle as a reversed force to mimic the greatest pull during activities like gripping or lifting. The simulation employs a static study to compute Von Mises stress, strain, and displacement, using a convergence criterion of less than 5% variation between mesh refinements. This detailed setup allows for the identification of stress concentrations, deformation patterns, and movement, guiding further design refinements to optimize the orthosis's performance.

3. RESULT AND DISCUSSION

The outcomes of the topology optimization and finite element analysis (FEA) conducted on the PETG hand orthosis, designed to enhance functionality for patients with phocomelia. Building on the methodology outlined earlier, the results evaluate the effectiveness of iterative mass reduction (0% to 50%) and the mechanical performance under a simulated 100 N load at a 90-degree angle. The discussion focuses on how optimized designs balance lightweight properties with structural integrity, assessing stress, strain, and displacement to ensure suitability for daily use. Comparisons with prior studies on 3D-printed orthotic devices provide context for interpreting the findings, highlighting advancements in patient-specific solutions. The analysis aims to demonstrate the potential of topology optimization and FEA in improving orthotic design, ultimately enhancing mobility and quality of life for phocomelia patients.

3.1 Topology Optimization

Topology optimization successfully minimized material usage while preserving the structural integrity of the PETG hand orthosis, achieving significant weight reductions across the design iterations. The process, conducted in SolidWorks 2024, iteratively reduced mass by 10% increments, from 0% to 50%, generating six sample sets, each with three models, totaling 18 samples. The baseline design (0% reduction) maintained its initial mass of 109.4 g, while the optimized models resulted in masses of 98.4 g (10% reduction), 87.5 g (20% reduction), 76.6 g (30% reduction), 65.5 g (40% reduction), and 54.7 g (50% reduction), as detailed in Table 2 and Figure 5. The optimization algorithm redistributed material to critical load-bearing regions, such as the socket walls and strap slot areas, ensuring the design could withstand forces encountered during daily activities. Material removal primarily occurred in low-stress regions, such as the outer non-contact surfaces, while preserving thickness in high-stress areas.

The 20% reduction design (87.5 g) was identified as the optimal balance, achieving a 20% mass reduction while maintaining sufficient material to support mechanical loads. This design reduced the orthosis's weight by 21.9 g compared to the baseline, a significant improvement for patient comfort, as excessive weight is a common complaint with traditional orthoses. The 50% reduction (54.7 g) achieved the lightest design but introduced potential risks, as material removal in critical areas increased stress concentrations, which were further evaluated through FEA. Fig. 3 illustrates the progression of optimized designs, with highlighting the material distribution at 20% reduction, showing a balanced structure compared to the 50% reduction model. These findings align with prior studies on material efficiency in assistive devices, where a 15–25% mass reduction is often optimal for balancing weight and durability [16]. The topology optimization results demonstrate the potential to create a lightweight orthosis [17,18] that enhances wearability for phocomelia patients, addressing the bulkiness of traditional designs while maintaining functionality.

Table 2. Mass reduction from topology optimization

Topology Optimization (%)	Mass (g)	Mass Reduction (g)	Percentage Reduction (%)
0	109.4	0.0	0.0
10	98.4	11.0	10.1
20	87.5	21.9	20.0
30	76.6	32.8	30.0
40	65.5	43.9	40.1
50	54.7	54.7	50.0

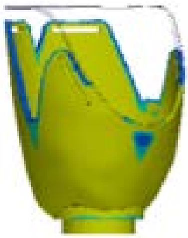
Topology optimization (%)	**Hand orthosis based on weight reduction**
0	
10	
20	
30	
40	
50	

Fig. 3. The topology optimization hand orthosis based on weight reduction

3.2 Finite Element Analysis

Finite Element Analysis (FEA provided a comprehensive evaluation of the mechanical performance of the optimized PETG hand orthosis under a 100 N load applied at a 90-degree angle, simulating real-world conditions such as gripping or lifting. The analysis focused on Von Mises stress, strain, and displacement across the six sample sets (0% to 50% mass reduction), revealing the trade-offs between lightweight design and structural integrity. The baseline design (0% reduction) exhibited a maximum Von Mises stress of 0.1695 MPa, displacement of 0.0155 mm, and strain of 0.000440, indicating a robust structure with minimal deformation. As material was reduced, the optimized designs showed a progressive increase in stress (0.1480–0.1855 MPa), displacement (0.0203–0.0361 mm), and strain (0.000464–0.001844), as detailed in Table 3. The 20% reduction design achieved an optimal balance, with a stress of 0.1479 MPa, displacement of 0.0208 mm, and strain of 0.001844, demonstrating minimal deformation while reducing weight by 20%. In contrast, the 50% reduction design exhibited the highest stress (0.1855 MPa), displacement (0.0361 mm), and a strain of 0.001242, indicating potential risks due to reduced material thickness.

The FEA results, enhanced by detailed visual analysis and graphical representation, provide critical insights into the mechanical behavior of the PETG hand orthosis across varying mass reductions. The 20% reduction design's stress of 0.1479 MPa, as shown in Table 3, remains significantly low compared to PETG's yield strength, ensuring the design can withstand typical loads during daily activities like gripping or lifting. Fig. 4(a) illustrates stress distribution, revealing concentrations near the strap slots and socket walls due to the applied 100 N load, yet these values align with prior studies that recommend keeping stress levels minimal for safety in biomedical devices. The displacement of 0.0208 mm, depicted in Fig. 4(b), indicates minimal movement, ensuring user comfort and stability during use, while the 50% reduction design's higher displacement (0.0361 mm) suggests potential instability over prolonged periods, which could lead to misalignment or discomfort. The strain distribution for the 20% reduction design, shown in Fig. 4(c), highlights a maximum strain of 0.001844 concentrated in the socket walls, which is comparable to values reported in similar studies on 3D-printed orthotics, confirming PETG's ability to deform acceptably underload without compromising functionality.

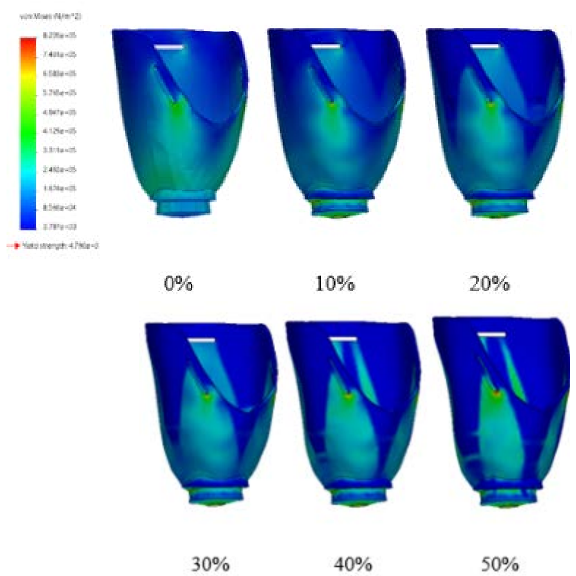
Stress concentrations were primarily observed near the strap slots and socket walls. The 20% reduction design-maintained stresses well below PETG's yield strength (47.9 MPa), ensuring safety for daily use, while the 50%

reduction design approached critical levels in localized areas, suggesting a trade-off between weight reduction and durability. Displacement patterns, illustrated in Fig. 4(b), showed that the 20% reduction design experienced acceptable movement (0.0208 mm), ensuring comfort during use, whereas the 50% reduction design's higher displacement (0.0361 mm) could lead to instability over prolonged use. Strain analysis further confirmed that the 20% reduction in design balanced deformation effectively, with values comparable to those reported in similar studies on 3D-printed biomedical devices. All designs remained within safe operational limits, with stresses significantly below PETG's failure threshold, validating the design's suitability for phocomelia patients.

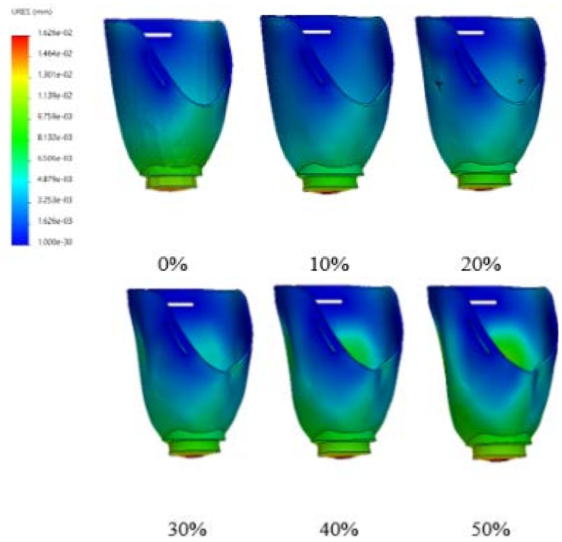
Table 3. FEA results for PETG hand orthosis under 100N load

Topology Optimization (%)	Stress (MPa)	Displacement (mm)	Strain
0	0.1695	0.0155	0.000440
10	0.1480	0.0203	0.000464
20	0.1479	0.0208	0.001844
30	0.1602	0.0229	0.001601
40	0.1785	0.0285	0.001584
50	0.1855	0.0361	0.001242

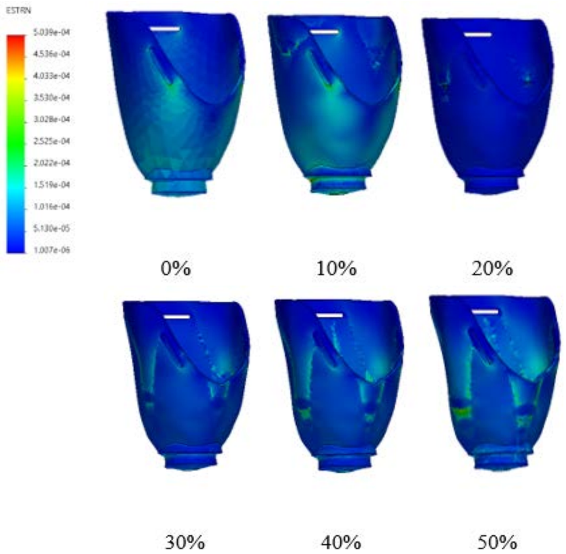
The FEA results underscore the effectiveness of combining topology optimization with FEA to achieve a lightweight yet robust orthosis. The 20% reduction design offers a practical solution, reducing weight by 20% while maintaining mechanical performance, aligning with prior studies that recommend a 15–25% mass reduction for optimal orthotic design. However, the increased stress and displacement at higher reductions (e.g., 50%) highlight the need for careful optimization to avoid compromising long-term durability. These findings contribute to the growing body of research on patient-specific orthotic solutions, demonstrating that computational methods can significantly improve design outcomes, enhancing mobility and quality of life for phocomelia patients.



(a) stress distribution



(b) displacement distribution

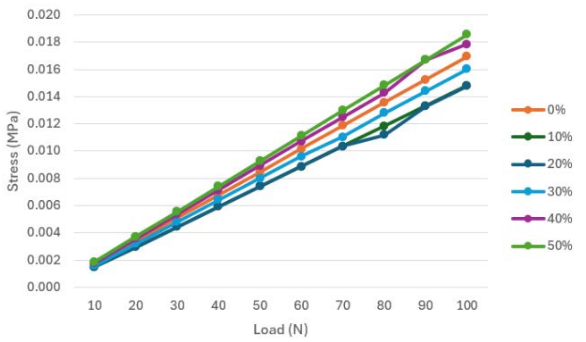


(c) strain distribution

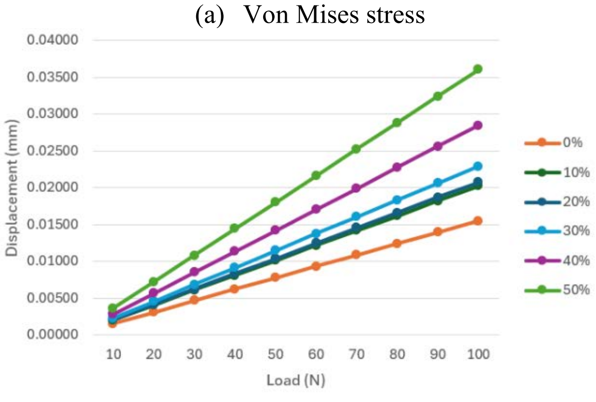
Fig. 4. FEA results on PETG hand orthosis at different percentage of topology optimization (0%-50%)

The graphical representation in Fig. 5, plotting stress, displacement, and strain against mass reduction (0% to 50%), further clarifies these trends and supports the selection of the 20% reduction design. The stress curve shows a slight dip at 20% reduction (0.1479 MPa) before rising to 0.1855 MPa at 50%, indicating that material removal beyond 20% significantly increases stress concentrations in load-bearing regions, such as the strap slots, potentially leading to localized failure under repeated use. The displacement curve exhibits a steady increase, with a notable jump from 0.0208 mm at 20% to 0.0361 mm at 50%, underscoring the trade-off between weight reduction and structural stability, as excessive displacement can affect the orthosis's fit and user comfort over time. The strain curve peaks at 20% (0.001844) before decreasing to 0.001242 at 50%, suggesting that the 20% reduction design experiences a higher strain due to its balanced material distribution, while the 50% reduction design's lower strain may result from excessive material removal, leading to stress concentrations rather than distributed deformation. This graphical analysis highlights the 20% reduction design as the optimal balance, minimizing weight while keeping stress, displacement, and strain within acceptable limits for daily use by phocomelia patients.

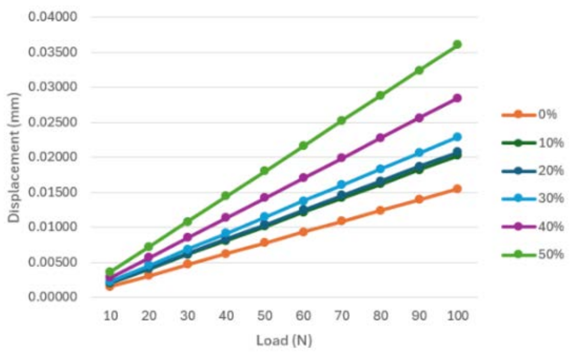
The visual and graphical analyses also reveal potential areas for improvement. Fig. 5(c) shows that strain concentrations in the socket walls could become problematic under cyclic loading, potentially leading to micro-cracks or deformation over extended use, especially if the orthosis is subjected to repeated gripping or lifting activities. The FEA's reliance on static loading 100 N at 90 degrees limits its ability to predict performance under dynamic conditions, such as cyclic loads ranging from 50–150 N, which could better simulate real-world usage and reveal fatigue-related issues. Additionally, the simulation assumes uniform material properties for PETG, which may not account for variations introduced during 3D printing, such as layer adhesion inconsistencies or porosity, that could reduce effective strength and impact long-term durability. Environmental factors, such as temperature and humidity, which can affect PETG's mechanical properties heat distortion temperature of 71°C, as per Table 1 which could influence performance in varying climates.



(a) Von Mises stress



(b) Displacement



(c) Strain

Fig. 5. Comparison of FEA results at increased loading magnitude (10N – 100N)

Future research should incorporate dynamic loading scenarios to assess fatigue performance, particularly for higher mass reductions like 50%, where Fig. 4 indicates increased displacement and stress. Nonlinear FEA could provide deeper insights into material nonlinearity and large deformations, enhancing the design's reliability under complex loading conditions, such as twisting or bending motions common in daily activities. Experimental validation through mechanical testing of 3D-printed prototypes would further confirm the accuracy of the stress, displacement, and strain distributions observed in Fig. 6 and the trends in Fig. 7, addressing the computation-only limitation of this study. This approach would provide a more comprehensive understanding of the orthosis's real-world performance, potentially revealing discrepancies between simulated and actual mechanical behavior that could guide further design refinements. The FEA results, supported by these visual and graphical analyses, demonstrate the effectiveness of computational methods in optimizing orthotic design, offering a lightweight solution for phocomelia patients that reduces fatigue, improves mobility, and enhances quality of life, while contributing to advancements in patient-specific biomedical device design [4].

4. CONCLUSION

This study demonstrates the successful integration of topology optimization and finite element analysis (FEA) to develop a lightweight and structurally reliable PETG hand orthosis for phocomelia patients. By iteratively reducing mass in 10% increments using SolidWorks 2024, a total of 18 design samples were evaluated, with the 20% reduction model identified as the optimal balance—offering a 21.9 g weight reduction (from 109.4 g to 87.5 g) while maintaining mechanical integrity under a 100 N load. FEA results confirmed that this design kept stress, displacement, and strain within safe operational limits, avoiding critical concentrations that appeared in higher reduction models (e.g., 50%). The optimized material redistribution preserved critical structural regions while minimizing mass in low-stress areas, effectively addressing bulkiness issues in traditional orthoses. These findings highlight the potential of computational tools in designing patient-specific biomedical devices that enhance comfort, usability, and overall quality of life, with future work recommended to include dynamic loading simulations and experimental validations to further refine the design's real-world applicability

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