Automated Workflow of the Re-Design and Topology Optimization of a Wrist Hand Splint for Additive

Flux de travail automatisé de la refonte et de l'optimisation topologique d'une attelle de poignet-main pour la fabrication additive

M. Farih[1], M. Ouardouz[2]

[1] University Abdelmalek Essaâdi, Faculty of sciences and techniques of Tangier, farih.mouad@gmail.com
[2] University Abdelmalek Essaâdi, Faculty of sciences and techniques of Tangier, mouardouz@uae.ac.ma

ABSTRACT. In recent years, additive manufacturing has emerged as a revolutionary technology, opening up new design possibilities. In this article, we examine the redesign and optimization of a wrist splint topology for additive manufacturing techniques. By taking advantage of the capabilities of this advanced manufacturing method. This study proposes to improve the functionality, ergonomics and overall performance of the wrist splint. The design process includes customized measurements based on CT scan or 3d scan, 3D modeling, and simulation to ensure optimal fit and structural integrity of the device. After finite element analysis, we evaluate the mechanical properties of the topologically optimized design. The results confirm that the proposed approach offers significant improvements in raw material consumption while maintaining the strength and ventilation required for patient comfort. Compared with the solid splint, the weight of the optimized wrist and hand splint is reduced by 46%.

RÉSUMÉ. Ces dernières années, la fabrication additive a émergé comme une technologie révolutionnaire, ouvrant de nouvelles possibilités de conception. Dans cet article, nous examinons la refonte et l'optimisation de la topologie d'une attelle de poignet pour les techniques de fabrication additive. En tirant parti des capacités de cette méthode de fabrication avancée, cette étude propose d'améliorer la fonctionnalité, l'ergonomie et les performances globales de l'attelle de poignet. Le processus de conception comprend des mesures personnalisées basées sur des scans CT ou 3D, la modélisation 3D et la simulation pour assurer un ajustement optimal et l'intégrité structurelle du dispositif. Après une analyse par éléments finis, nous évaluons les propriétés mécaniques du design optimisé topologiquement. Les résultats confirment que l'approche proposée offre des améliorations significatives en termes de consommation de matière première tout en maintenant la solidité et la ventilation nécessaires au confort du patient. Comparée à l'attelle solide, le poids de l'attelle de poignet et de main optimisée est réduit de 46%.

KEYWORDS. Medical splint, Topology optimization, Additive manufacturing, Wrist hand.
MOTS-CLÉS. Attelle médicale, Optimisation topologique, Fabrication additive, Poignet-main.

1. Introduction

Additive fabrication, widely referred to as 3D printing, has been increasingly adopted in the medical field due to its ability to fabricate customized, patient-specific devices [NEE 18]. This technology allows for the creation of complex geometric structures, enabling the production of medical implants, prosthetics, and orthopedic devices that are tailored to the individual's unique anatomy and requirements [JEM 19].

One such application of additive manufacturing in the medical field is the design and production of wrist-hand splints. These splints are essential orthopedic devices used to immobilize the wrist and hand, promoting healing and preventing patients from secondary injuries [TAC 16]. In addition to comfort, proper fit, and appearance, it is important to consider other significant factors that influence patient adherence [SAV 22, SÜR 22]. Issues such as pressure points, inadequate ventilation, and challenges with cleaning contribute to patients declining extended use of splints [ALL 19]. Traditionally, wrist hand splints have been manufactured using standard molds or off-the-shelf components, which can result in a suboptimal fit and limited functionality [HON 18].

In the case of wrist hand splints, the ability to personalize the design and optimize the structure can lead to significant improvements in comfort, fit, and overall effectiveness [FAC 22]. Previous studies have highlighted the potential of 3D printing in the development of orthopedic devices, particularly in terms of enhancing patient-specific fit and functionality [TAC 16 , HON 18].

A practical approach involves integrating finite element analysis(FEA) into the splint processing. FEA allows for simulating and assessing whether the digital models meet the required mechanical performance, providing a theoretical basis for making adjustments to the splint [MIA 23]. Topology optimization is a design approach that uses finite element analysis to iteratively remove material from the structure while maintaining its mechanical performance. This method helps in reducing the weight and volume of the model without compromising its strength and functionality [SRI 20]. topology optimization (TO) based on FEA represents a viable approach to enhance the design of wrist hand splints for additive manufacturing.

There is a lack of extensive research on the use of finite element analysis and topology optimization in designing medical splints for additive manufacturing [STE 23]. Furthermore, there is a need for an orthotic design and production framework that can be implemented in clinical settings. This framework should integrate additive manufacturing as well as topology optimization techniques to provide effective solutions for patient’s needs.

In this study, we introduced a splint design approach that integrates topological optimization with additive manufacturing techniques. A prototype was produced using the fused filament fabrication (FFF) process. This design approach and manufacturing process hold potential for wider use in producing various orthotics and splints through additive manufacturing methods.

The paper is structured as follows: Section 2 describes the design and topology optimization methodology, as well as the manufacturing of the customized wrist hand splint. Section 3 discusses the results and implications of this study, while Section 4 concludes the paper and outlines future research directions.

2. Material and Methods

The primary aim of this study is to propose an operational workflow for the re-design of splints for additive manufacturing using topology optimization techniques. This sampling approach includes data collection through 3D scanning, digital modeling, finite element analysis, topology optimization, and additive manufacturing.

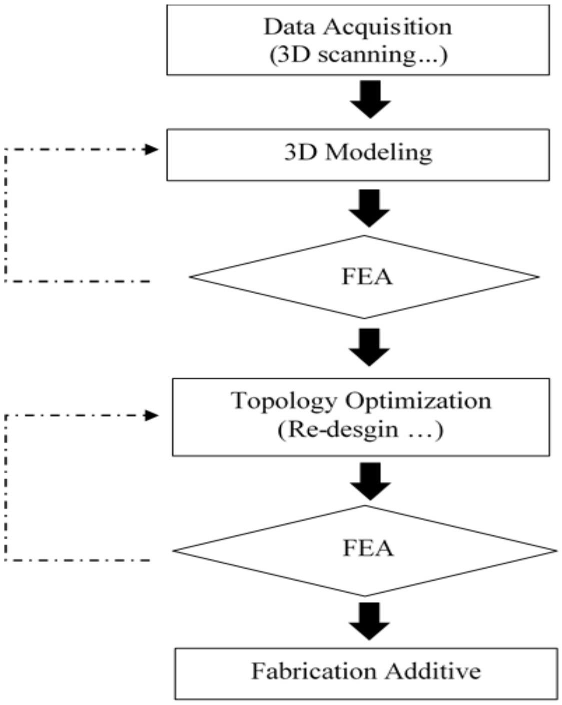

Figure 1. *Topology optimization and fabrication additive workflow.*

2.1. *Data Acquisition and 3D Modeling*

To begin, a volunteer's wrist-hand was scanned using a 3D scanning device to capture the precise dimensions and geometry of the limb. During the scan stage, we instructed the subject to minimize movement as much as possible to reduce scanning errors. This process took approximately 10 minutes to complete. Following this, any background elements and surface artifacts were removed through cleaning of the scan data. The cleaned data was used to create a mesh using specialized software for scans (FreeScan X5), from which the mesh was imported into a nTopology CAD program for further refinement and 3D CAD model creation by fitting the surface of the 3D Hand mesh model, As shown in Figure 2.

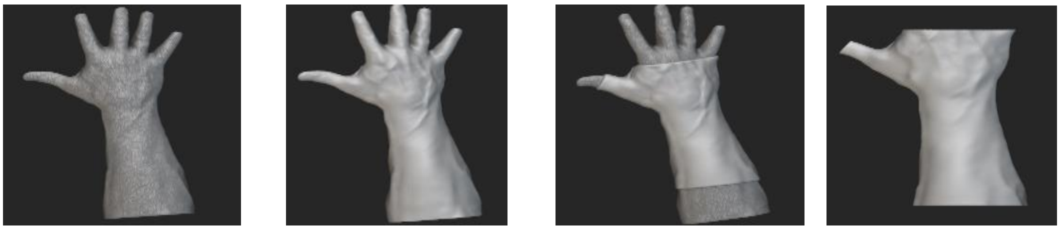

Figure 2. *Acquisition of wrist-hand data and development of the foundational model.*

2.2. *Design & Topology Optimization*

The initial solid splint model with uniform thickness was investigated through finite element analysis (FEA). The splint material is defined as uniform linear elastic PLA, the material characteristics included in the FE model, as shown in Table 1, were obtained from academic sources and online materials.

	Young's Modulus (MPa)	Poisson Ratio	Yield strength (MPa)
PLA	3466	0.30	60

Table 1. *Properties of the 3D printing materials.*

The input model was meshed into 345,059 tetrahedral elements (2 mm size, 86,837 nodes). The boundary conditions were defined with the proximal edge of the splint fixed and a load of 30 N was applied to the distal area of the splint, simulating a scenario of accidental impacts, Figure 3. The results revealed that the splint had adequate strength to withstand the applied load, but opportunities existed to optimize the design by reducing overall weight and material usage without compromising structural integrity.

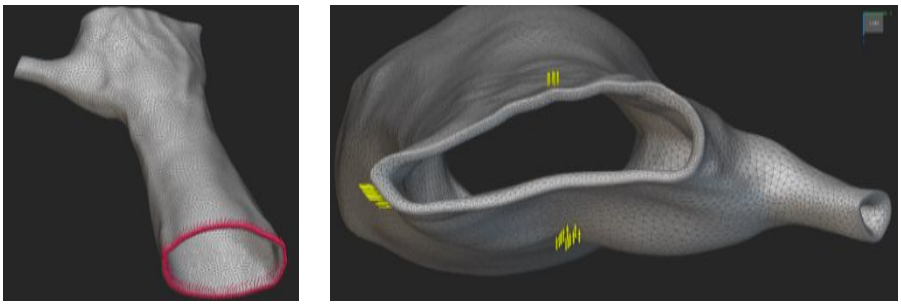

Figure 3. *BCs, Loads cases.*

Topology optimization was then performed on the initial splint model using the commercial software nTopology. The goal of the optimization was to reduce the total mass of the splint while still meeting the necessary structural strength and rigidity. The conditions boundary and load cases remained unchanged from the original FEA analysis. Through topology optimization, the material was removed from areas with low-stress concentrations, resulting in a perforated or latticed structure for the splint, Figure 4.

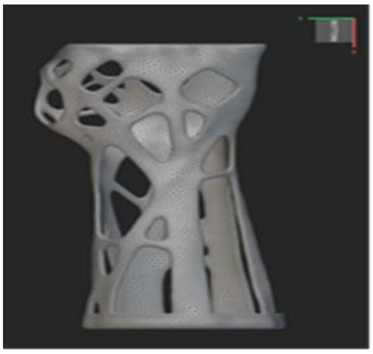

Figure 4. *Design of the splint after topology optimization.*

After conducting topology optimization, the newly created design was subjected to further analysis using finite element analysis. The applied loads, boundary conditions, and material properties required for solving the optimization process are consistent with those illustrated in Figure 3 and Table 1.

2.3. *Fabrication*

The optimized splint design was produced using 3D printing technology known as fused deposition modeling. This method is particularly suitable for creating intricate shapes and lattice structures resulting from topology optimization. The splint was printed using the same PLA material as the original design.

The optimized design file was first repaired and prepared for additive manufacturing using dedicated software, which included fixing any mesh errors, orienting the part, generating necessary support structures, and optimizing print settings to ensure desired results. Following this, the component was produced using a 3D printer equipped with a nozzle diameter of 0.4 mm and layer height of 0.2 mm. Once the printing was finished, any leftover support structures were manually eliminated to achieve a polished surface.

Two of the key design considerations in additive manufacturing are build time and material consumption. To evaluate these factors, the splint was printed in two different orientations (0°, and 90°). These ranged from 0° (flat on the build plate) to 90° (standing on its side). Printing at a 90° angle had the lowest material consumption and fastest build. This orientation was selected for the final production of the optimized splint design.

3. Results and discussion

The original solid splint model had a total mass of 317g. The finite element analysis revealed a maximum von Mises stress of 2.32 MPa under the 30 N loading condition, indicating the splint would withstand the applied loads.

After topology optimization, the optimized design had a total mass of 169g, representing a 46% reduction in material usage compared to the original splint. The maximum von Mises stress in the optimized splint was 2.53 MPa, which is still below the failure limit of the PLA material, Table2, Figure5.

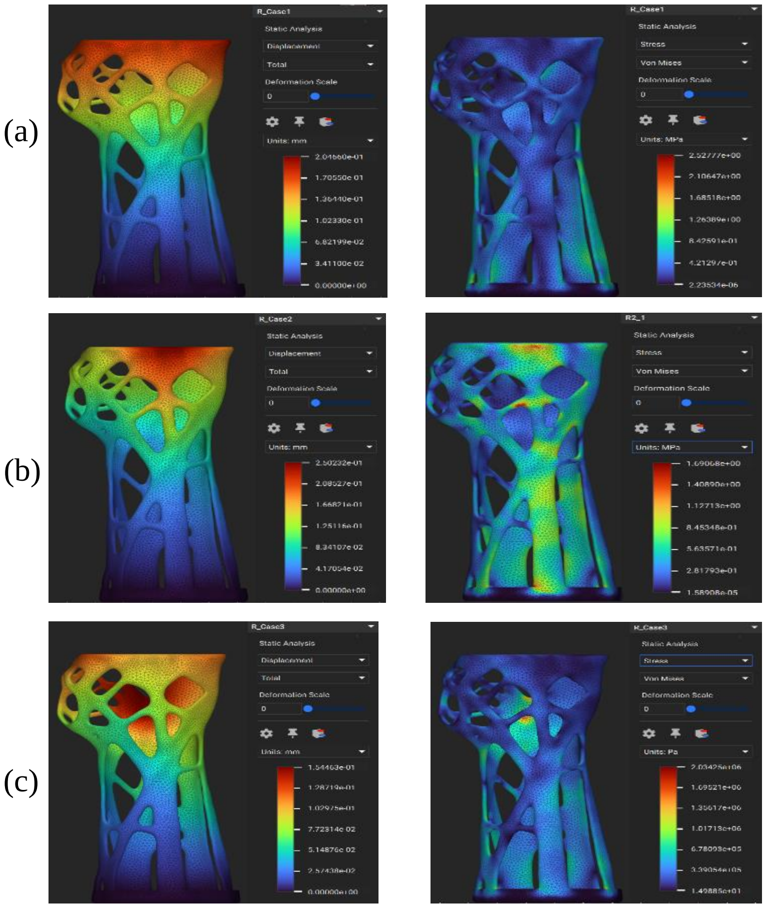

Figure 5. *FEA of topology-optimized splint (a) Load case 1, (b) Load case 2, (c) Load case3.*

	Load	Max Displacement (mm)	Max Von Mises Stress (MPa)
Load Case 1 (+Y)	30N	0.20	2.53
Load Case 2 (+X)	30N	0.25	1.69
Load Case 3 (-X)	30N	0.15	2.03

Table 2. *The displacement and Von Mises stress results of the topology-optimized splint.*

The final 3D printed splint exhibited a sleek, latticed appearance with improved ventilation and comfort for the user, as shown in Figure. The optimized splint was 46% lighter than the original solid design while maintaining the necessary structural integrity, demonstrating the effectiveness of the topology optimization approach.

4. Conclusion

This case study illustrates the utilization of topology optimization in creating a personalized wrist-hand splint through 3D printing. The optimized design led to a 46% decrease in material usage and weight compared to the initial solid model, while maintaining structural integrity. Through the integration of topology optimization and additive manufacturing, tailored medical devices can be produced that are both practical and visually pleasing for patients. This approach has potential applications for enhancing the design of various orthopedic and assistive devices to enhance comfort, reduce weight, and improve overall user satisfaction.

Future research should investigate the clinical assessment of 3D-printed splints to confirm their efficacy and comfort for the end-user. Additionally, further enhancements could focus on improving ventilation, reducing weight, cost-effective production, as well as exploring alternative materials.

References

[NEE 18] NEERAJHA, N., Agnes, D B., Erdem, K., Pinar Z.,& Nihal, E V. « Enabling personalized implant and controllable biosystem development through 3D printing» , *Biotechnology Advances*, *36*(2), 521–533, 2018.

[JEM 19] JIMENEZ, M., Romero, L., Somonte, M D., Espinosa, M D M B., & Domínguez, M. « Additive Manufacturing Technologies: An Overview of 3D Printing Methods and Future Prospects», *Complexity*, 1–30, 2019.

[TAC 16] TACK, P., VICTOR, J., GEMMEL, P., & ANNEMANS, L. « 3D-printing techniques in a medical setting: a systematic literature review », *BioMed Central*, 15(1), 2016.

[SAV 22] Savaş, S., & Aydoğan, Ç. « Factors affecting orthosis adherence after acute traumatic hand tendon repairs: A prospective cohort study », *Journal of Hand Therapy*, *35*(1), 32–40, 2022.

[SÜR 22] Sürücü, S., Aydin, M., Batma, A G., Karaşahin, D., & Mahiroğullari, M. « Evaluation of the patient satisfaction of using a 3D printed medical casting in fracture treatment », *Joint Diseases and Related Surgery*, 33(1), 180–186, 2022.

[ALL 19] Allison, J R., Currie, C C., Trainor, J., Corson, M., & Durham, J. « Patient satisfaction with a postal service for occlusal splints », *Oral Surgery*, 12(3), 224–229, 2019.

[HON 18] Honigmann, P., Sharma, N., Okolo, B., Popp, U., Msallem, B., & Thieringer, F M. « Patient-Specific Surgical Implants Made of 3D Printed PEEK: Material, Technology, and Scope of Surgical Application », *BioMed Research International*, 1–8, 2018.

[FAC 22] Factor, S., Atlan, F., Pritsch, T., Rumack, N., Golden, E., & Dadia, S. « In-hospital production of 3D-printed casts for non-displaced wrist and hand fractures », *SICOT-J*, 8, 20, 2022.

[MIA 23] Mian, S H., Umer, U., Moiduddin, K., & Alkhalefah, H. « Finite Element Analysis of Upper Limb Splint Designs and Materials for 3D Printing », *Polymers*, 15(14), 2993, 2023.

[SRI 20] Srivastava, S P., Salunkhe, S., Pande, S., & Kapadiya, B. « Topology optimization of steering knuckle structure », *International Journal for Simulation and Multidisciplinary Design Optimization*, 11, 4, 2020.

[STE 23] Steck, P., Scherb, D., Witzgall, C., Miehling, J., & Wartzack, S. « Design and Additive Manufacturing of a Passive Ankle–Foot Orthosis Incorporating Material Characterization for Fiber-Reinforced PETG-CF15 », *Materials* , 16(9), 3503, 2023.

[ALK 23] Umer, U., Mian, S. H., Moiduddin, K., & Alkhalefah, H. « Exploring orthosis designs for 3D printing applying the finite element approach: study of different materials and loading conditions », *Journal of Disability Research*, *2*(1), 2023.

[COR 24] Cordero, M., Dedić, R., Jelačić, Z., & Toshev, R. « Optimizing Mechanical Design for an Additively Manufactured Prosthetic Leg », *Procedia Computer Science*, *232*, *2973*–2983, 2024.

[LI 18] Li, J., & Tanaka, H. « Rapid customization system for 3D-printed splint using programmable modeling technique – a practical approach. *BioMed Central*, 4(1), 2018.

[OKS 20] Oksiuta, Z.; Jalbrzykowski, M.; Mystkowska, J.; Romanczuk, E.; Osiecki, T. « Mechanical and Thermal Properties of Polylactide (PLA) Composites Modified with Mg, Fe, and Polyethylene (PE) Additives ». *Polymers*, 2020.

[SEP 21] Sepahi, M.T.; Abusalma, H.; Jovanovic, V.; Eisazadeh, H. « Mechanical Properties of 3D-Printed Parts Made of Polyethylene Terephthalate » Glycol. J. Mater. Eng. Perform, *Journal of Materials Engineering and Performance*, 30(9), 6851–6861, 2021.