JURNAL POLIMESIN
Unit Penelitian dan Pengabdian Kepada Masyarakat (P2M)
Politeknik Negeri Lhokseumawe
ISSN Print: 1693-5462, ISSN Online: 2549-1199
Website: http://e-jurnal.pnl.ac.id/index.php/polimesin

Design optimization of sleeve finger splint model using Finite Element Analysis

Zakki Fuadi Emzain[1*], Utsman Syah Amrullah[1], Am. Mufarrih[1], Nanang Qosim[1], and Yusuf Dewantoro Herlambang[2]
[1] Mechanical Engineering Department, Politeknik Negeri Malang
Malang, 65141, Indonesia
[2] Mechanical Engineering Department, Politeknik Negeri Semarang
Semarang, 50275, Indonesia
*Corresponding author: zfemzain@polinema.ac.id

Abstract

One of the rehabilitation alternatives for fingers injuries is to use a finger splint. Some existing finger splint models still use excessive material, and the size is not appropriate. The purpose of this study was to propose a customized sleeve finger splint model with a conical shape along with the finger surface from the proximal phalanges to the distal phalanges. Design optimization using topology optimization was carried out to reduce mass and volume while maintaining the stress strength of the model. The stages of the method in this research were modeling design, preprocessing analysis, topology optimization, and postprocessing analysis. Topology optimization design was set with 70% mass in response constraint. The analysis results showed a significant reduction in the model mass of 42.18%, from 6.78 grams to 3.92 grams. Meanwhile, the maximum equivalent stress increased slightly by 3.42%, from 8.12 MPa to 8.4 MPa. Even though there was an increase in equivalent stress after topology optimization, the sleeve finger splint model was still categorized as safe, with a safety factor of 3.39.

Keywords: Finite element analysis; sleeve finger splint; topology optimization.

1. Introduction

Fingers are organs that are very important for daily activities such as touching, holding, and carrying objects. However, handball athletes such as baseball, basketball, rugby, and volleyball will often experience hand injuries. Nearly 60% of injuries to the hand are in the fingers [1]. The fingers' various kinds of injuries are arthritis, mallet finger, jersey finger, gamekeeper's thumb, trigger finger, dislocation, and even finger fracture [2]. It needs proper treatment so that the finger can return to normal. For example, a mallet finger injury occurs due to a hard impact on the distal interphalangeal (DIP) fingertip in the flexor position so that the extensor tendon in the DIP joint ruptures or broken. This case causes an inability to straighten the fingertips or requires assistance to straighten them. If the mallet finger is not handled correctly, it can cause swan-neck deformation [2].

Several kinds of mallet finger injury treatment can be done using splints, therapy, surgery, and miniplate implants [3]. However, most mallet finger injuries can be treated using a splint without surgery [4]. The finger will be splinted in a straight position so that the finger does not bend, and the tendon will recover. Splints are very familiar to patients for rehabilitation of muscle tone reduction in limb extremities. Splints are generally made of thermoplastic so that they are easy to shape with adjusting to the shape of the human body [5]. However, the setting up of this thermoplastic splint also depends on the skills of the medical personnel. It also takes a long time to form, use excess material, and leave unused material [6].

Several researchers have carried out several previous studies related to the development of finger splints. Lisa J. O'Brien and friends compared stack splints with aluminum and thermoplastic splints [7]. Simin Nasseri and colleagues developed a splint by combining a flexible polymer material with aluminum or carbon fiber [8]. Hyeounwoo Choi and his friends made splints with a porous design using a 3D printer [9]. Ali Zolfagharian and his friends optimized the stuck splint design by reducing the weight of the splint [10]. Amartya Gupta developed a splint design with the shape of the base layer following the surface of the finger with several holes and given a clamp at the top [11].

Although previous researchers developed several kinds of finger splint models, even many of them are sold commercially. However, it still has drawbacks, namely using expensive materials, the design form being too complex, and spending excess materials. In addition, there are also some patients with mallet finger injuries who feel uncomfortable, difficult to use, and irritation occurs because the skin is tightly closed, and the appearance of the finger splint is less attractive [11]. Based on that description, developing a finger splint model design and its fabrication using additive manufacturing technology is necessary.

The aim of this study is to design and analyze a proposed sleeve finger splint model using finite element analysis. Design optimization is also conducted by using the model to get the optimal design form. Using the finite element method, the model's strength, deformation, and feasibility to withstand static loads with a safe safety factor value can be determined.

2. Materials and Methods

2.1. Materials

The sleeve finger splint model will be fabricated using fused deposition modeling (FDM) 3D Printing. Hence in this study, the Acrylonitrile Butadiene Styrene (ABS) material was chosen because it has higher tensile strength and elasticity than other FDM 3D Printing filament types such as PLA and Nylon. Due to the purpose of the sleeve finger splint model being designed is to resist hypertonic forces, the material with high tensile strength is chosen as a priority [12]. The mechanical properties of ABS material can be seen in Table 1 [13]. The material data was inputted manually into the Ansys Workbench 2021 R1 engineering data.

Table 1. Mechanical properties of ABS material

Characteristics	Value	Unit
Density	1.04	gr/cm^3
Young’s Modulus	2400	MPa
Poisson's Ratio	0.37	
Yield Strength	28.5	MPa

2.2. Methods

This research process began with a literature study stage to find references to similar previous studies. Then, it proceeded to the 3D modeling stage to basic and simple finger splint design. The next step was to analyze the finger splint model using the finite element software method consisting of preprocessing, topology optimization, and postprocessing. Preprocessing includes setting material parameters, meshing, boundary, and loading conditions. Topology optimization consists of the setting of optimization region, response constraint, and manufacturing constraint. Meanwhile, postprocessing includes the result of equivalent stress, deformation, and safety factor. Figure 1 is a flowchart of the stages of this research [14].

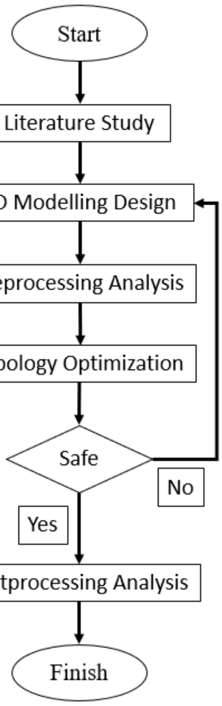

Figure 1. Flowchart of research stages

2.3. Model Design

The design of the sleeve finger splint model is shaped like an elongated cone following the relief of the finger surface from the proximal phalanges to the distal phalanges. The diameter of the circle adjusts the width and height of each finger size. Autodesk Inventor 2020 CAD software was used to design 3D modeling of the sleeve finger splint model. The following five sample design parameters on the index finger can be seen in Figure 2. The model dimensions are assumed to cover the average finger size of ordinary adult men in Indonesia, as shown in Table 2.

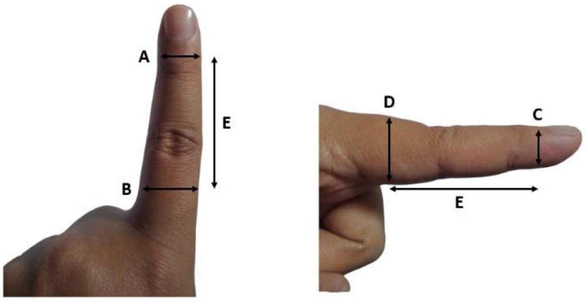

Figure 2. Model size parameters

Table 2. Dimensions of the model

Parameter	Dimensions	Value (mm)
A	Width DIP	16
B	Width PIP	20.5
C	Height DIP	14
D	Height DIP	21
E	Length DIP-PIP	50

2.4. Preprocessing

At the meshing stage, element size was inputted manually. The addition of setting the span angle center was fine, and high smoothing made the refinement meshing process better. A convergence test on element size was carried out to find an element size close to valid. Figure 3 shows that the size of the elements has relatively convergent stress results. The element's size was chosen as the highest stress of the convergence value, 0.6 mm. The results of the mesh metric with the Skewness scale showed the highest number of TET10 elements (10 tetrahedral nodes) between 0.25 – 0.5, as shown in Figure 4. This result proves that the quality of the elements is categorized as good [15]. Figure 5 illustrates a meshing view of the model with 59839 nodes and 33497 elements.

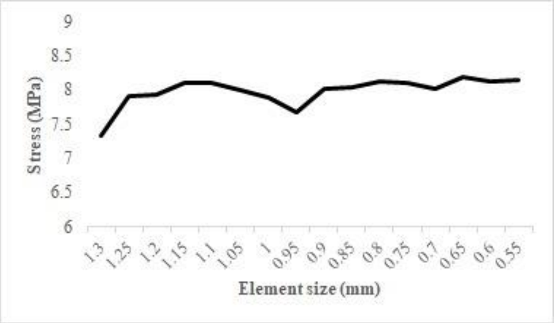

Figure 3. Element size convergence test

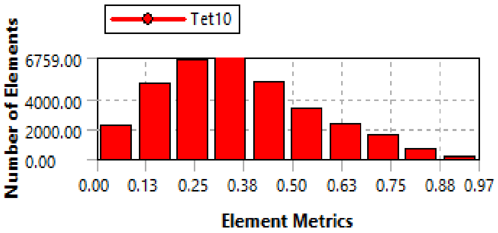

Figure 4. Quality of mesh metrics

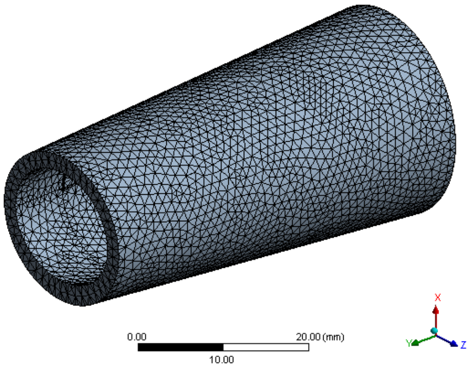

Figure 5. Shape meshing model

Boundary conditions for fixing support were around the area in the proximal phalanx. Meanwhile, a force was applied to the base of the distal phalanges downward, assuming 60 N. The additional force was applied at the palm of the distal phalanges joint in an upward direction, assuming 58.94 N [10]. Figure 3 shows the boundary conditions of the sleeve finger splint.

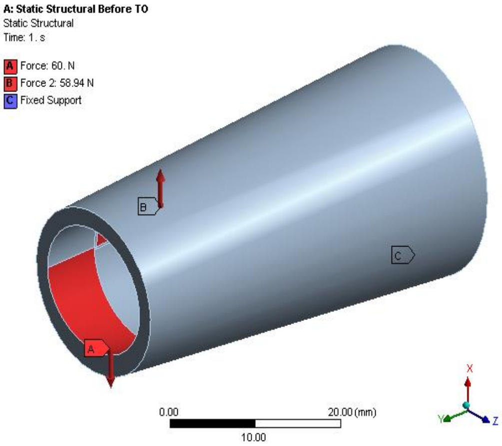

Figure 6. Boundary condition model

3. Results and Discussion

The analysis results presented in this study are topology optimization and postprocessing analysis, such as total deformation, equivalent stress, and safety factor. Parameter analysis of total deformation can determine changes in the shape of the sleeve finger splint model that occurs when it is loaded. The following parameter analysis is equivalent stress was designed to determine the maximum stress in the sleeve finger splint model. At the same time, the safety factor parameter analysis was served to measure the ability of the model and its material to withstand a given static load.

3.1. Topology optimization

The optimization region was set the entire geometry of the cone finger splint model except for the exclusion region at the boundary condition. The optimization target was the minimum, and the response type was compliance. The minimum member size in the manufacturing constraint was 3.8 mm. The percentage to retain was 70% on the response constraint. Figure 7 illustrates the optimization results with retain region. Figure 8 illustrates the smoothing design. The mass model of sleeve finger splint originally was 6.78 grams. After topology optimization with smoothing design applied, the properties of the mass model became 3.92 grams.

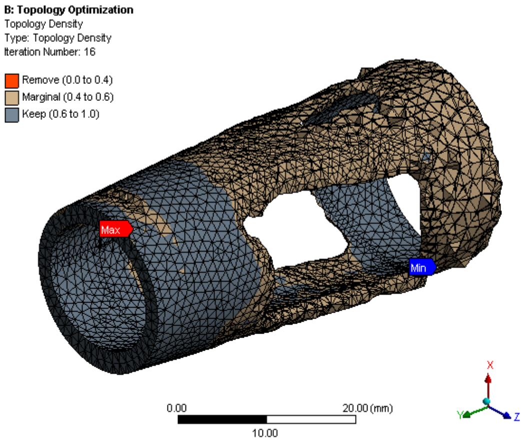

Figure 7. Retain region of topology density

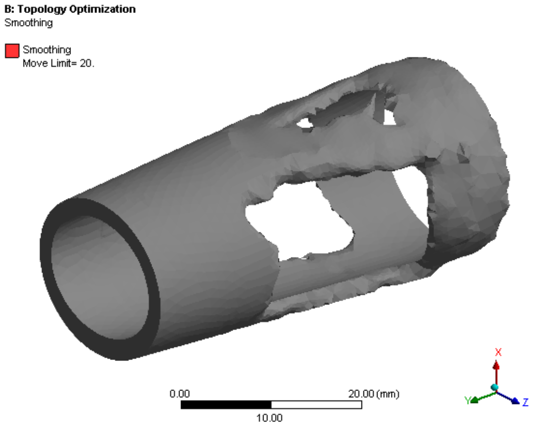

Figure 8. Smoothing design

3.2. Total deformation

The maximum value of total deformation in the sleeve finger splint model before topology optimization was 0.098 mm. In comparison, the maximum value of total deformation after topology optimization is 0.125 mm. Each maximal point is in the same area, namely at the base end of the distal phalanges handle. Figure 9 and Figure 10 illustrate the total deformation of the sleeve finger splint model before and after topology optimization.

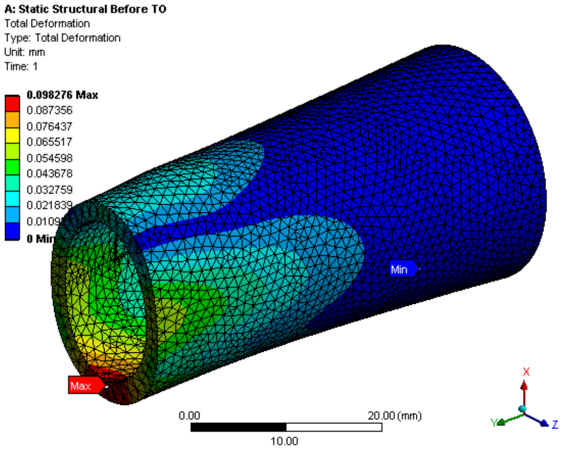

Figure 9. Results of total deformation before topology optimization

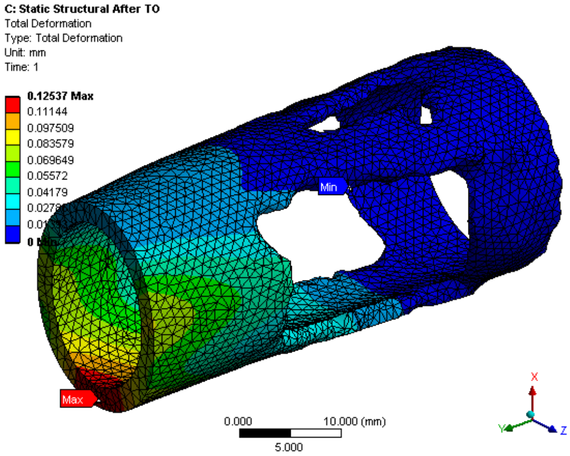

Figure 10. Results of total deformation after topology optimization

3.3. Equivalent stress

The results of the equivalent stress on the sleeve finger splint model both before and after topology optimization can be seen in Figure 11 and Figure 12. The analysis results showed that the maximum area of equivalent stress occurred on the right and left sides inner diameter of the handle of the distal phalanges. The maximum values of equivalent stress at the tip of model sleeve finger splint before and after topology optimization were 8.12 MPa and 8.4 MPa.

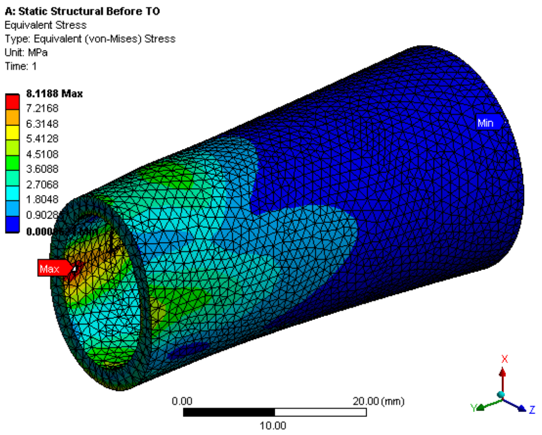

Figure 11. Equivalent stress results before topology optimization

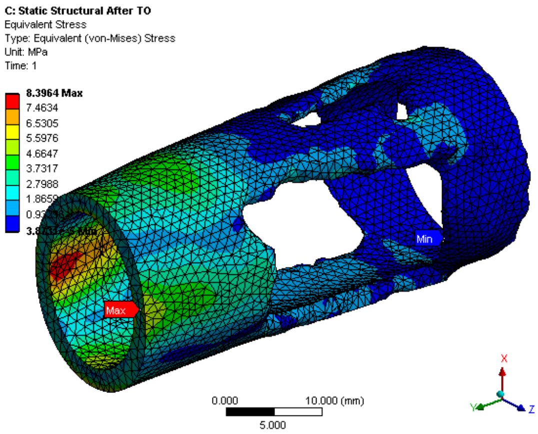

Figure 12. Equivalent stress results after topology optimization

3.4. Safety factor

The safety factor analysis results showed that the sleeve finger splint model before topology optimization was 3.51, while after topology optimization was 3.39. Figure 13 and Figure 14 illustrate an area with a minimum safety factor before and after topology optimization. The safety factor had decreased due to reducing some parts of the model on the sides and top.

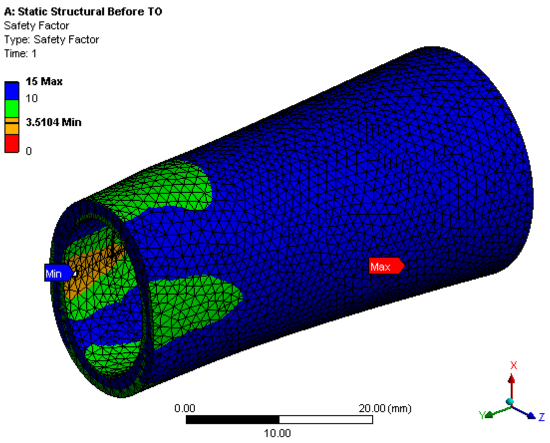

Figure 13. Safety factor results before topology optimization

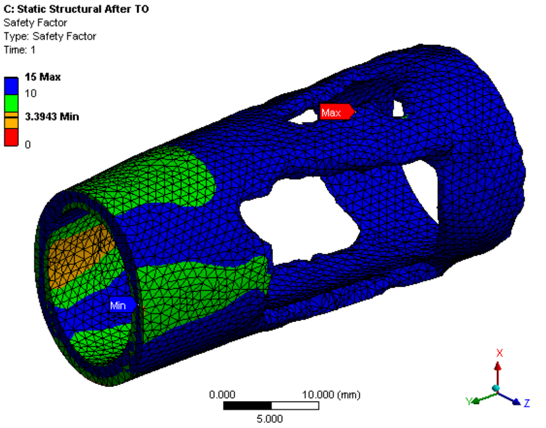

Figure 14. Safety factor results after topology optimization

The results of the data analysis above showed that the equivalent stress and total deformation increased while the safety factor and mass decreased. The comparison summary of the sleeve finger splint model before and after topology optimization (TO) can be seen in Table 3.

Table 3. Comparison before and after topology optimization

Comparison	Before TO	After TO	Percentage
Massa	6.78 grams	3.92 grams	-42.18 %
Total Deformation	0.098 mm	0.125 mm	27.57 %
Equivalent stress	8.12 MPa	8.4 MPa	3.42 %
Safety factor	3.51	3.39	-3.31 %

4. Conclusions

Results of the study showed that after topology optimization, the mass of the sleeve finger splint model was significantly reduced by 42.18%, from 6.78 grams to 3.92 grams. Decreasing the mass increases the total deformation by 27.57%, and the equivalent stress increased slightly by 3.42%, from 8.12 MPa to 8.4 MPa. Although the safety factor also decreased by 3.31% to 3.39, it was still categorized as safe. For further study, the sleeve finger splint model will be fabricated using FDM 3D Printing, and experimental tests will be carried out on the prototype model.

References

[1] S. Yarar, J. M. Rueger, and C. Schlickewei, “Finger injuries in ball sports,” *Unfallchirurg*, vol. 118, no. 6, pp. 496–506, 2015.

[2] D. T. Netscher, D. T. Pham, and K. G. Staines, "Finger injuries in ball sports," *Hand Clin.*, vol. 33, no. 1, pp. 119–139, 2017.

[3] N. Qosim, R. Monasari, Z. F. Emzain, L. Hakim, and A. Sai'in, "Finite Element Analysis of Miniplate for Post-Fracture Finger Rehabilitation Device," *J. Appl. Eng. Technol. Sci.*, vol. 2, no. 1, pp. 21–26, 2020.

[4] J. P. Y. Cheung, B. Fung, and W. Y. Ip, "Review on mallet finger treatment," *Hand Surg.*, vol. 17, no. 03, pp. 439–447, 2012.

[5] J. S. Lin and J. B. Samora, "Surgical and nonsurgical management of mallet finger: a systematic review," *J. Hand Surg. Am.*, vol. 43, no. 2, pp. 146–163, 2018.

[6] L. O'Brien, "Adherence to therapeutic splint wear in adults with acute upper limb injuries: a systematic review," *Hand Ther.*, vol. 15, no. 1, pp. 3–12, 2010.

[7] L. J. O'Brien and M. J. Bailey, "Single blind, prospective, randomized controlled trial comparing dorsal aluminum and custom thermoplastic splints to stack splint for acute mallet finger," *Arch. Phys. Med. Rehabil.*, vol. 92, no. 2, pp. 191–198, 2011.

[8] S. Nasseri, V. K. Castellano, and M. Kotwal, "On Fabrication and Mechanical Testing of a New Finger Support," 2018.

[9] H. Choi, A. Seo, and J. Lee, "Mallet Finger Lattice Casts Using 3D Printing," *J. Healthc. Eng.*, vol. 2019, 2019.

[10] A. Zolfagharian, T. M. Gregory, M. Bodaghi, S. Gharaie, and P. Fay, "Patient-specific 3D-printed splint for mallet finger injury," *Int. J. Bioprinting*, vol. 6, no. 2, 2020.

[11] A. Gupta, S. Chaturvedi, A. K. Bhat, and M. Samheel, "Design and Manufacture of Customizable Finger Immobilizer and Mallet Finger Splints," in *2019 International Conference on Biomedical Innovations and Applications (BIA)*, 2019, pp. 1–4.

[12] Y.-S. Yang, Z. F. Emzain, and S.-C. Huang, "Biomechanical Evaluation of Dynamic Splint Based on Pulley Rotation Design for Management of Hand Spasticity," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 29, pp. 683–689, 2021.

[13] Z. F. Emzain, S.-C. Huang, Y.-S. Yang, and N. Qosim, "Design and Analysis of a Dynamic Splint Based on Pulley Rotation for Post-Stroke Finger Extension Rehabilitation Device," *Rekayasa Mesin*, vol. 11, no. 3, pp. 477–485, 2020.

[14] Z. F. Emzain, U. S. Amrullah, and A. M. Mufarrih, “Desain dan Analisis Elemen Hingga Model Prosthetic Ankle-Foot,” *Infotekmesin*, vol. 11, no. 2, pp. 87–93, 2020.

[15] Z. F. Emzain, U. S. Amrullah, and A. M. Mufarrih, “Analisis elemen hingga untuk siklus berjalan pada model prostetik lentur pergelangan kaki,” *J. POLIMESIN*, vol. 18, no. 2, pp. 91–98, 2020.