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Lightweight design of Knee-Ankle-Foot Orthotic Devices using Voronoi patterns for Additive Manufacturing

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Abstract. Traditionally fabricated knee-ankle-foot orthosis (KAFO) device that is used to aid in the mobility user is uncomfortable. Problems such as weight and enclosure in almost all the part of the leg make it strenuous and humid for the user to wear for a long time. Furthermore, in the traditional production method, it can take up to a week to fabricate. The aim of this study is to redesign the knee-ankle-foot-orthosis by using the application of topology optimization in order to reduce the material used on the product and to make it lightweight. The parameters of the KAFO were determined by using indirect method; similar to traditional method. The modelling and analysis of the KAFO is completed by using CAD and CAE software. Optimization of the product is performed by redesigning the shape and applying topology optimization function. It is able to reduce the maximum stress of the product by 22.56% and the volume by 4.33%. Application of the Voronoi pattern further reduces the mass of the KAFO and produces more organic looks to the product. SLS Lisa Pro 3D printer is used to produce the KAFO in a period of less than a week. This prove to be a viable alternative for producing customized KAFO.

1. Introduction

Standardized orthosis devices are used to aid mobility. Orthotic gadgets have numerous applications and generally serve one of three purposes which are protection or immobilization, correction and functional assistance. The standardized orthosis with the uniform thickness, materials and trim lines does not grant sufficient help to the mentioned purposes [1]. Furthermore, there are no proven standard to customize the fabrication of orthosis with the desired thickness and configuration of trim lines for specific patients. Besides, the current standardized orthosis does not supply sturdy proof about the impact on different materials used in them. Orthotic devices are usually classified by means of the joints they cross. For example, a WHO is a wrist-hand orthosis, a KAFO is a knee-ankle-foot orthosis, and a TLSO is a thoracic-lumbar-sacral orthosis [2].

A knee, ankle, and foot orthosis (KAFO) are a long-leg orthosis that spans the knee, ankle, and foot in order to stabilize the joints and support the leg muscles. There is study done on the current standardize and custom KAFO on the market today in order to improve the design. The material usually use for the manufacturing of KAFO are leather, metal and thermoplastic [3].

The traditional method of making orthoses takes a long time [4]. The shape and proportions of the orthosis must be manually adjusted to fit the patient's physique. Furthermore, producing many personalized orthoses of the same quality is difficult, and sophisticated designs might be difficult to apply. Based on the study by Choo et al., the time that is required for the custom orthosis device to be manually produced is approximately 1 week [5].

When traditional methods fail to produce complex mechanical parts, additive manufacturing methods are becoming increasingly common in the industry. The key benefit of these approaches is that they allow designers a lot of leeway. Simulating structures with complex shapes that precisely fulfil the mechanical requirements can be done using theoretical and computational topology optimization methods at the same time although requiring the least amount of material possible. The combination of additive manufacturing and topology optimization in the design of leading-edge droop nose ribs for the Airbus 380 are an example of a topology optimization approach that reduce the material weight while still met the requirement needed [6]. Combining topology optimization and additive manufacturing procedures to produce optimized mechanical parts appears to be a promising solution [7]. As this method has been proven effective in many fields and it has a potential to be used in orthosis devices production. Choo et al. [8] found that orthosis can be created with precise proportions by a computer software employing recently developed three-dimensional (3D) printing technology, and the aforementioned shortcomings of the traditional method can be adequately solved because 3D printers are extremely precise. It also said that while traditional method of producing orthosis device will take 1 week, by using the application of 3D printing it will only take a day [5]. Alqahtani et al. [9] conducted a study on the present state of orthotic creation with additive manufacturing. They found that the application of additive manufacturing for orthosis device also had been applied for mass personalization which means the orthosis device can be made in a large number of sizes at a low cost, and it can materialize any shape that is intended [9].

Additive manufacturing (AM), also known as 3D printing, is a latest method of manufacturing that allows the manufacture to creates lighter parts while maintaining the strength of the parts. Using computer-aided design (CAD) or 3D object scanners, additive manufacturing allows for the creation of products with accurate geometric features. These are made layer by layer, as opposed to traditional manufacturing, which typically involves milling or other operations to remove excess material [10]. Because they adapt to the geometrical complexity and bespoke design of the item to be created, additive manufacturing techniques offer significant competitive advantages [11].

Topology optimization is a method of optimizing material layout and structure inside a given 3D geometrical design space according to a set of user-defined rules. The purpose is to mathematically model and optimize for external influences, boundary conditions, and restrictions in order to maximize the system's performance [12]. To achieve the most effective design, topology optimization takes a 3D design space and literally whittles away material within it. The system is unconcerned with aesthetics, conventional methods, or any other design restriction. If you define the loading and restriction system at the most basic level, it calculates the amount of material that is required to develop the load component. Each factor communicates its stress and strain energy, or how hard it is working. Many elements that do not absorb a lot of stress and have a low strain energy are doomed. They will be removed from the mesh by the topology optimizer. If it removes these elements, it will keep an eye on how their absence affects the overall changing structure [13]. The Voronoi diagram is an organic scheme for dividing space into sub-spaces. The concept of applying Voronoi diagram into design usually is to increase the stiffness body where it actually will increase the stress distribution dealt by the body. Spots are used to generate cells that surround these points in the diagram. Points can be placed randomly or in the direction of a specific data set, and tessellation can be applied accordingly. Instead of directly imitating nature, designers utilize this graphic to create a more organic-looking design [14].

2. Materials and Methods

By using the indirectly method rather than 3D scanning; the dimensions of the leg are measured manually and are directly transferred to the process of drawing the CAD model. The dimension to be determined is the general volume of foot, calf and thigh. After the process of data configuration where leg dimensions were obtained (Figure 1), the design process was done using the dimensions to draw the KAFO in the CAD software as a solid block for each part of the leg. The dimensions are increased to around 5mm since the cutting process in the design software is done from inside instead of outside to create solid shell of all the parts. The design of each part is then assembled into one KAFO product as shown in Figure 2.

(a) Foot length and height measurement

(b) Foot width and calf height measurement

(c) Calf length and width measurement

(d) Thigh height and width measurement

Figure 1. Manually measuring the general volume of foot, calf and thigh.

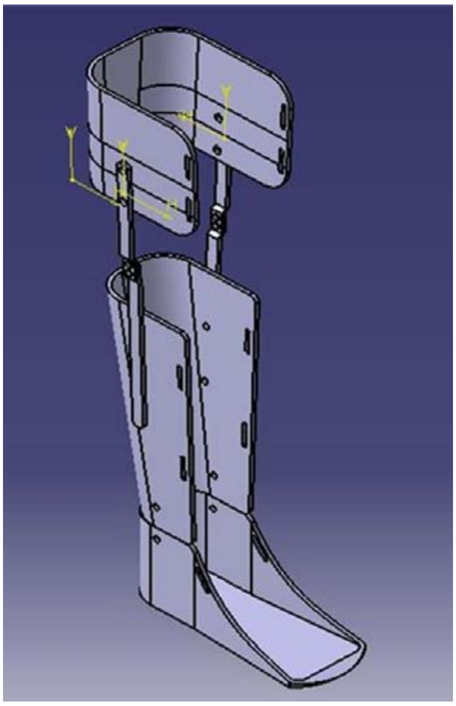


Figure 2. Design of KAFO assembly based on the measured dimension.

Finite elements analysis was performed on the KAFO using predefined meshing elements and assigning materials of stainless steel and acrylonitrile butadiene styrene (ABS). Force applied to KAFO in the direction of F_x, F_y and F_z is 29.19 N, 36.5 N and 304.60 N; respectively [15,16]. The main concern for performance assessment of the loaded KAFO is on the value of maximum stress and deflection. The objective is to optimize the design for lightweight KAFO that is able to reduce or have equal maximum value of stress and deflection. Initially process is redesigning the part that dealt with maximum stress and to reduce its stress. Topology Optimization procedure is then applied to remove the unneeded part from the KAFO based on the structural analysis result. Figure 3 show the setup of region for optimization. In redesigning process of the KAFO after topology optimization, certain element is cut to make sure the resulted KAFO is able to fulfill it intended design requirement and still be manufacturable. Finite element analysis is used to validate the original design and the optimized KAFO using the same force value. Voronoi diagram is then used to create non-uniform cellular structure on part of the KAFO that receives lower stress or no stress at all in order to further reduce the Volumatic weight of the KAFO. Autodesk Meshmixer is used to generated the Voronoi pattern on the product (Figure 4).
Figure 5 shows the methodology flow chart for optimization of KAFO design and fabrication utilizing Voronoi and AM technology.

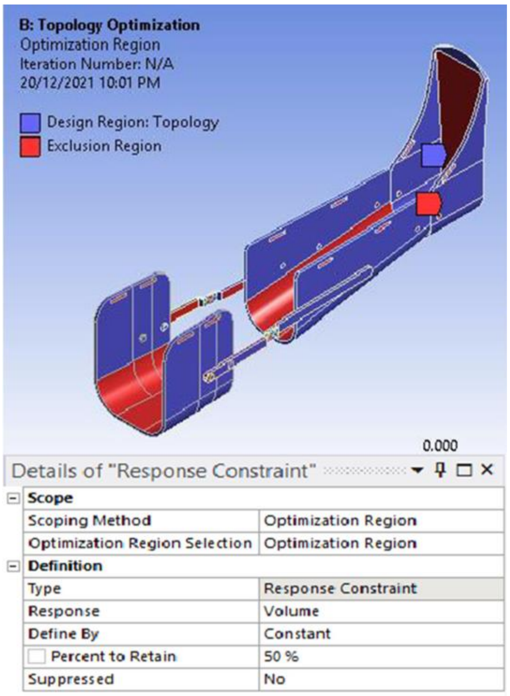


Figure 3. Region for topology optimization.

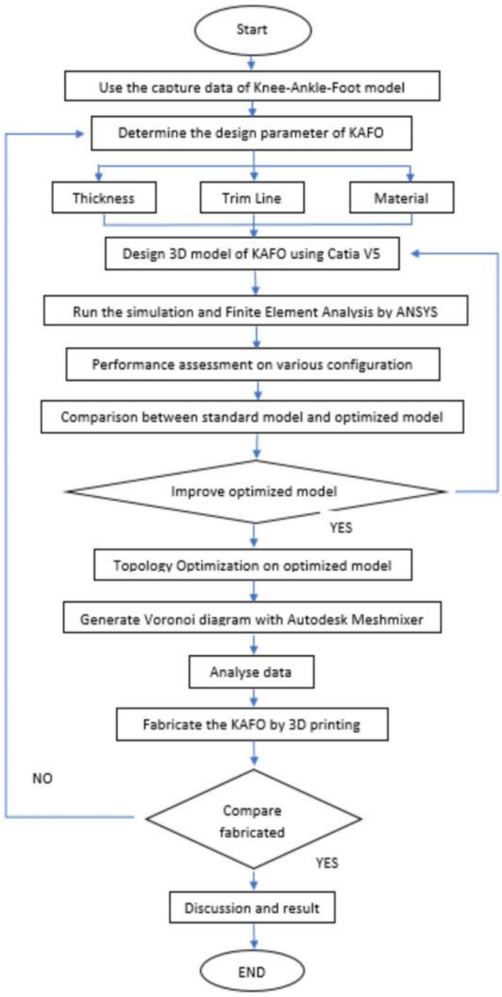


Figure 4. Methodology flow diagram.

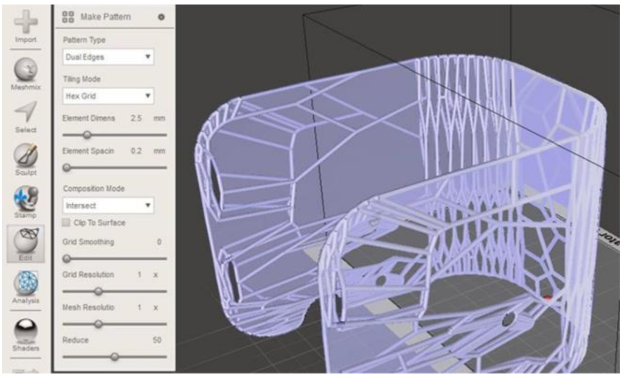


Figure 5. Design of KAFO assembly based on the measured dimension.

3. Results and Discussion

KAFO model analysis was conducted to detect if there are any interferences between the assemble parts of the KAFO before structural analysis was conducted. Figure 6 shows the clash analysis done to the 3D drawing where it shows there is no clash between the assembly part. The contact and clearance are ignored since it is part of the design. Clash analysis is done in order to detect if there is any clash between the assembly part or not since it is going to be used for meshing and other analysis. Total deformation and equivalent stress were determined for the KAFO after force is applied for structural analysis in ANSYS. The values to be looking at are the maximum deformation and the maximum stress. Figure 7 shows the equivalent stress on KAFO, the maximum value of stress is 3.3683MPa. While in Figure 8 shows the total deformation of the KAFO to be 1.5072×10-5 m. A comparison on equivalent stress was made between the original KAFO and the redesigned KAFO as shown in Figure 9. A reduction of almost 50% in equivalent stress was noticed in the redesigned KAFO.

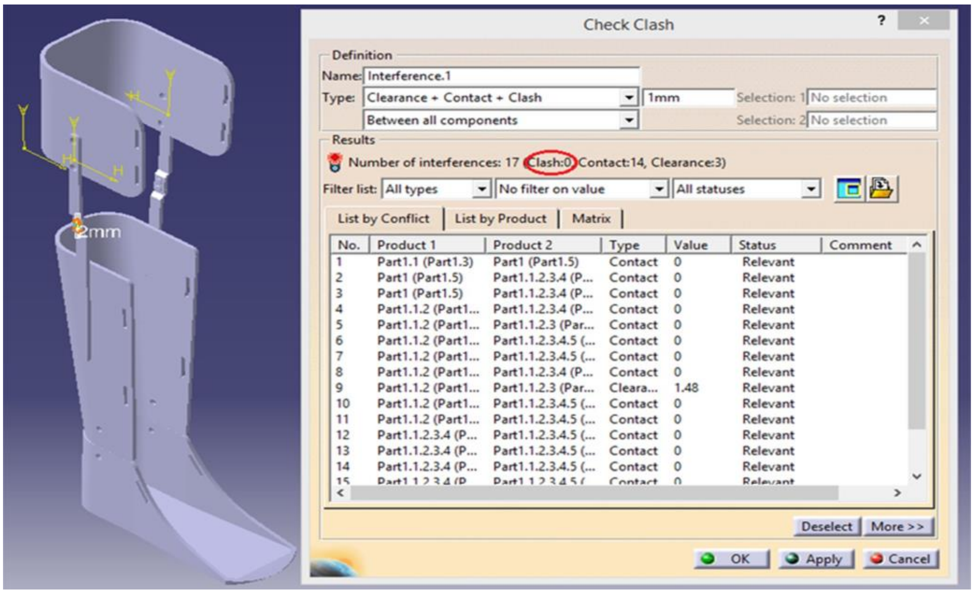


Figure 6. Clash analysis of assembly.

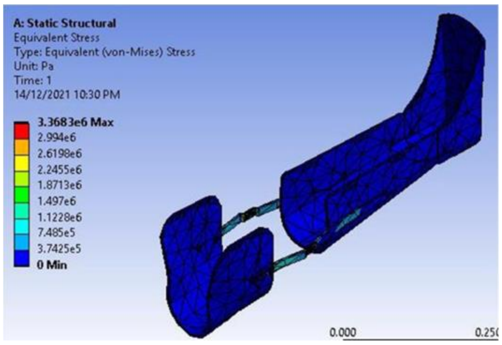


Figure 7. Equivalent Stress of the original design.

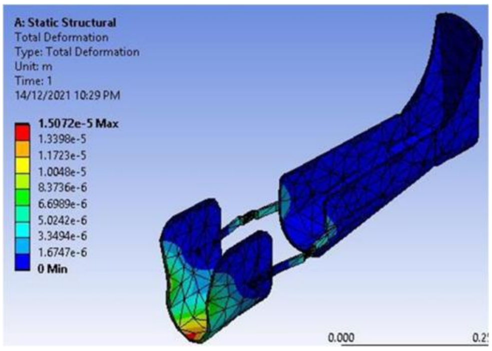
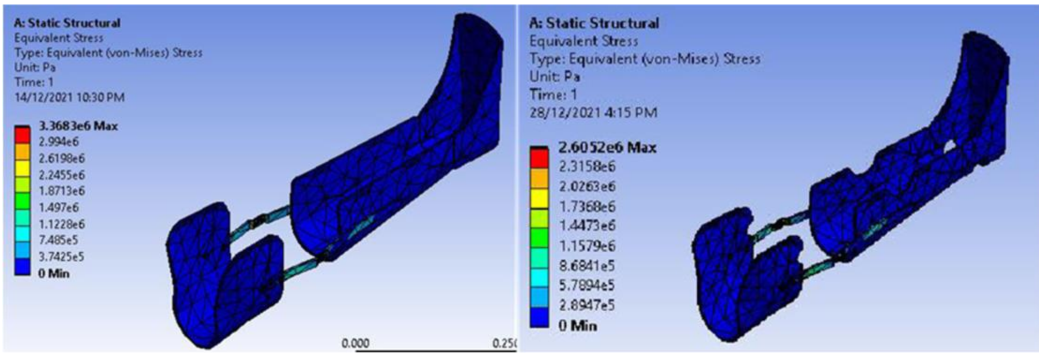


Figure 8. Total Deformation of the original design.



(a) (b)

Figure 9. Comparison of Equivalent Stress of the original design (a) and after volume reduction of 50% based on topology desity (b).

Table 1 shows a reduction trend on the measured value after the original KAFO have been optimized after structural analysis was done. It shows a total of 22.65% decreases in maximum stress, 4.33% decreases in product volume and 3.13% decreases in mass.

Table 1. Measured value for original and optimized design.

	Original	Optimized	Percent Reduction (%)
Maximum stress (Pa)	3.3683e6	2.6052e6	22.65
Volume (m^3)	0.001026	0.00098157	4.33
Mass (kg)	1.4634	1.4176	3.13

Table 2 shows the total volume of KAFO before and after the Voronoi pattern is being applied. All the parts show a decreasing pattern except foot but still the overall volume shows decreasing in volume up to 17.85%. This is as shown in Figure 10 where reduction of material created by Voronoi pattern is noticeable when compare to the model of optimized KAFO in Figure 11.

Table 2: Volume Comparison of when Voronoi pattern is applied to optimized KAFO.

Part Name	Without Voronoi (m^3)	With Voronoi (m^3)
Calf	3.732e-4	3.022e-4
Thigh	2.938e-4	1.895e-4
Foot	2.517e-4	2.526e-4
Connector	5.849e-5	5.849e-5
Total	**9.772e-4**	**8.028e-4**

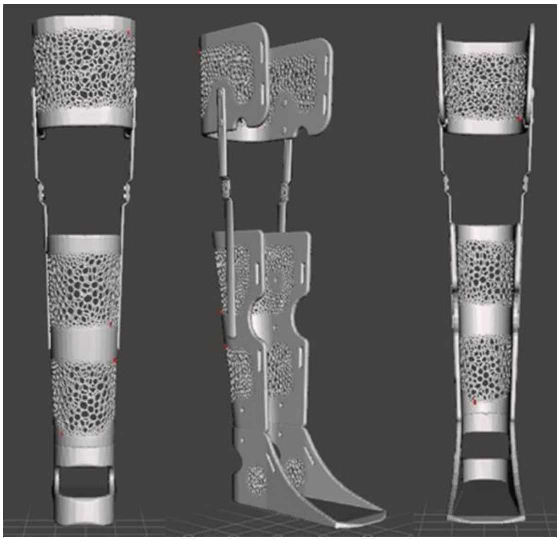


Figure 10. Voronoi model of KAFO with a reduce volume of $1.744e^{-4}$ m^3.

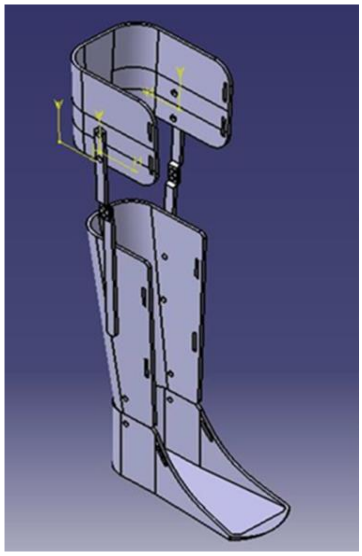


Figure 11. Model of optimized KAFO with a volume of 9.772e-4 m^3.

Several materials are used in 3D printing process, from previous research [17] it is found that 13% Kevlar fibre is the best material printing. Analysis is carried out with different type of material which is acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), nylon (PA12), polypropylene (PP) and 13% Kevlar fibre reinforced ultra-high molecular weight polyethylene (UHMWPE) to determine whether the finding is true.

The finding depicted in Table 3 shows 13% Kevlar fibre did deal with the stress far better compared to other printing material. Since it deals with the stress better, it always a possibility to further reduce the volume to decrease the weight of the printed product. However, the production cost of KAFO using composite material such as Kevlar is on the high side. The second-best option is polypropylene, but a product with nets like shape as Voronoi pattern might not be too convenient since the material tend to warp in cooling process which might damage the pattern [18]. Of course, in choosing the printing material there are some other factors to be considered such as price and availability of the material. The material that was used for this printing is PA12.

Table 3: Maximum stress and weight for printing material.

Type of Material	Maximum Stress (MPa)	Weight (kg)
ABS	2.6052	1.4176
13% Kevlar Fibre	2.0696	1.3946
PA12	2.6240	1.3992
PLA	2.5709	1.5367
PP	2.5322	1.3338

4. Conclusion

In this study, a redesign of the knee-ankle-foot-orthosis was conducted by using the application of topology optimization to reduce material usage and to make it lighter. The KAFO was modelled based on the general volume of foot, calf and thigh. The optimized design using topology optimization exhibits a considerable reduction in the maximum stress as well as a 3.13% reduction in overall mass. With a total volume decrease of up to 17.85%, the Voronoi pattern further improved the volume and material utilization of the aforementioned optimized model. This method results in meeting the requirement of mass reduction and sustaining the structural integrity of the customized KAFO. Furthermore, with the aids of FEA evaluations of structural feasibility with selected material against predictable forces and deform or collapse of the custom KAFO, useful design decisions are made. Thus, reducing the time for the creation of physical prototypes. Since the design of the custom KAFO exhibits organic structure, the AM process stands out as a viable option for the production of the custom KAFO. SLS using PA12 was chosen as the printing material for the Voronoi model of KAFO based on the price and material performance. The model took less than a week to be printed. Based on these findings, the redesign resulted in substantial decrease in maximum stress, volume, and weight while maintaining structural integrity as well as reduction in design and fabrication time, indicates the possibility of using this digital fabrication methodology to produce customised lightweight KAFO that meets certain KAFO design objectives that provides greater comfort, ergonomic, lightweight, removable and waterproof, mobility, hygiene and aesthetics. This study did not capture the design intent of clinical practitioner and further investigations are needed to study the workflow.

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