Topology Optimization and Analysis of Interchangeable Compliant Limb Attachment for Use in a Modular Lower Extremity Exoskeleton

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Abstract. Cost and size have always been a central problem in bringing rehabilitative exoskeleton technology to the masses. The huge bulk due to actuators, mounting and structural frame limits the exoskeleton's application to only within the indoor confines of hospitals. Their steep cost particularly due to expensive actuators and sophisticated gearing systems and low modularity becomes the reasoning on why this technology is not yet widely adapted in the current scenario. This paper presents a developmental framework in producing a material-efficient exoskeleton limb attachment that is compliant to individual limb geometries fabricated using the Fused Deposition Modelling (FDM) process using a Zortrax M200 3D Printer. Limb are scanned using a low-cost 3D scanner and from this scanned geometry, a limb attachment is designed. A Finite Element Analysis is configured to simulate the contact between the limb geometry and the limb attachment. From these results, a topology optimization scheme is performed to optimize the geometries so that the force distribution is constant across the attachment. Constraints in terms of structural integrity and rigidity is set to ensure the feasibility of the limb attachments.

Keywords: Design Optimization, Exoskeleton, Lower Limb, Human Centered Design, Compliant Design

1. INTRODUCTION

Topology Optimization (TO) is a mathematical technique that optimizes material within a design space based on goals (ie. Minimization of weight, volume, stresses) limited by constraints. TO have been employed in various industries in order to produce parts that are more material-efficient while maintaining structural integrity. Employing TO produces components that have lower cost, lighter mass and is more efficient in its function as well as reducing overall time taken for product development if implemented during the earlier stages of product development (Durgun & Yildiz, 2012). Although Topology Optimization is widely practiced in automotive industries for crashworthiness (Mayer, Kikuchi, & Scott, 1996), efficient vehicular structure (R. Yang & Chahande, 1995) and so forth, it has yet to be widely adapted in the design process for wearable, human-centered devices such as Powered Exoskeletons.

Powered Exoskeletons are wearable devices that functions to provide or augment the user movement through the use of motors or actuators. In the design for wearable device, a very important aspect is the ergonomic factors of the human interface between the limbs and the exoskeleton structure. Due to the differences of human anthropometry (Cavalli-Sforza, Luigi L.,1969), there is a wide variance on the topology of the limb contacts as well as different subjective parameters such as comfort and easiness of use. Traditional methods employ artisan methods through the use of casting (Chu & Reddy, 1995) where a cast is made by laying-up plaster on the wearer's limb. This process takes time and thus increases the time required to fabricate a custom limb attachment. Traditional rehabilitation process is costly due to the manpower and equipment associated cost (Taha et al., 2015) and unfortunately, this is also a huge obstacle in the adaption of Rehabilitative Exoskeletons. Most assistive rehabilitative exoskeletons have a huge upfront cost (Unluhisarcikli, Pietrusinski, Weinberg, Bonato, & Mavroidis, 2011; Weiss et al., 2013) and is designed to be non-modular in fashion (Naruse, Kawai, Yokoi, & Kakazu, 2003) where once the patient who uses the exoskeletons finishes the whole rehabilitation process, the same exoskeleton cannot be re-used by another patient. There is currently a growing demand for a modular exoskeleton (C.-J. Yang, Zhang, Chen, Dong, & Zhang, 2008) and this paper partially address the solution to the problems of designing a modular exoskeleton.

2. METHODOLOGY

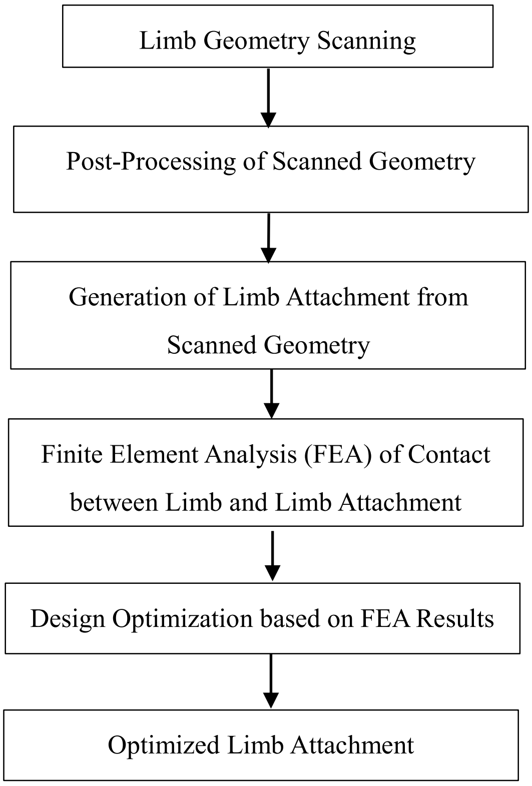

Figure 1: Overall Research Methodology

The human limb is first scanned using a portable 3D Scanner device to obtain the 3D limb model needed to design a conforming shaped limb attachment. The raw geometry obtained from the scanning is then post-processed so that it can be modified in the 3D Computer Aided Design (CAD) software. Then the limb attachment is designed in a shape conforming to the shape of the scanned limb. A finite element analysis (FEA) is performed on the limb attachment based on forces obtained from Experimentation. The results of the FEA (stresses, deformation) is used in the optimization algorithm. The optimization algorithm removes material based on the stress distribution to produce an optimized limb attachment. The FEA software used in this paper is ABAQUS and most terms and notations are based on this software.

3. 3D SCAN & LIMB ATTACHMENT DESIGN PROCESS

Figure 2: 3D Scanning process using Microsoft Kinect (Left), Output 3D Limb Geometry (Right)

In order to reduce the time taken to design the limb attachment, the scanning for the limb measurement is automated through the use of the Microsoft Kinect device. The Microsoft Kinect is an image capture device that provides a convenient, cost-efficient yet reliable means of 3D Scanning. The scan process is also rapid, taking a short while to setup and generate the geometries. In terms of accuracy, the Kinect is sufficiently accurate with differences measured in the 3D Geometry for all regions are less than 5% in difference with actual measurement according to previous research (Taha, Aris, Ahmad, Hassan, & Sahim, 2013). The geometry produced are of very high resolution, ranging from 200,000 to 400,000 polygon faces.

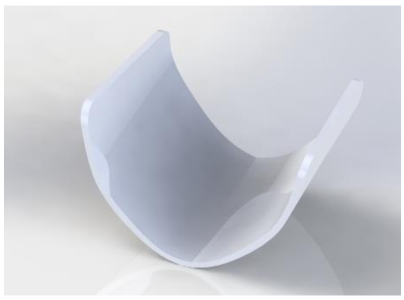

Figure 3: Limb Attachment designed based on scanned limb geometry

The individual scanned is a healthy male subject, 172 cm tall and weighing 76 kg. The region scanned is from the shank till the foot. In order to be able to modify the scanned limb model in a 3D CAD software, the geometry is smoothened and simplified in Meshlab using the Quadratic Edge Collapse Decimation, a method removing redundant faces without losing too much geometry accuracy (Zhou & Wang, 2012). The final geometry is reduced from 289,314 faces to 30,104 faces. The post-processed geometry is imported into SolidWorks. A 5mm thick, conforming, shell limb attachment (at the calf region) is then designed (as shown in Figure 3) based on the scanned geometry and is used as the initial limb attachment design.

Density	Yield Tensile Strength			Modulus of Elasticity	Ultimate Tensile Strength		
	X-Axis	Y-Axis	Z-Axis		X-Axis	Y-Axis	Z-Axis
1030 Kg/m^3	18.62 MPa	14.64 MPa	3.46 MPa	0.32	14.61 MPa	8.68 MPa	2.77 MPa

Table 1: Material Properties for Z-ABS

4. FINITE ELEMENT ANALYSIS

4.1. Material Properties for Z-ABS

In order to obtain accurate design optimization results, accurate material properties are required especially for anisotropic material such as Acrylonitrile Butadiene Styrene (ABS). ABS is a commonly used thermoplastic used in Fused Deposition Modelling (FDM). It is used in the form of filaments in which the parts are printed layers by layers. ABS is an anisotropic material in which the physical properties of the printed parts depend on the print orientation. A tensile test specimen was prepared and tested based on the ASTM D638-14 Tensile Test Standards (ASTM International, 2003). Five specimens were tested for each principle axis (There are 3 principal axes in this case based on the direction of printing in the FDM machine.) In total, there are 15 specimens tested; 5 for each principal axes. Specimens which fractures outside of the neck area had been disregarded. The resulting engineering stress and strain plots for each specimen is shown in Figure 4. The mean reading for all the values will be used in the Finite Element Analysis (FEA) and are presented at Table 1. In order to ensure component strength, the part must be oriented so that the direction major force that the component must withstand is parallel to the filament during printing as shown in Figure 5. (Ziemian, Sharma, & Ziemian, 2012)

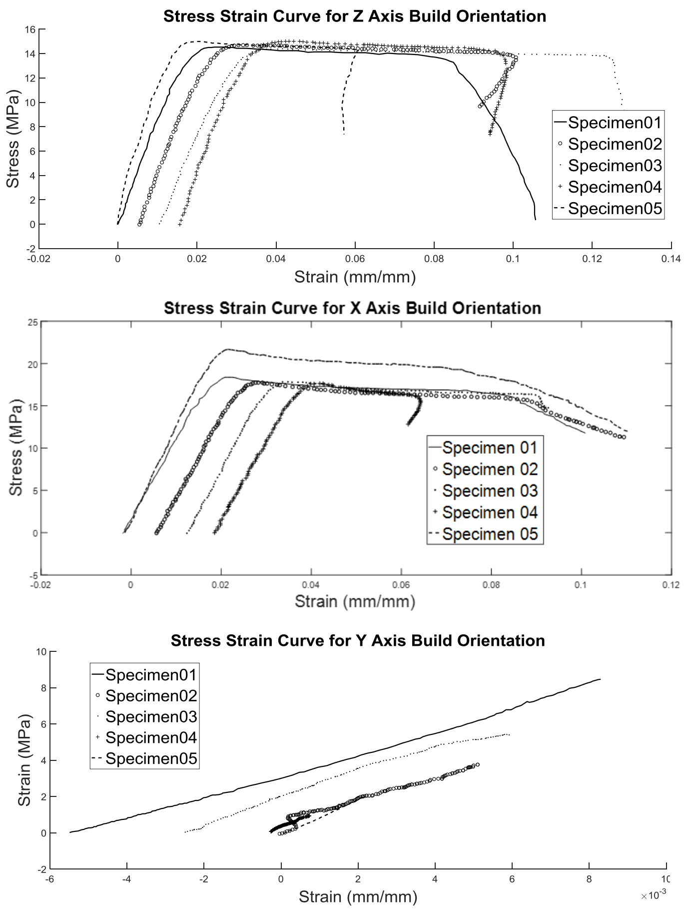

Figure 4: Engineering Stress Strain Curves for Z-ABS Material for X, Y, Z Orientations (from top) Respectively

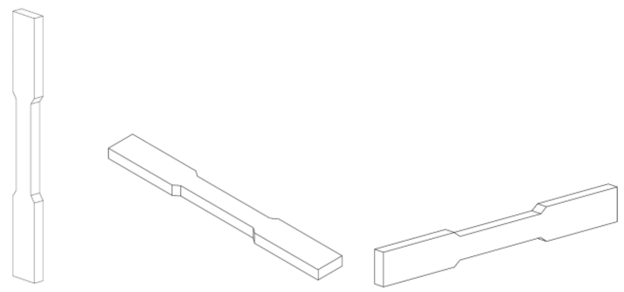

Figure 5: Specimen Build orientations for Z, X, Y (from left, respectively).

4.2. Finite Element Model

4.2.1. Boundary Conditions

Forces applied based on Force Sensitive Resistors (FSR) sensor reading on the fabricated initial limb attachment.

The FSR sensors are placed at different region, with D being the proximal point and C, B, A towards the distal point. FSR readings are taken for the same individual as the one in the scanning process. The results are shown in Table 2. These force readings is used as the force input to the FEA Model.

Points	Forces		
	X-Axis	Y-Axis	Z-Axis
A	0	0	9.51N
B	12.14N	0	33.17N
C	0	0	89.30N
D	0	0	140.01N

Table 2: Force Distribution to be Applied to the FEA Model

The side of the attachment is fixed in space (zero displacement for translation in X, Y, Z axis) as it is the attachment point to the exoskeleton.

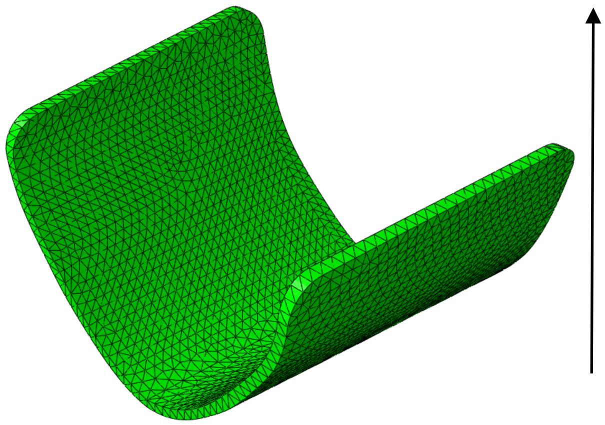

Figure 6: Meshed Limb Attachment and Boundary Conditions

4.2.2. Meshing Parameters

The component is meshed using a quadratic tetrahedron (C3D10) deformable solid mesh to allow geometries such as fillets to be meshed with consistent mesh size. The Element Size is 6.438mm. A fine mesh size is used to increase the accuracy of the optimization. The total mesh number is 19469 containing 34493 nodes. The resulting meshed geometry is shown in Figure 6.

4.2.3. Material Properties Assignment

Since Z-ABS is an anisotropic material, the material orientation in the simulation is aligned with the actual build direction on which the limb attachment is fabricated. In this case, the build direction is from bottom to top (as shown by the direction of the arrow in Figure 6). This is important because due to the directional strength of the anisotropic material, part strength differs according to where and how the forces are applied.

4.3. Topology Optimization using Solid Isotropic Microstructure with Penalization (SIMP)

The Topology Optimization was performed using the widely-used SIMP (also known as the penalized, proportional stiffness model) is a gradient-based model (Rouhi, 2004). This method is used as the SIMP algorithm is sensitive to multiple loads and ratio between them instead of the magnitude of the force.

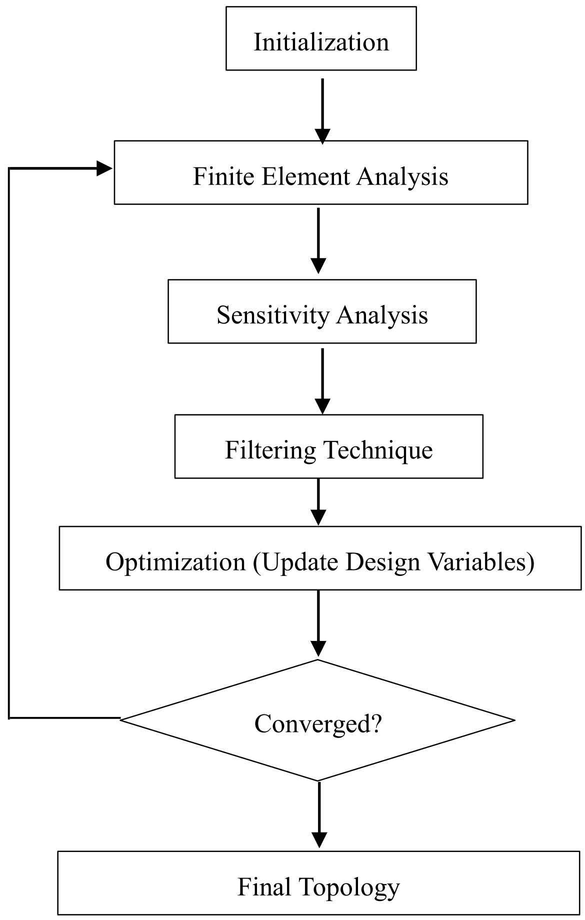

Figure 7: Workflow of SIMP (Wang, 2007) Algorithm used in this Paper.

SIMP iterates with uniform distribution densities within the elements of the design domain and volume fraction equal to the one specified. Firstly, the equilibrium equations are solved in the iterative analysis. This is then proceeded by a sensitivity analysis calculating the derivatives of the design variables. Simulation settings limit the possible amount of density updates. In order to maintain numerical stability, filtering techniques are performed before the densities are updated through the use of the minimum compliance criteria, followed by a new finite element analysis. This procedure is repeated until convergence has been reached as shown in Figure 7. In this analysis, the boundary conditions (fixtures) are frozen to ensure that the fixtures do not re-orientate based on the deformation of the component throughout the optimization iteration. The objective of the optimization is the minimization of volume (target minimization of 30%) as well as the minimization of strain energy. The reason of minimizing Strain Energy is so that the component has the highest stiffness possible in order to transfer the torque from the actuators of the Powered Exoskeleton to the human limb.

The initial weight of the limb attachment before optimization is 115.26 g with a volume of 1.13×10^5 mm^3. We used the software bundled with our 3D printer in order to calculate the total time to fabricate the component. The build time takes 20 hours and 4 minutes to complete under Solid material and small filament print size (0.09mm) settings. The FEA simulation result for this limb is shown in Figure 8.

4.4. Optimization Results

The Optimization Process yielded a satisfactory weight (101.85g) and volume (0.983×10^5 $mm^{3)}$ reduction of 13% leading to a fabrication time of 18 hours 34 minutes. The overall stiffness of the part had also increased due to the reduction of strain energy. As shown in the FEA results in Figure 9, no areas with high force concentration were found in the new optimized model. Although the design volume reduction from the optimization was modest, cumulative savings in both material and time in real-world applications would be significant due to the quantity of products fabricated.

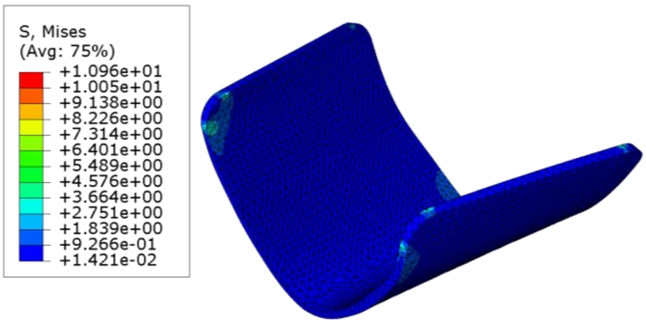

Figure 8: FEA Results for Limb Attachment (Before Optimization)

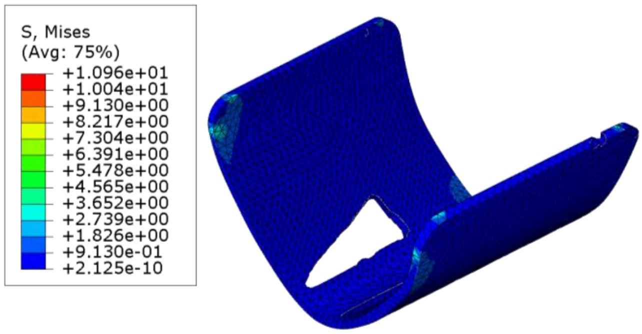

Figure 9: FEA Results for Limb Attachment (After Optimization)

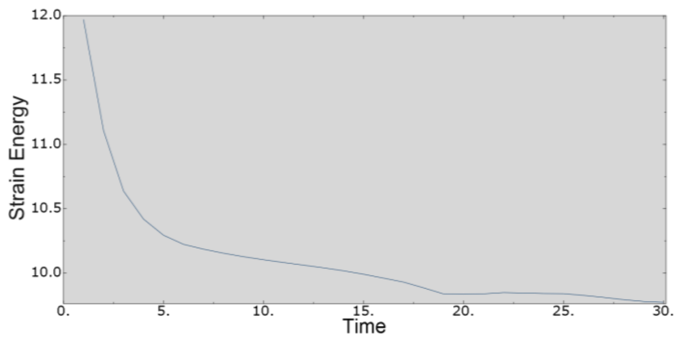

Figure 10: Strain Energy Change against Simulation Time

In reference to the optimization iteration graph (Figure 11), the volume reduction is noted to be the best at the time point of 25 seconds in terms of strain to volume reduction ratio giving a total volume of 101.2. The amount of strain energy reduction from that point onwards (Figure 10) is considerably small compared to the sacrifice in terms of volume increment. Since volume minimization is the main objective function in this paper, more weight/volume would be reduced if Artificial Intelligence (AI) methods are applied to pick the best iterative candidate.

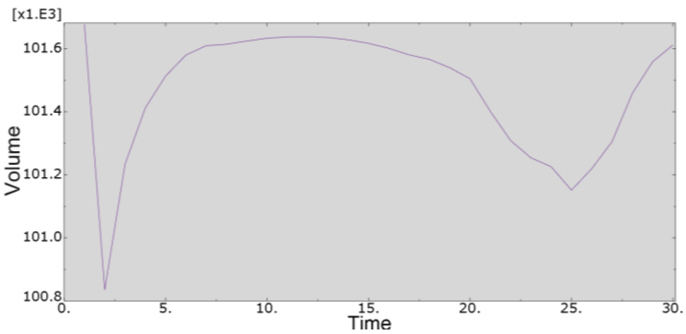

Figure 11: Volume Change against Simulation Time

5. CONCLUSION

In this paper, we introduced the application of Topological Optimization towards the design of a limb attachment with regards to the Fused Deposition Modelling (FDM) process of fabrication. We proposed a methodological framework on automating the process of limb attachment design by employing 3D scanners and the use of CAD and Computer Aided Engineering (CAE) software to speed up development times. This enables custom made limb attachments to be made for different individuals with different needs and anthropometry. Optimization is also included in the framework enabling material, cost and time savings in the fabrication of the said limb attachment.

The proposed developmental framework can be applied to the development of other products fabricated using the same Fused Deposition Modelling process though certain steps of the framework need to be modified in order to suit the design components and requirements. Future works for this research includes the implementation of artificial intelligence methods to evaluate the most optimized candidate as well as a more effective optimization algorithm.

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