Mechanical suitability of carbon fiber based composite for chopart prosthetic socket

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Abstract. Material selection has important role in the design of prosthetics. Presently, polyethylene (PE) has been majorly used in the manufacture of chopart prosthetic socket due to it mouldability and low cost, but suffers from large weight to strength ratio. In the present study, carbon fiber composite (CF) is compared with PE for its usability in chopart prosthetic sockets. 3 perlon layers-2 carbon fiber layer-3 perlon layers (3P-2C-3P) lamination was developed and tested for the mechanical properties. Later, the tested mechanical properties of PE and CF were used in finite element modelling to analyze stresses and deformation in the Chopart prosthetic socket. The study showed that use of CF in chopart prosthetic sockets reduces stress by 70.6% as compared to PE, and could be suggested as mechanically superior material in design of chopart prosthetic socket compared to PE.

1. Introduction
Ability to perform ambulation measures the independency in living and over all wellbeing of the person [1]. The need of performing an amputation suffocates the independency in performing day to day activities [2]. According to the United States National Health Survey in 1996, it was found that 1.27 million people in America were living with lower limb loss, and this number is estimated to rise by 3.6 million by 2050 [3]. Partial foot amputation (PFA) is the most common kind of amputation suffered by patients. Lisfranc and chopart amputations are such PFA that were introduced in 19th century by French surgeons. Lisfranc is disarticulation of metatarsal joint, while chopart shortens the foot by removing mid and forefoot of the patient [4,5]. Besides comfort studies and ease of use of prosthetics design [6], finite element (FE) modelling has become an important tool for material selection and design analysis of such prosthetics. FE analysis has been used to study polypropylene (PP) based ankle foot orthosis (AFO) for drop foot patients [7]. Biomechanics together with FE modelling was earlier used to study impact of shoe soles in rehabilitation [8]. FE models have been developed to study tarsal bone degeneration in Hansen's disease [9]. A dynamic FE analysis of human foot was implemented with explicit dynamics with assumptions to be isotropic, linearly elastic and homogeneous [10].

In general, the polymeric material used in manufacturing prosthetics socket consist of polymers, Polyamide, Polyester, Copolyester, Polypropylene, Polyethylene, Polyphenylene sulfide, Polyvinylidene fluoride [11]. Polypropylene has been a much sought material for the manufacture of prosthetic sockets owing to the low cost. However, studies have shown the loss of mechanical properties of polypropylene with time. Furthermore, manufacturing of polypropylene is associated with the risk for skin allergies, allergic bronchitis which may even lead to lung cancer in
manufacturing personals [12]. In recent time carbon fiber and glass fibers composites, owing to their better mechanical properties, have gained interest as a manufacturing material for prosthetic sockets [13].

The purpose of the present study is to evaluate carbon fiber composite as a potential material for the chopart socket prosthetic in terms of mechanical properties. Carbon fiber composite based socket is compared with the much popular polyethylene based socket using FE modelling.

2. Materials and Method

2.1. Estimation of Mechanical Properties

Test specimens for polyethylene (PE) and carbon fiber composite (CF) were fabricated for estimating the mechanical properties which was later used for finite element analysis.

2.1.1. Carbon fiber composite. The CF composite tested in the present study consisted of 2 layers of CF (Ottobock healthcare 616G15) sandwiched between 3 layers of perlon stockinet (Ottobock healthcare 623T3). 80:20 polyurethane and e-orthocryl lamination resin was used as an adhesive for the composite.

2.1.2. Fabrication of specimens. Vacuum molding with gypsum molds was used for the fabrication of CF composite lamination. Polyvinyl-alcohol (PVA, Ottobock healthcare 99B71) was used to cover the mold and lamination. Lamination resin and hardener was used in the standard ratio i.e. for each 100 part of acrylic resin mixed 2/3rd part of hardener. Constant vacuum of 35 mm of Hg was maintained until the composite materials come to room temperature. Three tensile and flexural test specimens were then machined according to ASTM D638 and ASTM D790 respectively [14]. Also, three PE specimens were machined from the 4 mm PE sheet for testing. Hence, the total 12 specimens were tested for tensile and flexural strength. Figure 1 shows the tested specimens and the test machine.

![Testing setup and specimen for PE and CF for (a) Tensile test and (b) Flexural test](image)

**Figure 1.** Testing setup and specimen for PE and CF for (a) Tensile test and (b) Flexural test

2.2. Finite Element (FE) Analysis

2.2.1. 3D Model Generation

Digital prototyping for the chopart socket was done using 3D scanning. First, cloud point of full scale human lower limb was obtained using 3D scanner (RangeVision smart). The point cloud was later imported in Autodesk Meshmixer for developing the solid model. The solid model file was then used to design the chopart socket using Autodesk Inventor as shown in figure 2.
2.2.2. **FE model setup**

The model was analyzed for stresses and deformation while 75 N force was applied at the chopart socket. The foot of the prosthetic was given the fixed constrain. The FE analysis was done in ANSYS (2016). The total number of mesh elements were 39744 with 61879 number of nodes. Figure 3 shows the ANSYS model. Von Misses theory of failure was assumed for the analysis. The analysis was done for the two materials considered in the study i.e. PE and CF.

![Generation mesh of prosthetics socket](image)

**Figure 3.** Generation mesh of prosthetics socket

3. **Results and discussion**

3.1. **Experimental Results**

The mechanical properties ($\sigma_y$, $\sigma_{ult}$ and $E$) as obtained from the test specimens is shown in Table 1. These properties were later used as input data in the ANSYS to simulate the prosthetic socket and analyse the stresses with the tested load condition.

| Materials | Yield Stress $\sigma_y$ (MPa) | Ultimate Stress $\sigma_{ult}$ (MPa) | Young’s Modulus $E$ (GPa) |
|-----------|-------------------------------|--------------------------------------|--------------------------|
| PE        | 18                            | 22                                   | 1.9                      |
| CF        | 22.5                          | 27                                   | 2.2                      |

![Table 1. The mechanical properties of the material tested.](image)
3.2. Simulation Results

The model was tested for the deformation and stresses for two materials considered in the study. Maximum deformation of 43 mm was found for PE compared to 11 mm for CF. The equivalent Von-Mises Stresses were evaluated. The highest stress value was 11.6 MPa in the socket made from PE, while the highest stress for CF based socket was 3.4 MPa. Heal was found to be the most stress concentrated region. Figure 4 shows the result from FE analysis.

![Simulation Results](image)

**Figure 4.** Total deformation and equivalent stresses for CF and PE chopart socket

While both of the CF and PE prosthetic socket gave a safe factor of safety, the CF socket has maximum equivalent stress of 3.4 MPa which was 70.6% lesser than the equivalent peak stress in PE socket. Hence, the CF socket can also be tested for lesser thickness at the heal as compared to PE socket. CF could be used a light weight alternative to reduce the physiological cost of the patient using the chopart socket. It is for this reason that CF is desired for the manufacture of prostheses, regardless of its high cost [15].

4. Conclusions

The goal of the current study was to access the suitability of carbon fibre composite in the design of chopart socket. From the mechanical tests, CF was found to have 20.4% and 18.5% high yield stress and ultimate respectively as compared to PE. Simulation study showed decrease in equivalent stress by 70.6% compared to PE. Also, CF provide significantly higher strength to weight ratio than PE. The simulated results indicated the suitability of CF based composite as a mechanically suitable choice for chopart prosthetics socket design.

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