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Mechanical performance and fatigue analysis of transfemoral prosthetic socket

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ABSTRACT

This study investigated the simulation and testing of a prosthetic socket made from two distinct composite material arrangements. The first arrangement consists of ten layers of carbon fiber, while the second is composed of ten layers of Perlon fibers. The prosthetic was designed for a 20-year-old female patient, measuring 155 cm in height and weighing 75 kg. Mechanical property analysis revealed that the ultimate tensile strength (σ_{ult}) and yield strength (σ_y) for Group 2 (Perlon) were 145 MPa and 137 MPa, respectively, while for Group 1 (carbon fiber), they were 285 MPa and 280 MPa. The fatigue limit for Group 2 was 145 MPa, while Group 1 had a fatigue limit of 78 MPa. The interface pressure on the stump was measured using F-Socket in four regions: anterior (495 kPa), lateral (427 kPa), posterior (384 kPa), and medial (351 kPa). Using ANSYS 14.5 software, the fatigue safety factor was determined, with Group 1 (carbon fiber) showing a safety factor of 1.2, which is considered adequate for design purposes, while Group 2 (Perlon) had a safety factor of 0.096, indicating failure.

Keywords: AK Prosthetic socket, interface pressure, socket suspension, fatigue, composite materials.

INTRODUCTION

The trans-femoral amputation or Above knee (AK) amputation level has a significant impact on the patient's life, as compared with the other levels of amputation. This impact happened because the patient lost two major joints which has a huge effect on the gait cycle. Also, the patient will not be able to achieve a normal gait in terms of velocity, cadence or walking efficiency [1]. This amputation has three levels: long, mid and short AK. Each level has certain characteristics; in long stump amputation, the patient will have good ischial weight bearing, good balance of muscular of the adductors and best energy efficiency. However, in medium stump, the patient will have reduced length stump which leads reduced range of motion of the adductors, in addition to increased flexion joint and greater energy consumption for lifting the prosthetic [2]. However, in short stump, the patient will have weak anterior and medial muscles with bad balance while using the prosthetic, the increase flexion and abduction joint will need more energy for lifting and walking, in addition to the weak prosthetic suspension [3–5]. The good length of above the knee amputation is about 7.5–10 cm from ischial bearing to the end of stump. There are several causes of amputations, including: trauma, vascular diseases, infection, and tumors) [4]. Abbas and Mohammed [6] studied the revo fit prosthetic solution with socket. Abbas, et al., [7–8] studied different layers of material of prosthesis and modeling simulation to improve the mechanical properties. Abbas [9] worked on fatigue characteristics and numerical modeling socket for patient with above knee prosthesis. Abbas and Kubba [10] studied the numerical modeling for different layers of prosthesis material amputation. Carabello et al. [11] investigated prosthesis socket management after Transfemoral Amputation. They emphasized the need for appropriate assistive technologies and the potential of further development of existing systems. Behera and Indalkar [12] studied three different socket suspensions on sample of ten amputees. They concluded that total elastic suspension is more flexible and comfortable for working. There is interesting research on socket materials and their effect on the mechanical properties [13–16]. Some research has addressed 3D printing and control systems related to the field of prosthetic and orthotic limbs, as this field is very important for a wide segment of people suffering from amputations at the level of the lower limbs [17–19].

In this work, a Revo fit solution was suggested to fix the outer surface of the prosthetic socket and the end connection of the silicon liner by a screw. This solution will give better suspension through swing phase than other technologies. Two groups of fiber-reinforced material samples made of (80:20 fiber and resin, respectively) with ten layers of fiber in both groups, Perlon fiber and carbon fiber were suggested for the two groups in this research, tensile fatigue tests were implemented to ASTM. The experimental data were implemented in a numerical solution using ANSYS work bench software to find the total deformation, equivalent stress and fatigue safety factor. The collected results from the experimental tests and the numerical analysis were used to manufacture an acceptable socket design for the above knee amputee patient.

EXPERIMENTAL PROCEDURE

Materials

The artificial limb manufacturing materials were shaped using vacuum technology [20]. The materials used are:

1. Carbon fiber: woven carbon fiber as a reinforced material.
2. Lamination resin: the matrix resin used was of PVA type.
3. Hardener: hardening powder for Orthocryl resins.
4. Polyvinyalcohol: which is a water-soluble synthetic polymer.
5. Perlon lamination 10 cm compatible with the PVA resin (Table 1).

Table 1. Type of above knee socket materials

No.	Thickness (mm)	Layers and materials
1	2.4	10 Carbon
2	4	10 Perlon

Tensile tests

The samples used were manufactured according to the ASTM D638 international standard [21], as shown in Figure 1. Three samples were used for each group in the tensile test. The experiments were conducted using Testometric Materials Testing Machines in the mechanical engineering laboratories at Al-Nahrain University. Tested at room temperature 25±2 °C. The test speed was 5 mm/min.

The fatigue test

In the fatigue test, samples were used for each type of the prostheses materials by using cyclic bending stress. The dimensions of the sample used in the fatigue test were 100 mm by 10 mm and had variable thickness depending on the type of material, as shown in Figure 2. The tests were conducted on a HI-TEICH fatigue machine for cantilever beam specimens. The fully reverse moment was applied at frequency of about 50 Hz. The deflection-controlled fatigue was carried out to evaluate the applied load and then moment.

The case study

The applied pressure to the stump muscles from between the inner surface of the socket for female patient age 20 years, height 155 cm, and weight 75 kg.

RESULTS AND DISCUSSION

Tensile test results

The results of the mechanical properties of these composite materials that are used in prosthesis sockets are shown in Table 2. Figure 3 as the first figure clarified the relationship between stress and strain for the two groups. The mechanical properties (σ_y, σ_{ult} and E) of the two groups are given in Table 2. It was found that the change of composite materials in the manufacture of the prosthesis from Perlon to carbon fiber in the number of layers affects the mechanical properties of the two groups. It was observed that this effect increases the mechanical properties in the

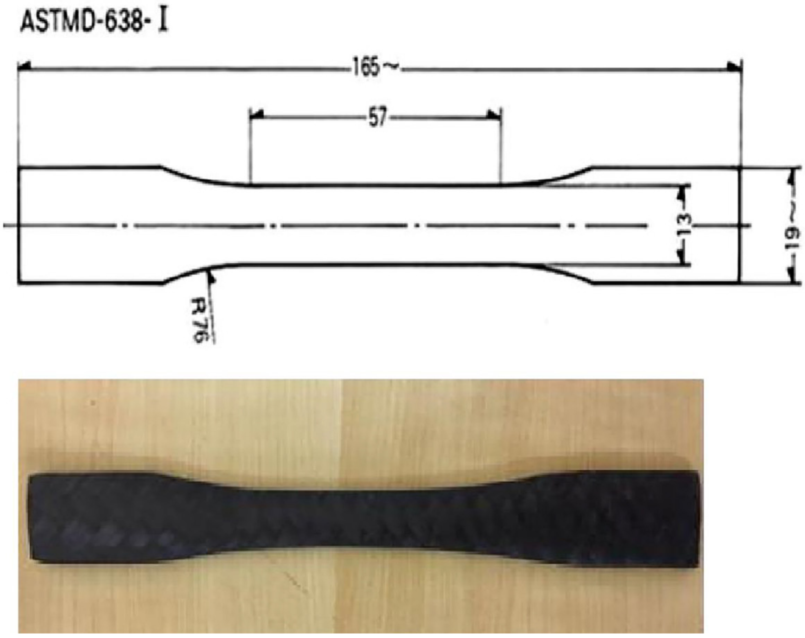

Figure 1. ASTM-638-I tensile test specimen dimensions and sample

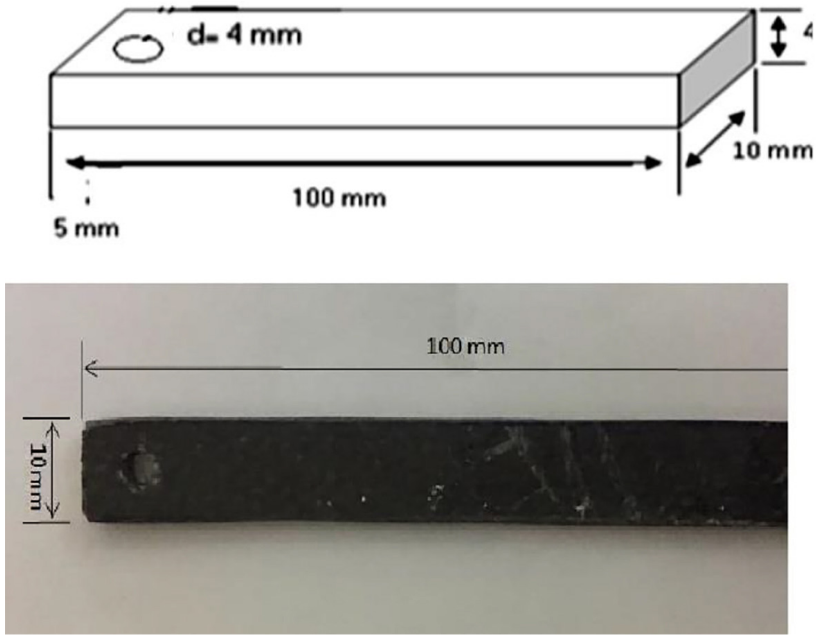

Figure 2. Fatigue test specimen dimensions and sample

Table 2. Mechanical properties of carbon fiber and Perlon

No.	Thickness (mm)	σ_y (MPa)	σ_{ult} (MPa)	E (GPa)
1	2.4	280	285	2.9
2	4	137	145	1.8

following proportions. σ_y, σ_{ult} and E in the rate of 101%, 96% and 61%, respectively. This difference in results from the high strength of carbon and gives the socket very high strength as well as durability compared to the fibers that can saturate and absorb high, but with less strength than carbon fibers. Reinforced composite for carbon fiber is more than for Perlon.

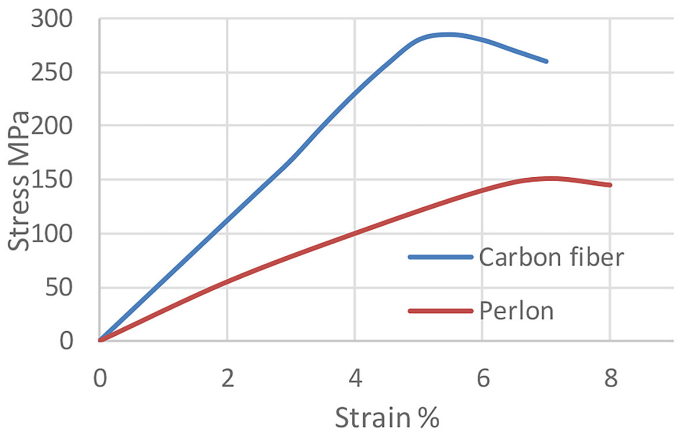

Figure 3. Stress and strain of Perlon and carbon fiber

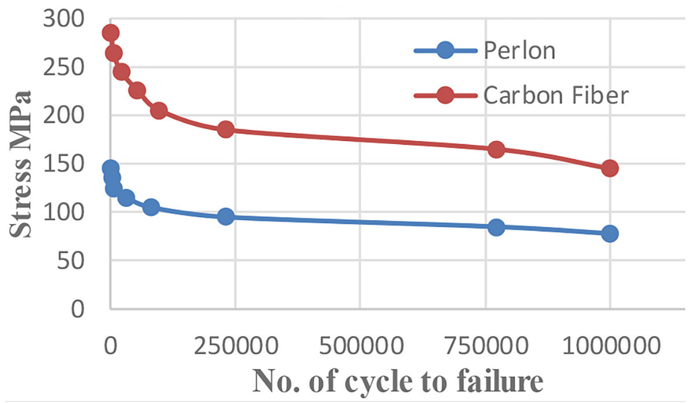

Figure 4. Fatigue stress with cycles

Fatigue results

The results of fatigue tests are shown in Figure 4 with the specific values of specimen failure points on the curve. The fatigue tests were conducted at room temperature. The fatigue tests were operated at eight stress values with approximately 10^6 cycles for the lowest stress value. The endurance strength values for the carbon fiber and Perlon specimens at 10^6 cycles are 145 MPa and 78 MPa, respectively.

F-Socket results

The generated interface pressure on the stump surface and the inner wall of the prosthetic socket (Fig. 5), was measured using F-Socket. The device interface pressure data are shown in Figures (6–9) which represent the four sides of the stump. The maximum values of the recorded pressures for each side are listed in Table 3. The maximum recorded pressure values were 495 kPa and 427 kPa at the areas of active muscles. The reason is due to the higher-pressure value on the anterior surface than the lateral surface of the stump was due to the high muscle activity and strength in these areas of the patient's stump.

ANSYS results

The performance analysis boundary conditions have been utilized to find a prosthetic limb behavior under the patient's usage. The presented socket was modeled numerically under the following assumptions:

Table 3. Pressure with walls socket

Regions	Anterior	Lateral	Posterior	Medial
Pressure (kPa)	495	427	384	351

Figure 5. Patient with Revo fit on the socket

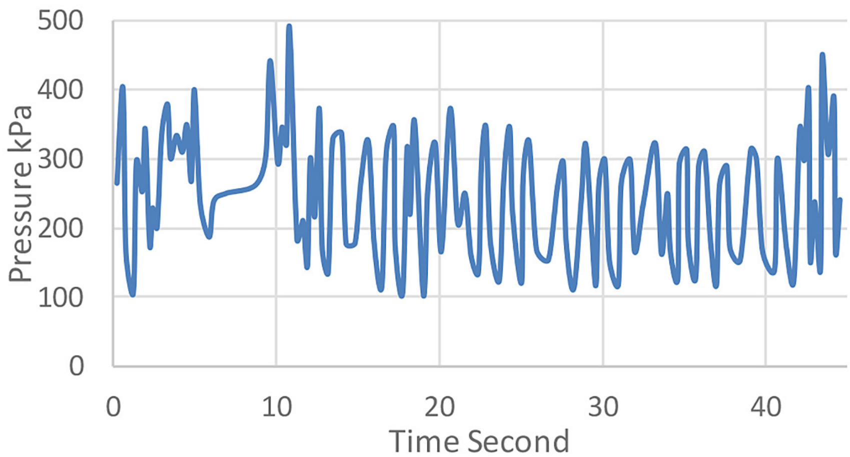

Figure 6. Interface pressure at anterior socket region

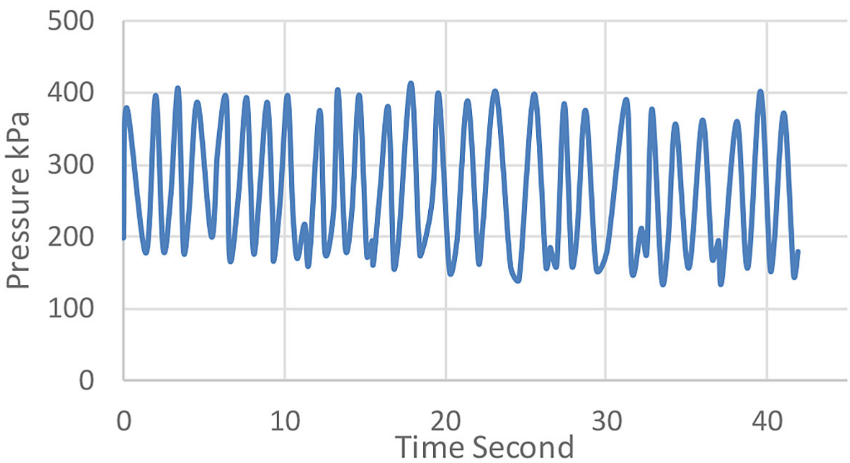

Figure 7. Interface pressure at lateral socket region

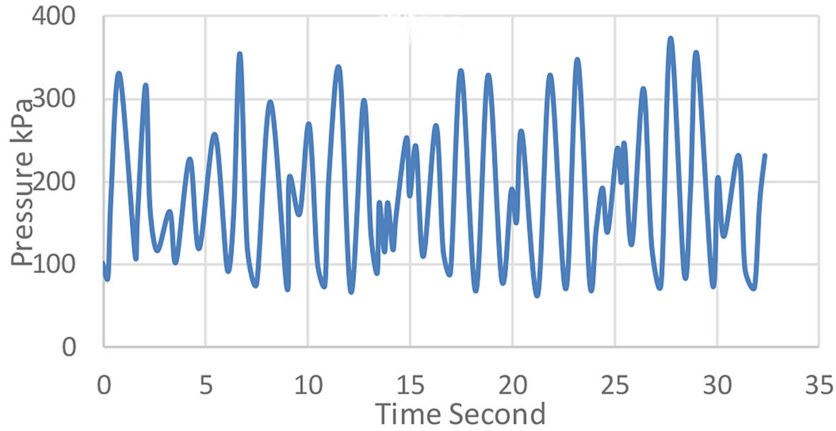

Figure 8. Interface pressure at Posterior Socket Region

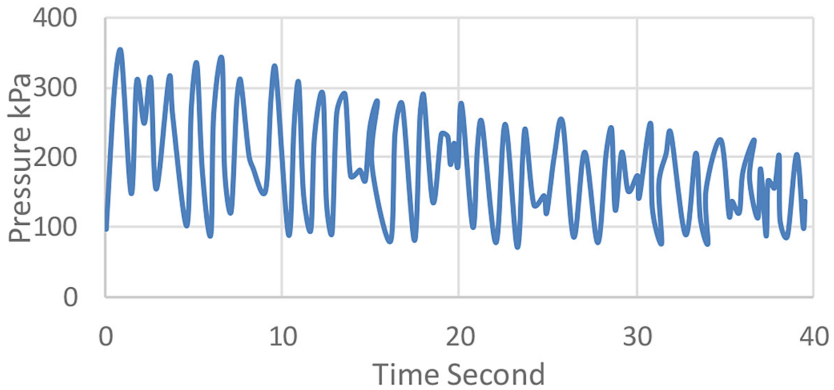

Figure 9. Interface pressure at Medial Socket Region

1. The contact area with the pylon was considered fixed.
2. The mean interface pressures obtained from the experimental tests were applied within the inner surface of the existing socket.
3. Homogeneous and isotropic socket material for same materials layer [22].

The calculated results from the analysis are the generated stresses, deformation values and the safety factor. These data were collected for the two groups of the materials which are used in the manufacture of the above the knee prosthesis socket.

The equivalent stress results of the AK socket models are shown in Figures 10 and 11, these figures show the results for the two groups of materials which are suggested in this research. The first group is reinforced with carbon fiber and the second one is reinforced with Perlon. The mechanical properties of the two groups of these materials are submitted to the software as collected from the collected experimental data. The results show that the maximum generated stress in the carbon fiber socket model is within the elastic limit of reinforced carbon fiber tested specimen in Table 2. On the other hand, the second group results with Perlon, show maximum generated stress in the socket model is higher than the elastic limit, which present a failure design for this socket according

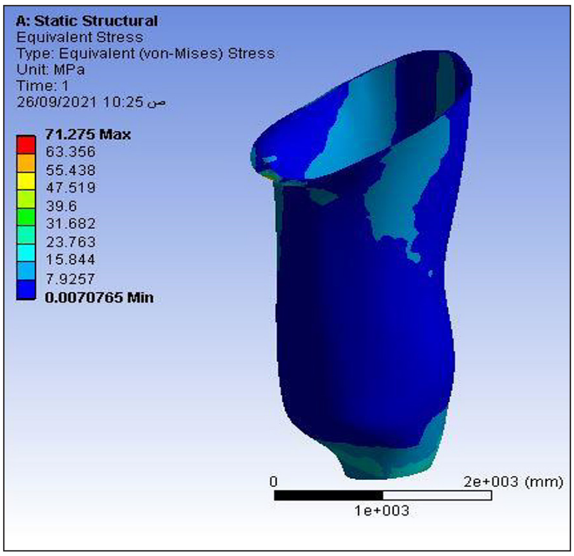

Figure 10. Equivalent stress (von Mises) in group 1

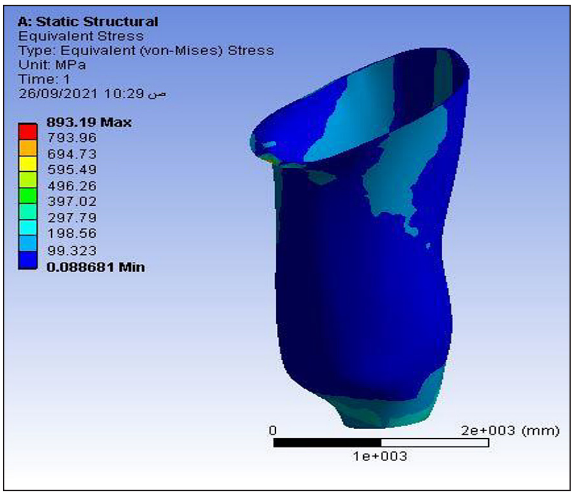

Figure 11. Equivalent stress (von Mises) in group 2

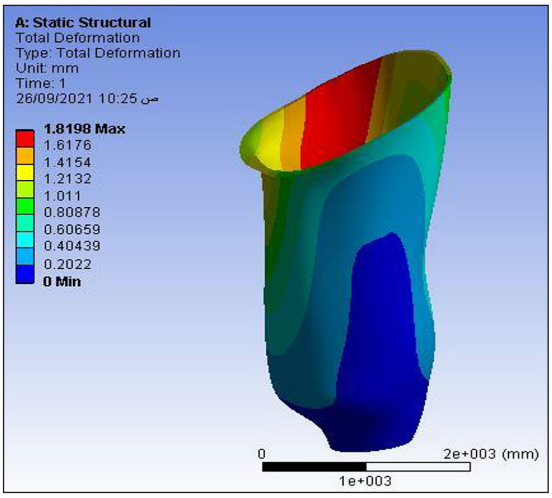

Figure 12. The total deformation in group 1

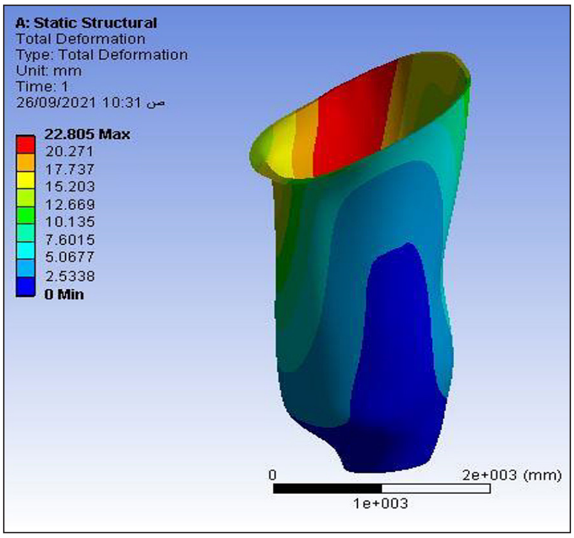

Figure 13. The total deformation in group 2

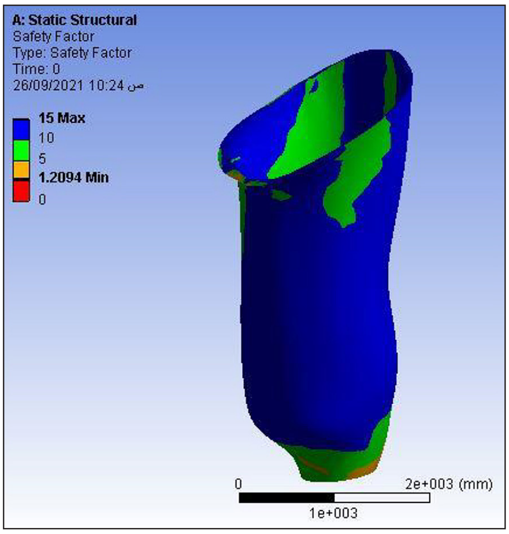

Figure 14. Group 1 fatigue factor of safety

to Von Mises stress results criteria. Figures 12. and 13 show deformations for materials, which also show remarkably high deformation in Perlon reinforced socket model which also not useful for socket design. This deformation which reaching to 20.8 mm (as shown in Fig. 13) is out of the reasonable accuracy for a prosthetic socket which led to unstable socket suspension during the patient gait cycle. The maximum deformation of the carbon fiber socket (group A) reaches less than 2 mm, which is acceptable for suspension system.

-The safety factors were calculated using Goodman equation, the fatigue strength factor used is 0.8 with fully reversed loading, SN-none with equivalent (Von Mises) stress used for applied stresses. The result from the numerical model for the first group, i.e. carbon fiber-reinforced

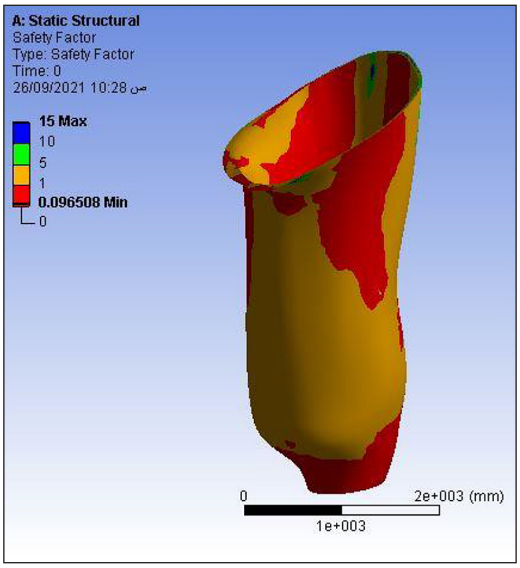

Figure 15. Group 2 fatigue factor of safety

socket model is shown in Figure 14. The result shows 1.2 minimum fatigue safety factor which can be considered acceptable in mechanical designs. However, in Perlon reinforced socket model shown in Figure 15, the result shows around 0.096 minimum fatigue safety factor which presents a failure.

CONCLUSIONS

The development of advanced materials for transfemoral prosthetic sockets has the potential to significantly improve the performance, comfort, and longevity of prosthetic devices. This study compares two materials, Perlon fibers and carbon fibers, used in the fabrication of transfemoral prosthetic sockets. The primary objective was to evaluate the mechanical properties, fatigue resistance, and structural integrity of sockets made from these materials. The findings of this study shed light on the critical differences in performance between these materials and provide valuable insights for future prosthetic designs.

1. Mechanical property improvements with carbon fiber. The transition from Perlon fibers to carbon fibers, while maintaining the same number of layers for both materials, resulted in a significant enhancement of mechanical properties. Specifically, the yield stress, ultimate stress, and modulus of elasticity showed increases of approximately 101%, 96%, and 61%, respectively. These improvements underscore the superior mechanical strength of Carbon fiber as compared to Perlon, making it a more robust material choice for transfemoral prosthetic sockets.
2. Fatigue resistance enhancement. Fatigue testing at one million loading cycles revealed a notable difference between the two materials. Carbon fiber demonstrated a fatigue limit of 145 MPa, while Perlon reached only 78 MPa. This represents an 85% increase in fatigue resistance for the carbon fiber specimens, indicating that carbon fiber can withstand more extensive use and loading cycles before failure, which is critical for long-term durability.
3. Deformation and structural integrity. The deformation measurements during testing revealed substantial differences between the two materials. The Perlon socket exhibited a deformation of approximately 22 mm, which exceeds the acceptable limit for maintaining proper suspension of the prosthetic limb. In contrast, the carbon fiber socket exhibited a deformation of less than 2 mm, remaining well within the acceptable threshold for functional and secure suspension.
4. Fatigue safety factor analysis. Simulation results provided by software analysis showed that the fatigue safety factor for the above-knee prosthetic socket made from carbon fiber was 1.2. This safety factor is considered acceptable in mechanical design, ensuring that the socket can withstand normal usage without premature failure. On the other hand, the Perlon socket exhibited a safety factor of 0.096, indicating a design that is insufficient to reliably withstand the forces it would encounter during use.

While the current study demonstrates the superior performance of carbon fiber over Perlon fibers in transfemoral prosthetic sockets, several areas warrant further investigation. Future research should explore the long-term performance of carbon fiber sockets under various environmental conditions, such as exposure to moisture, temperature fluctuations, and wear over extended periods. Additionally, studies should focus on optimizing the manufacturing processes for Carbon fiber sockets to reduce costs and improve accessibility for patients. Finally, the integration of sensor technology into prosthetic sockets for real-time monitoring of performance and wear could lead to even greater advancements in prosthetic design and user outcomes.

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