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Research Paper

Enhancement of materials for patellar tendon load-bearing orthosis: Design, analysis, and manufacturing study

Ghanim SH. Sadiq [1], ***Salsabil K. Mohammed*** [2], ***and Saif M. Abbas*** [2]

[1] *Mechanical Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq.*
[2] *Prosthetic and Orthotic Engineering Department, College of Engineering, Al-Nahrain University, Baghdad , Iraq.*

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ABSTRACT

A patellar tendon bearing orthosis (PTBO) is used to support and shift body weight away from the area below the knee. Evaluation of various composite materials, Patellar Tendon Bearing Orthosis was conducted. Important details on the mechanical properties of each group by tensile and fatigue testing. Drawing and analysis PTBO model using Ansys Workbench 17.2. For perlon, the modulus of elasticity (E), yield stress, and ultimate stress were found to be 10.580 MPa, 37.895 MPa, and 1.253 GPa, respectively. Carbon fiber had better mechanical properties, with a modulus of elasticity (E) of 1.958 GPa, a yield stress of 116.878 MPa, and an ultimate stress of 174.163 MPa. In conclusion, Glass fiber displayed an ultimate stress of 99.725 MPa, a yield stress of 90.672 MPa, and a modulus of elasticity (E) of 1.589 GPa. The fatigue resistance of carbon fiber was found to be superior to that of perlon, indicating the extended lifespan made of carbon fiber. The outcomes of the experimental interface pressure tests show that the highest recorded values are on the lateral side (320 kPa) and the posterior side (253 kPa). This shows that the pressure was dispersed uniformly throughout the tissue and away from the bony areas, enhancing walking comfort for the patient. Acceptable in the PTBO model design were the safety factors, total deformation, and (Von-Mises) stress distribution obtained from numerical analysis for the carbon fiber PTBO model, which were 1.49, 0.969 mm, and 86.009 MPa respectively.

1. Introduction

Orthoses are external devices that support, align, and stabilize body components in order to interrupt or facilitate movement. They can prevent or treat abnormalities and improve the way dynamic body components work. Orthotics is used to govern, correct, facilitate, limit, or prohibit mobility of the spine or extremities, among other things. They can also reduce muscular stiffness and make up for paralyzed or weak muscles. These goals do not have to conflict with one another; in fact, in many therapeutic settings, using these functions in concert is necessary to get the best possible patient results. [1–3]. An orthotic device called a patellar tendon bearing orthosis (PTBO) is used to support and shift body weight away from the area below the knee. The orthosis is made with a stiff framework at the lateral and medial sides of the lower leg and is padded with soft material in the inner part of the orthosis to provide comfort, support and relieve the pressure in certain areas, such as the patellar tendon and bone area. This orthosis is helpful in controlling lower limb disorders or injuries such as fractures, tendinitis, or arthritis since it helps to preserve correct alignment and reduces discomfort during weight-bearing activities [4–8]. the orthosis functions best for restricted motion range at the ankle joint [9]. When the patient recovers that lead to expand the range of motion. The PTBO's main function is to support and release body weight from the region below the knee, particularly when there is pain or structural issues [10–13]. Using a dynamic plantar pressure system analysis, H. Tanaka et al. assessed the unloading case effects of the patellar tendon-bearing (PTB) model for five healthy individuals. a technique to improve the PTB's unloading effect, which was then verified using the same system[14–16]. A large number of important studies on prosthetic materials and sockets have been completed. Saif Mohammed Abbas and Mohammed Hassan Abbas looked at the usage of carbon fiber and Revo-Fit technology to improve socket suspension, as stated in reference [17]. In an effort to increase socket safety factors, Saif M. Abbas investigated a unique resin composition using ANSYS Workbench 14.5, carbon fiber, and fiberglass [18]. M.R. Ismail et al. focused on the prosthesis's shank section for patients with below-knee amputations in their research [19]. Kadhim and K. Resan collaborated on several lower limb prosthetics-related elements to provide the patients with both functionality and support [8, 20]. In this work determine the optimal material properties for an acceptable mechanical performance for a patellar tendon load-bearing orthosis. Tensile and fatigue testing were done on composite materials, including glass, carbon, and polyester fibers. It was ultimately decided to calculate the fatigue safety factor using ANSYS Workbench.

2. Experimental procedures

2.1 Material

The materials of the PTBO for this study are as follows and shown in Table 1 and Fig. 1, [21].

2.2 Samples for tensile tests

Three tensile test samples were made for the study for each lamination group in compliance with ASTM D638 type I [22] requirements. These samples were created with varying thicknesses according to vacuum technique. Figure 2 shows the dimensions of a typical tensile test sample as well as a visual representation of the sample's form and the testing equipment.

*Corresponding Author.
E-mail address: ghanim.s.sadiq@nahrainuniv.edu.iq ; Tel: (+964) 770 253-7378 (Ghanim Sadiq)

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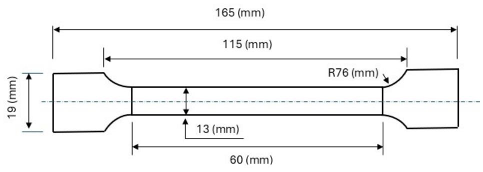
Nomenclature

PTBO	Patellar tendon bearing orthosis
P	Prosthesis
O	Orthosis
PTB	Patellar tendon bearing
S − N	Stress – no of cycle
CS	Compressive Strength
ASTM	American Society for Testing and Materials Information
FEM	Finite element method
IP	Interphase pressure
Greek Symbols	
σ_y	Yield stress (MPa)
σ_{ult}	Ultimate stress (MPa)
E	Modules of elasticity (GPa)
YSc	Compression Yield Strength

Table 1. Lamination manufacture layups.

No. of Lamination	Thickness (mm)	Total No of layers	Fiber Type	Fiber Volume Fraction (v_f)
Group A	2.2	10	Perlon	43.40%
Group B	2.7	10	Carbonfiber	28.40%
Group C	2.6	10	Glass fiber	16.75%

Figure 1. Materials for orthosis.



(a) Schematic, [22]

(b) Actual specimen

Figure 2. The Dimensions of Tensile Specimen.

2.3 Samples for fatigue tests

To build the S-N curve for each lamination group, ten data points were collected during the fatigue testing phase. For every data point, three specimens were tested, and the representative value was calculated by averaging the three test results. The fatigue specimen's dimensions are displayed in Fig. 3, and the fatigue test device is shown in Fig. 4.

2.4 Interface pressure test

The interface pressure analysis using an F-socket and the gait cycle analysis while walking on a force plate. In order to quantify the contact pressure at the interface between the patient's stump and the prosthetic socket, sensors were strategically placed on the patient's anterior, lateral, posterior, and medial sides. Data gathering while the patient was moving Fig. 1. Materials for orthosis. using either an F-socket or a Matscan sensor connected to a computer with the necessary software, allowed for an accurate assessment of contact pressure between the socket and the amputation. To evaluate the pressure distribution between the patient's leg at various orthotic wall regions, contact interface pressure was assessed. With ethical approval from Al-Nahrain University's College of Engineering (02/2020), these measurements test for a patient wearing a PTB orthosis included a height of 1.55 meters, a female gender, suffering from left pain in the ankle and foot, and a weight of 65 kilograms. This allowed for an evaluation of how the pressure is distributed during walking.

(a) Schematic, [23]

(b) Actual specimen

Figure 3. The Shape of Fatigue Specimen.

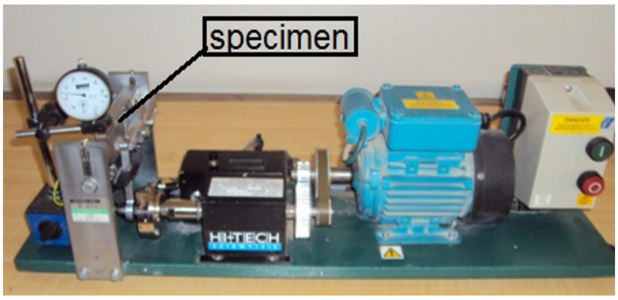


Figure 4. Fatigue test device

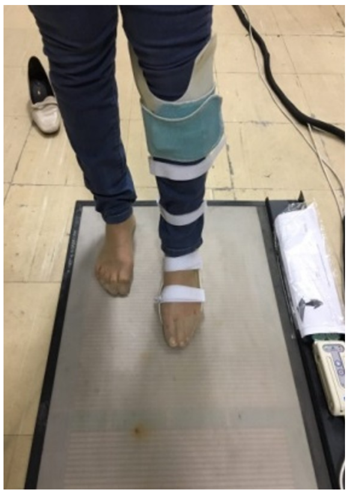


Figure 5. Patient with PTB Orthosis.

3. Numerical analysis

With the aid of ANSYS Workbench 17.2, a PTBO orthosis numerical analysis was performed. This research used the finite element approach with solid, brick 8-node 45-element models, as shown in Fig. 6. The investigation was conducted with consideration for the mechanical properties of the materials Perlon, glass, and carbon fibers employed in the PTBO model. Among these properties are Young's modulus (E), yield strength (σ_y), and ultimate tensile strength (σ_{ult}). Furthermore, defining contact pressure was one of the study's solution criteria. The objectives of the investigation were to determine the fatigue life of the socket material, assess the fatigue safety factor, look into deformation, and find out how stress is distributed throughout the orthosis. The size of the foot zone served as the displacement boundary condition, simulating a fixed support. Table 3 and Fig. 6 display the maximum pressure on the orthosis's lateral wall.

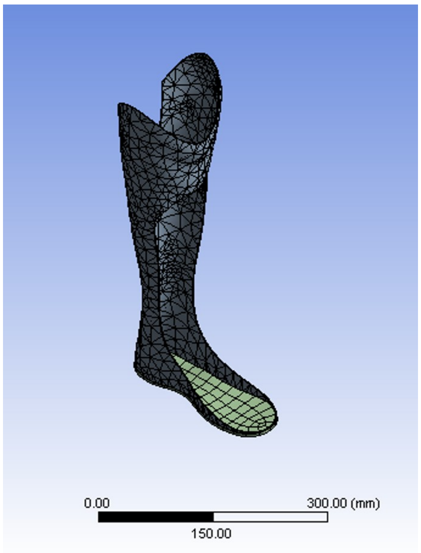


Figure 6. The PTBO orthosis element.

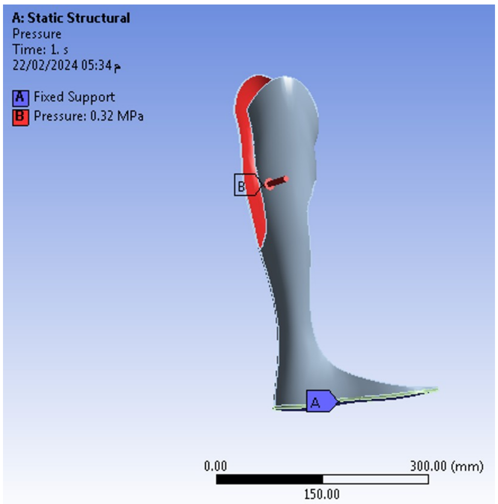


Figure 7. The boundary condition of PTBO orthosis.

4. Results and discussion

4.1 Tensile properties results

A summary of the tensile test results and the mechanical properties for each group are shown in Table 2. These findings are shown in Fig. 8. Yield Stress (σ_y): Yield stress increases by a significant 91% in the second group compared to the first, but only by 88.3% in the third. This indicates that higher stresses may be applied to the material in the second and third groups before it irreversibly deforms. Ultimate Stress (σ_{ult}): The ultimate stress (σ_{ult}) of the second and third groups is likewise much greater than that of the first group, increasing by approximately 78.25% and 62%, respectively. Stress levels are greater in the second group. The second and third groups of materials have stiffness and resistance to deformation that are 36% and 21% stronger than the first group, respectively, based on the modulus of elasticity (E). This indicates that, in comparison to Perlon, the material in the second group is stiffer and less likely to bend under stress.

Table 2. Mechanical properties evaluated from stress -strain curves.

Group	Layers	Thick (*mm*)	σ_y *MPa*	σ_{ult} *MPa*	E *GPa*
Group A	10	2.2	010.580	37.895	1.253
Group B	10	2.7	116.878	174.16	1.958
Group C	10	2.6	090.672	99.725	1.589

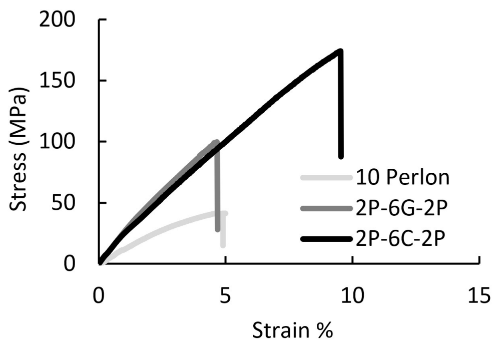


Figure 8. Stress-strain curve of tensile test.

4.2 Fatigue properties results

The applied stress levels and the total number of cycles till failure were included in the fatigue test results for the group samples. Since every test was carried out at room temperature, information on the materials' fatigue resistance under these circumstances was gathered. In comparison to Group A, Group B's materials, especially those in the second group that included carbon fiber, had a longer fatigue life, suggesting that Group B's materials were more fatigue resistant. The second group's longer fatigue life can be attributed to carbon fiber's superior load-bearing properties, which outperform those of perlon. These results highlight the advantages of employing carbon fiber to increase fatigue resistance in prosthetic sockets. The applied fatigue stress load and the total number of cycles before failure for Groups A, B, and C are shown in Fig. 9.

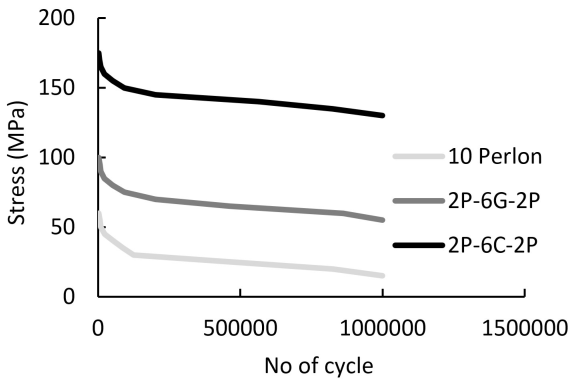


Figure 9. Figure 7 S-N curve of fatigue test.

4.3 Interface Pressure Result

The resulting data is shown visually in Figs. 10, 11, 12, and 13. Table 3 offers a thorough overview of all the information acquired, including the sensor's placement on the socket. Surprisingly, the lateral side had the greatest contact pressure value ever measured 320 kPa. Moreover, a contact pressure of 253 kPa was observed in the posterior region of the stump. This data trend can be explained by the purposeful application of pressure, which enhances suspension, to the lateral and posterior areas of the orsthetic. This phenomenon is further influenced by the fact that more tissue is located in the posterior and lateral portions, which are farther away from the bone and hence more actively involved when walking.

Table 3. Values of interface pressure for prosthetic socket.

Socket Regions	Anterior	Lateral	Posterior	Medial
Pressure (KPa)	240	320	253	210

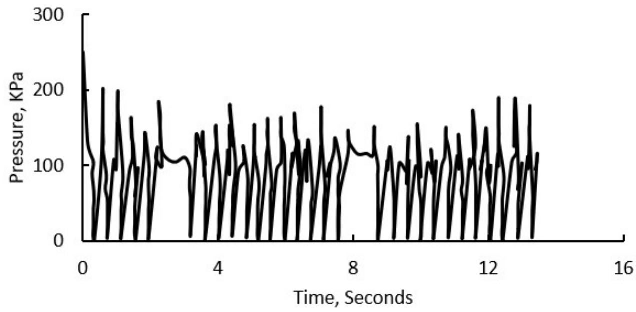


Figure 10. Anterior socket pressure V.S time.

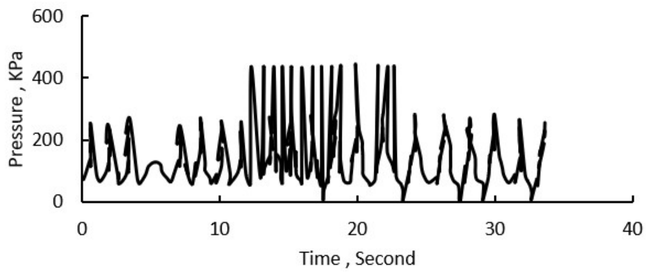


Figure 11. Lateral socket pressure V.S time.

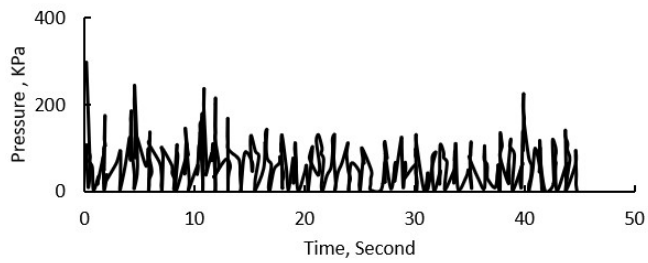


Figure 12. Posterior socket pressure V.S time.

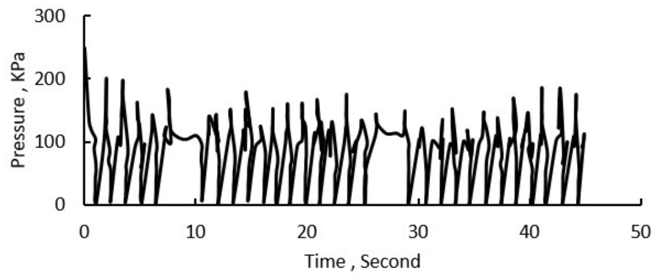


Figure 13. Medial socket pressure V.S time.

4.4 Numerical Results

The socket model, designed for patients whose legs had been amputated below the knee, was analyzed using ANSYS 17.2. Measurements of the deformation brought on by the pressure of the stump contact and an examination of the stress distribution along the socket wall were part of the investigation. Additionally, the experiment determined the fatigue safety factor for two composite material groups used in socket manufacturing. Safety rules require composite material parts to have a minimum fatigue safety factor of 1.25 [24]. Table 4 and Figs. 14, 15, and 16 display the safety factors, total deformation, and (Von-Mises) stress distribution obtained from numerical analysis for the PTBO model.

Table 4. Values of interface pressure for prosthetic socket.

Group	Von-Mises stress (MPa)	Safety Factor	Total deformation (mm)
A	229.36	0.559	2.548
B	86.009	1.490	0.969
C	132.6	0.966	1.494

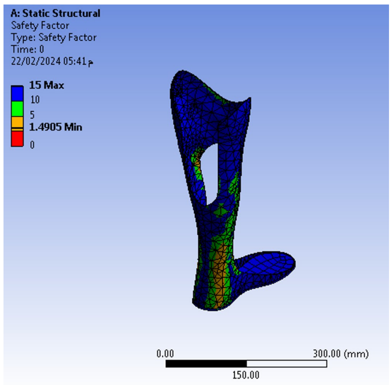


Figure 14. Fatigue factor of safety.

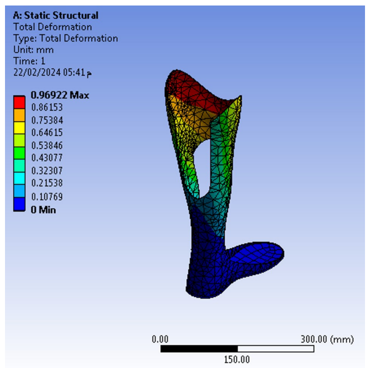


Figure 15. Total deformation.

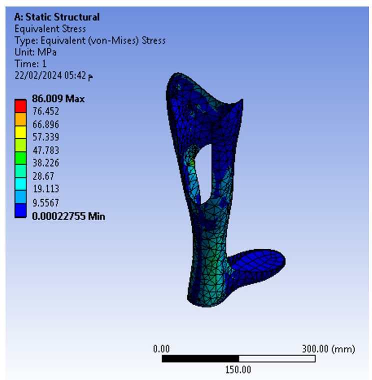


Figure 16. Equivalent stress (Von Mises).

5. Conclusions

- Yield Stress (σ_y): The group B exhibits a significant 91% increase in yield stress compared to the group A, whereas the group C only exhibits an 88.3% increase. This indicates that higher stresses may be applied to the material in the B and C groups before it irreversibly deforms.
- Ultimate Stress (σ_{ult}): The group B and C are likewise much larger than that of the group A by approximately 78.25% and 62%, respectively. The stress levels are greater in group B. The B and C groups of materials have stiffness and resistance to deformation that are 36% and 21% stronger than the group A, respectively, based on the modulus of elasticity (E).
- Acceptable in the PTBO model design were the safety factors, total deformation, and (Von-Mises) stress distribution obtained from numerical analysis for the PTBO model group B, which were 1.49, 0.969mm, and 86.009 MPa, respectively.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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