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A Study of the Mechanical Properties and Gait Cycle Parameter for a Below-Knee Prosthetic Socket

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Abstract. This work involved an experimental study into the tensile and fatigue properties of selected below-knee prosthetic socket materials fabricated using a vacuum moulding technique. The composite materials were composed of number of carbon-fibre layers (8 layers) and carbon fibre with perlon layers (11 layers). The Ground Reaction Force (GRF), Center of Pressure (COP) and pressure distribution for a patient of around 27 years old of height 170cm and weight 75kg were measured, and the results showed that the ultimate stress (Ϭul) for carbon fibre was 135 MPa, while for carbon fibre with perlon in an 80:20 matrix, it was 98 MPa. The fatigue limit for carbon fibre was 30 MPa and for carbon fibre with perlon it was 45 MPa. The data on gait cycle GRF was gained by using a force plate to measure pressure distribution using an F-socket, and these were collected using a patient with a below-knee amputation wearing a prosthetic of type BK. The internal pressure between the patient’s stump and the prosthetic socket was measured by using the F-socket Mat scan sensor; this reached its maximum value (52KPa) at both heel strike and toe off.

Keyword. BK, Tensile, Fatigue, Force plate, F-socket, Perlon, Carbon Fibre.

1. Introduction

Below-knee or “BK” amputations, also known also transtibial amputations, represent the largest percentage of lower limb amputations. Thus, more than half of lower-limb amputations are below-knee amputations at different levels (long, mid, and short), and consideration of these is thus important in education and training for the manufacturing of prosthetics and patient rehabilitation. These varying levels mean that persons with below knee amputations must be rehabilitated with specific regard to their amputation levels [1]. The types of prosthetics most commonly used are silicone, with urethane or elastomeric gels the fit directly to the stump and hold the prosthetic in place using ring or pin locks. BK prostheses, as seen in Fig.(1), are typically comprised of a socket, suspension shin piece, foot piece, and adapters.

Fig.(1) Below knee prosthesis [1].
Prosthetic socket design is largely determined by the need to maintain the comfort and motion of a below knee prosthesis. The BK socket that encloses the stump and forms a union between the stump and artificial limb must be designed to fit the patient precisely, as this socket is both attached to the residual limb and coupled with the prosthesis [2][3].

Polymer and fiberglass sockets can easily be moulded to the leg contours, thus reducing patient discomfort and allowing a better fitting prosthetic. In the construction of a socket, a silicon suction liner is put around the patient’s leg to simulate the stump’s final shape. Relief pads are added to the bottom of the socket, on the outside surface of the liner where the contact with the remainder of the prosthesis occurs[4]

The socket of the prosthesis is then shaped with equal distribution of pressure on the inner sides of the stump. The socket is fixed, and alignment on the pipe shifted to increase the load of patient on the patellar ligament and reduce the pressure on more sensitive and bony areas such as the fibular head, tibia, and condyles[5].

Jweeg et al. [6] determined the modulus of elasticity for long, short, woven, powder, and particle reinforcement of composite materials with different volume fractions experimentally. It was shown that the best modulus of elasticity for reinforcement composites were unidirectional fibre types in the longitudinal direction and the woven reinforcement type in the transverse direction.

In the current work, a fatigue test was applied to different samples of laminated from perlon with carbon fibre that could be used in the manufacturing of below-knee prostheses to achieve the requirements of BK socket material design, with the goal of improving mechanical characteristics and minimising cost.

2. Experimental procedures
2-1. Materials

The materials required to test the laminations for this study were as follows [7]. Perlon stockinet white, carbon fibre, lamination 80:20 resin, hardening powder, a polyvinyl alcohol (PVA) bag, and Jepson for casting.

2-2. Equipment

- A positive Jepson mould of rectangular shape and size 10 x 15 x 25 cm³.
- A vacuum pressure system including a pump and stands for hold the Jepson pipes.
- A mechanical workshop for cutting, forming, and assembling the prosthetic.
- Universal instrument machine test (testometric) for tensile testing; material fatigue testing kit for flat specimens.
- Force plate device used to analysis the gait cycle of the patient.
- F-socket device used to determine the internal pressure on the prosthetic socket.

2-3. Preparation of materials for tensile and fatigue testing.

The below-knee mould was fixed at the mouth of the pressure vacuum and connected with the pressure system by means o pipes. A layer of PVA was placed on the positive mould, and the pressure valves opened to a value of 40KPa at room temperature. The carbon fibre (8 carbon fibre) layers were added, then the outer PVA covering placed over the layers of composite material, with string being used to tie off the end of the PVA bag.

This procedure was repeated for perlon with carbon fibre (4 perlon + 3 carbon fibre + 4 perlon) layers. The lamination 80:20 resin was mixed with the hardener: about 500 to 600ml of resin was mixed with one or two pieces of hardener, and the solution was distributed homogeneously over all layers of the composite materials. The composite materials were cut to create manufacturing samples after cooling to allow testing for tensile strength, flexural bending, and fatigue. For the tensile test, three samples of each type of composite material were prepared according to ASTM D638[8], with thickness varying according to the number of layers. Fig (2) shows the shapes and dimensions of the tensile samples.
For the fatigue test, eight samples for each type of composite material were machined. The dimensions of these samples were length 100mm and width 10mm, while the thickness varied with the type of lay-up. Fig (3) shows the shape and dimensions of the fatigue samples.

The average thickness for the samples of the two lamination types were measured as shown in Table (1).

### Table (1) Lamination manufacture layups

| No. of Lamination | Thickness (mm) | Lay up Symbol | Total No of layers | Lamination layup procedures                           |
|-------------------|----------------|---------------|--------------------|-------------------------------------------------------|
| Lamination 1      | 3.4            | 404           | 8                  | (4 carbon fibre + zero perlon + 4 carbon fibre) layers |
| Lamination 2      | 4              | 434           | 11                 | (4 Perlon + 3 carbon fibre + 4 Perlon) layers         |

3. Results and Discussions

3.1. Tensile properties

The mechanical properties for all laminations are shown in Table (2). Three specimens for each lamination type were tested to obtain a stress-strain curve, and Fig (4) shows stress-strain curve for one of the samples of lamination 1 and one of the samples of lamination 2. From these curves, the mechanical properties of each sample were determined as recorded in Table (2). The results explain the effects of increasing the number of carbon fibre layers rather than Perlon layers on the mechanical properties, leading to increases in $\sigma_y$ and $\sigma_{ult}$.

### Table (2) Mechanical properties determined from stress-strain curves

| No. of Lam. | No of sample | Thickness (mm) | Lay up Symbol | $\sigma_y$ MPa | $\sigma_{ult}$ MPa | E GPa | Elong. at Break (mm) |
|-------------|--------------|----------------|---------------|----------------|-------------------|-------|----------------------|
| Lamination 1| 1            | 3.4            | 404           | 122            | 135               | 2.4   | 3.38                 |
| Lamination 1| 2            | 3.4            | 404           | 118            | 131               | 2.4   | 3.38                 |
| Lamination 1| 3            | 3.4            | 404           | 120            | 133               | 2.36  | 3.38                 |
| Lamination 2| 1            | 4              | 434           | 57             | 97                | 2.1   | 3.65                 |
| Lamination 2| 2            | 4              | 434           | 54             | 95                | 2.1   | 3.65                 |
| Lamination 2| 3            | 4              | 434           | 54             | 96                | 2.1   | 3.65                 |
This leads to increases in the mechanical properties $\sigma_y$ and $\sigma_{ult}$; however, elongation at the break decreases because of increases in the absorbing ability caused by increasing the lamination thickness of samples and the differences in plastic behaviour between the materials. These results explain the effects on mechanical properties of increasing carbon fibre layers with a constant number of perlon layers that leads to increased $\sigma$ and $\sigma_{ult}$ [9]. The composite material created from eight layers of carbon fibre displayed optimum performance in terms of mechanical characteristics and reduced cost for socket lamination[10].

3-2. Fatigue properties

The results of fatigue test are shown in tables (3) and (4). Fig(5) shows the S-N curve for samples of each lamination type; the stress failure rates of samples decrease and the number of cycles to reach the failure point increases at constant temperature.

**Table (3)** Fatigue results for carbon fibre materials.

| NO | Stress MPa | N     | Log N |
|----|------------|-------|-------|
| 1  | 135        | 2154  | 3.33  |
| 2  | 120        | 5350  | 3.73  |
| 3  | 105        | 32536 | 4.51  |
| 4  | 90         | 54361 | 4.74  |
| 5  | 75         | 351678| 5.55  |
| 6  | 60         | 675497| 5.83  |
| 7  | 45         | 889243| 5.95  |
| 8  | 30         | 1000491| 6     |

**Table (4)** Fatigue results for Perlon with carbon fibre materials

| NO | Stress MPa | N     | Log N |
|----|------------|-------|-------|
| 1  | 97         | 3625  | 3.56  |
| 2  | 90         | 5517  | 3.74  |
| 3  | 83         | 12445 | 4.1   |
| 4  | 76         | 35407 | 4.55  |
| 5  | 69         | 69927 | 4.85  |
| 6  | 62         | 614500| 5.78  |
| 7  | 55         | 894514| 5.95  |
| 8  | 45         | 1000597| 6     |
Fig (5) S-N curve for carbon fibre and for perlon and carbon fibre.

3-3. Force plate and F-socket BK results.
Kinetics and kinematics data were collected from a young subject with a below-knee amputation wearing a BK prosthetic. The patient’s age was about 27, and his height and weight were 170 cm and 75 kg, respectively. This data was collected while acknowledging major differences for the parameters of right and left legs. The subject was wearing a composite socket prosthetic, as shown in Fig (6).

Fig (6) Case study

The gait table and gait cycle table drawn from the patient results are tables (5) and (6), respectively.

**Table (5) Gait Table.**

| Gait Table                | Patient |
|---------------------------|---------|
| Number of Strikes         | 11      |
| Cadence (steps/min)       | 92.5    |
| Gait Time (sec)           | 4.54    |
| Gait Distance (m)         | 3.622   |
| Gait Velocity (m/sec)     | 0.797   |

**Table (6) Gait Cycle Table (sec)**

| Gait Cycle Table (sec)   | Patient |
|--------------------------|---------|
|                          | Left    | Right   | Difference |
| Time of Gait Cycle       | 1.26    | 1.25    | -0.01      |
| Time of Stance           | 0.82    | 0.86    | 0.04       |
| Time of Swing            | 0.44    | 0.39    | -0.05      |
| Time of Single Support   | 0.38    | 0.40    | 0.02       |
| Time of Initial Double Support | 0.20 | 0.21 | 0.00 |
| Time of Terminal Double Support | 0.21 | 0.20 | -0.00 |
| Time of Total Double Support | 0.41 | 0.41 | 0.00 |
| Time of Heel Contact | 0.45 | 0.40 | -0.06 |
| Time of Foot Flat | 0.19 | 0.22 | 0.03 |
| Time of Mid stance | 0.24 | 0.11 | -0.12 |
| Time of Propulsion | 0.36 | 0.46 | 0.10 |
| Time of Active Propulsion | 0.16 | 0.25 | 0.09 |
| Time of Passive Propulsion | 0.20 | 0.21 | 0.01 |

### Table (7) Step-Stride Table.

| Step | Stride Table | Patient |
|------|--------------|---------|
|      | Left         | Right   | Difference |
| Time of Step (sec) | 0.65 | 0.65 | 0.00 |
| Length of Step (m) | 0.564 | 0.457 | -0.107 |
| Velocity of Step (m/sec) | 0.871 | 0.703 | -0.168 |
| Step Width (m) | 0.11 | 0.11 | 0.00 |
| Stride Time (sec) | 1.26 | 1.25 | -0.01 |
| Stride Length (m) | 1.015 | 0.956 | -0.059 |
| Stride Velocity (m/sec) | 0.808 | 0.766 | -0.042 |
| RMS Force (N) | 574.17 | 625.44 | 51.27 |
| Impulse (N*sec) | 314.89 | 379.39 | 64.46 |
| RMS Pressure (KPa) | 205 | 272 | 67 |
| Foot Angle (degree) | -2 | 2 | 4 |

The force distribution developed under the sole due to patient gait for both feet is shown in Fig. (7) in units of Newtons.

![Force vs. Time](image1)

**Fig (7) Force vs. Time.**

![Pressure vs. Time](image2)

**Fig (8) Pressure vs. Time.**

![Image](image3)
The centres of pressure for the patient wearing a below-knee prosthetic to travel in both parallel and normal directions are shown in Fig. (10). The green colour suggests a healthy foot and the red colour refers to a dropped foot.

The internal pressure between the patient’s stump and the prosthetic was measured using an F-socket mat scan sensor; this reached its maximum value (52KPa) at the moments of heel strike and toe off, as shown in Fig. (12).

4. Acknowledgements
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5. Conclusions
The following conclusions concerning the fatigue life and the contact pressure between the stump and the socket can be made:

1. The obtained yield strength of the socket material was 122MPa for lamination 1 (8 layers of carbon fibre) and 57 MPa for lamination 2 (4 perlon +3 carbon fibre +4 perlon), which means that it has a very good stiffness if compared with polypropylene (43 MPa max), combinations commonly used in socket fabrication.

2. The interface pressure of the prosthetic socket follows a wave pattern that reached its maximum value (52KPa) at the points of heel strike and toe off.

3. The ground reaction force in the normal leg takes a wave form with two peaks, again at heel strike and toe off, with a valley mid stance; in an amputated leg, the peak continues through out all the three segments.

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