Effects of Temperature on the Characterisation of a New Design for a Non-Articulated Prosthetic Foot

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Abstract. This paper presents a new design for a non-articulated prosthetic foot made from high density polyethylene. The mechanical and physical properties of the proposed design are then compared with a Solid Ankle Cushioned Heel (SACH) foot based in a numerical and experimental investigation. The prosthetic foot failure characteristics at room temperature and at a relatively high temperature (60 °C) were determined using a fatigue foot tester and the dorsiflexion angle was measured using inclined compression. The numerical solution can be used to find the safety factor for the new design using SolidWorks software and ANSYS. From the results in this case, the maximum dorsiflexion angle at toe off for the SACH and new prosthetic foot are 4.7° and 6.3°, respectively. Fracture of the new prosthetic foot occurs at 1,104,732 and 1,089,463 cycles for tests performed at room temperature (23 °C) and at (60 °C) respectively.

Keyword. Prosthetic foot, fatigue, dorsiflexion, polyethylene, ANSYS.

1. Introduction
A prosthetic foot cannot replicate the exact properties of a normal human foot. However, recent studies have shown the ability to improve the properties of these replacement parts, and prosthetic foot design has advanced in the last two decades to allow below-knee amputees to access almost a full range of walking capabilities. In Iraq, young and elderly people represent the highest percentage of those suffering from below-knee amputations, generally due to disease of the limbs or landmine incidents [1-3].

The amputee may wish to be able to perform a variety of activities without requiring a different prosthesis. It is thus important to establish the properties of the foot as used in different operations. This study thus includes various activities within the normal gait cycle for walking. Additionally, below-knee prostheses are comprised of four major components: socket, prosthetic foot, shank, and adapters. The main purpose of the pylon and socket in the prosthetic foot are to provide a means of replacing the lost structure and function of the skeleton and muscles of the foot, ankle, and pylon, [4].

Many researchers have studied and investigated different types of prosthetic feet. Trost [5] used different materials that return energy when compressed by body mass during the stance phase, and...
concluded the energy storing feet could be a valuable addition to the prosthetic armamentarium. Lehmann and Colleagues [6] conducted a similar analysis to determine the relationship between the load and deflection of prosthetic feet using a compression loading machine. They concluded that because the heel of the SACH foot is softer, it compresses more, allowing the centre of pressure to move further forward and thus causing the ground reaction force line to come closer to the knee, thus reducing knee moment. Hansen et al [7] analytically studied the effective foot length ratios (EFLRs) for different prosthetic feet, including the SACH foot. They recommended that EFLRs for prosthetic feet be held between 0.63 and 0.81. Jweeg et al [8] designed a non-articulated foot with good characteristics when compared with the SACH foot, such as good dorsiflexion (7.8˚).

This study presents a further new design for a non–articulated prosthetic foot, and includes a detailed comparison with a typical prosthetic foot.

2. Gait cycle with prosthetic foot

The gait cycle is the repetition of steps and strides involved in walking. The step time is the time from one foot striking the ground to the other foot hitting the floor. Step length can be described as the space between the two different feet [9-10]. The gait cycle thus involves two main phases: the stance phase (heel strike, mid stance, toe off) and the swing phase. The stance phase represents about 60% of the gait cycle, while the swing phase accounts for the remaining 40%. During the gait cycle, ground reaction force is generated, and the value of force at heel and toe off equal about 1.25 of the person's total bodyweight.

3. Experimental Work

3.1. Materials

Modern prosthetic foot materials are highly effective cornerstones of the design of a new prosthetic foot. The key point is to select the proper prosthetic materials and thus incorporate them effectively into the device. A thorough understanding of prosthetic foot materials thus enables the designer to combine these to the best advantage of the patient, [11]. Polyethylene, for example, is a thermoplastic polymer consisting of long chains of monomer ethylene. It is low cost, is easy to process, has very good chemical resistance, and is an excellent insulator.

3.2. Mechanical properties of high density polyethylene (HDPE)

Tensile strength: tensile strength is a short-term property that provides a basis for classification or comparison when established at specific conditions of temperature and rates of loading. The tensile strength of an HDPE specimen is typically determined in accordance with ASTM D638 type 2 by tensile testing [12]. In this test, HDPE specimens were prepared and pulled in a controlled environment at a constant rate of strain. The hardness of the material was examined using a hardness test device (shore D) and three readings were taken from different sites on the polyethylene specimen. The S-N curve as shown in figure (1) was adopted from reference [13], and the number of cycles decreased with increasing stress values.

| Yield strength (MPa) | Ultimate strength (MPa) | Modulus of elasticity (GPa) | Hardness Shore D |
|----------------------|-------------------------|----------------------------|------------------|
| 23.6                 | 37.4                    | 0.93                       | 98               |
3.3. Stages of foot manufacture
The shape of the foot was drawn in SolidWorks software and the drawing was transferred to the CNC machine. The new foot was then made from a high density polyethylene block using this machine. Figure (2) shows the main stages of foot manufacture.

![Figure (2) Stages of prosthetic foot manufacture](image)

3.4. Design and manufacturing of fatigue foot tester
A fatigue foot tester, as seen in figure (3), was designed and built using the requirements of ISO 10328. The fatigue tester was designed to simulate a person's gait cycle by alternating load at toe off and heel loadings. The mechanical and electrical components for the fatigue foot tester at each cycle test station consisted of a pair of solenoid valves, and a pair of pneumatic cylinders of 40 mm bore and 60 mm stroke, along with a counter to record the number of test cycles completed, a control system, an air filter, an air compressor, and a thermal chamber including a heater, fan, type-K thermocouple, and control panel. All components were mounted onto a frame with a pressure regulator. The value of applied load according to ISO 10328 for an amputee of 70 creates a ground reaction force of about 875 N.
3.5. Prosthetic foot tester

3.5.1. Fatigue foot tester (with and without temperature effects)
The new prosthetic foot was placed on the fatigue tester in order to obtain its fatigue life. The load was alternated to simulate the ground reaction force. The first piston struck the heel of the foot and then the second piston struck the forefoot. These actions continued in a sequence to represent a cyclic load. The fatigue foot tester included a counter which recorded the number of strikes. In addition, a frequency meter was used to control the frequency of strike according to ISO standards. The test was performed while the foot was subjected to a temperature of 23 °C and again where the temperature was 60 °C. Similar tests were also performed for the SACH foot for purposes of comparison.

3.5.2. Dorsiflexion test
In order to complete the dorsiflexion test, the available compression device was modified using a triangular piece of wood which was supported with a vertical ruler grading. This piece of wood was put in the compression device, which was replaced under the crosshead. The prosthetic foot touched the triangle of wood and applied force to simulate the ground reaction force. The dorsiflexion test was also performed for the SACH foot in order to compare both sets of results with the corresponding normal human foot. The amount of dorsiflexion was related to the vertical displacement and length of the foot and was therefore determined by the toe lever of the foot. From figure (4), the dorsiflexion can be determined using equation (1) [5].

\[
\text{Dorsiflexion angle} = \tan^{-1} \left( \frac{Y_{\text{distance}}}{X_{\text{distance}}} \right) \quad (1)
\]
4. **Numerical analysis of new prosthetic foot**

The finite element method (FEM) is widely used in many fields of engineering and science. In this work, SolidWorks was used with aid of ANSYS Workbench 15.5 software as a numerical tool to determine the maximum stress, fatigue life, and safety factor of the proposed design. The meshing of the prosthetic foot, using a tetrahedron element, is shown in Figure (5). The boundary condition used in the ANSYS Workbench software was the fixed support at the adapter at the ankle of the foot, while the interface pressure was distributed according to the ground reaction force at heel and toe off at the appropriate sequence time. The solution was considered to be convergent when the relative error was less in each field between two consecutive iterations [14-18]. The total number of elements was 78,297 with a total number of nodes of 206,384.

![Figure (5) Finite element of prosthetic foot](image)

5. **Results and Discussion**

5.1. **Numerical results**

The numerical results are shown in Figure (6), where the temperature effect is not considered. It can be seen in this figure that the minimum safety factor is located in new prosthetic foot; the maximum Von Misses stress is 2.3 MPa, and the fatigue safety factor is 4.9, which clearly indicates the safe design of the foot.
5.2. Experimental results

5.2.1. Fatigue foot tester results
In order to determine the validity of the new foot fatigue tester in comparison to other testers currently being used, the standard SACH foot was tested. The fractures of the new and SACH feet occurred at 11,047,321 and 964,869 cycles, respectively, when the test was performed at room temperature (23 °C), while fracture of these types of foot (new and SACH) occurred at 1,089,463 and 765,042 cycles, respectively, when the temperature was 60 °C. The forefoot of the SACH was composed from rubber foam, making it more affected by the temperature change, while the new prosthetic foot was made from high density polyethylene, which has good resistance to temperature effects.

5.2.2. Dorsiflexion
The dorsiflexion angle was obtained experimentally by modifying the compression test, as explained previously. The maximum dorsiflexion angle at toe off for the SACH and new prosthetic foot were 4.7° and 6.3°, respectively. These values of dorsiflexion suggest good characteristic for both types of foot.

6. Conclusions
1. The new prosthetic foot has better dorsiflexion and fatigue life compared with the SACH foot
2. The numerical results revealed that the new design is safe from a fatigue failure point of view.
3. The temperature effect is clearer in the results relating to the SACH foot.
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