

Original Article

Mechanical Characterization of Prosthetic Feet for the Manufacture of a Tibia Prosthesis Adaptable to Active Patients

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Abstract - In Chad, since the war of 1979, the country has been manufacturing medical devices such as tibia prostheses to help the disabled walk. These devices are artificial organs that replace the lower limbs of the human body and are often used as part of an amputation or to replace a damaged joint. The tibia prosthesis is composed of a socket, a sleeve, a tibial axis, and a prosthetic foot. In Chad, the Kabalaye Apparatus and Rehabilitation Center based in N'Djamena (CARK), provides amputee patients with tibia prostheses with an imported prosthetic foot, commonly called a SACH foot (Solid Ankle Cushion Heel), made of polyurethane. However, this imported foot is heavy and is not suitable for active patients. It is dedicated to patients with reduced mobility, such as the elderly and other sick people. The problem is that if active patients use the prosthesis to walk, the prosthetic foot cracks quickly after a while. In this work, we propose a new prosthetic foot manufactured locally using extruded polystyrene (called the Alhanouna foot) to replace the SACH foot. We then carry out a mechanical characterization of the flexion and compression of these two feet for the validation of the newly manufactured foot. The results of the comparison between these two feet show that the Alhanouna foot is light, resistant to compression, and allows amputees to move long distances (up to 3 kilometers). The results are promising, especially for a country with limited resources like Chad, where the local manufacture of tibia prostheses is a boon for amputees.

Keywords - Alhanouna foot, Mechanical characterization, SACH foot, Tibia amputee, Tibia prosthesis.

1. Introduction

Prosthetic feet are medical devices designed to replace part of the amputated foot, allowing amputees to walk, run, and lead an active lifestyle. They are custom-made to fit the user's anatomy and can vary depending on the type of amputation, activity level, and personal preferences of the user [1]. There are different types of prosthetic feet, namely passive prosthetic feet, which are simple devices and do not have active mechanisms [2]. They are generally lightweight and designed to provide an aesthetic appearance, but they do not absorb energy or respond to movement [3].

Articulated prosthetic feet are prostheses with joints that allow for flexibility and natural movement [4]. These can simulate the movement of the foot. Dynamic prosthetic feet are feet designed to provide a good level of performance, especially for active people [5]. They may include elements such as springs to store and release energy when walking or running [6]. Prosthetic feet with microprocessors, among which are some advanced models, use sensors and electronic technologies to automatically adjust the behavior of the prosthesis according to the terrain and the user's movements.

The operation of prosthetic feet depends on the type of system used; we have cushioning and propulsion. Modern prosthetic feet often use cushioning systems that absorb shock upon impact with the ground, reducing pressure on the remaining joints [1]. Some models use springs or elastic compounds to provide propulsion during the push-off phase of walking. The adaptability of advanced prosthetic feet equipped with microprocessors can adjust their rigidity or flexibility instantly according to the user's movements, allowing for a more natural gait and better balance.

For maximum functionality, rehabilitation is a program that can help the user adapt to their prosthesis by improving their gait and balance [7]. In Chad, the imported SACH prosthetic foot is used. This imported foot is not suitable for active amputees. Polymer materials are well-suited for biomedical applications due to their wide variety of lightweight, strong, flexible, and rigid properties. The imported foot (SACH) is made from polyurethane, and the local foot (ALHANOUNA) is made from extruded polystyrene. Extruded polystyrene is more resistant than polyurethane [8].



The problem is that if active patients use the prosthesis with the SACH foot to walk, this one cracks quickly after a while. In this context, it was necessary to find a lightweight, strong, and durable prosthetic foot. This is why the Alhanouna foot was created. Mechanical characterization tests were carried out to compare the two feet. To characterize the behaviour of the materials (polyurethane and extruded polystyrene) of two prosthetic feet, mechanical tests (compression and bending tests) are generally used, which allow the prosthetic feet to be stressed in a pre-defined stress state. The values of the applied forces and the deformations induced by these mechanical stresses are recorded using sensors. Force gauges measure the applied forces, and strain gauges measure the deformations of two prosthetic feet. Extruded Polystyrene (XPS) and Polyurethane (PUR) are two types of insulation commonly used in construction and industry [9]. Extruded Polystyrene (XPS) is obtained by extrusion of polystyrene, which gives it closed cells. It is lightweight and easy to handle. It is resistant to moisture and water, and has good compressive strength. Its advantages include excellent thermal performance, with a low coefficient of thermal conductivity and resistance to deformation, making it suitable for use under concrete slabs or other heavy-duty applications. It does not degrade easily due to humidity, making it a good choice for outdoor applications or in humid conditions [10].

Polyurethane (PUR), on the other hand, is obtained from the reaction between polyols and isocyanates, forming a composite material with open or closed cells, and it offers high insulating performance with low thermal conductivity [11]. These advantages are that it has excellent thermal insulation properties, even in reduced thickness, and good mechanical and flexibility characteristics [8]. It can be applied in the form of sprayed foam, which allows cavities to be filled that are difficult to access. In this work, the problem is that the prosthesis that is provided to amputee patients by the Kabalaye Apparatus and Rehabilitation Center, based in N'Djamena (CARK), which is commonly called a SACH foot, is manufactured in polyurethane. This imported foot is heavy and is not suitable for active patients. It is dedicated to patients with reduced mobility. The problem is that if active patients use the prosthesis to walk, the prosthetic foot cracks quickly after a while. In this work, we propose a new prosthetic foot manufactured locally using extruded polystyrene (called the Alhanouna foot) to replace the SACH foot. In the following sections, we carry out a mechanical characterization of the flexion and compression of these two feet for the validation of the newly manufactured foot.

The simplest, most rudimentary foot is the SACH (Solid Ankle Cushion Heel) foot. It is rigid, and heel strike is improved by the inclusion of a flexible heel wedge. Other, more sophisticated feet exist, known as propulsive or energy-returning feet, composed of carbon blades that, in theory, improve gait by restoring a certain portion of the energy

stored during the ground support phase of the prosthetic foot. In this work, a rigid foot like the SACH foot is remanufactured, but with a different type of material (extruded polystyrene), and it is subjected to mechanical testing. In parallel with our work, the author, Aude Louessard [13], worked on the design and prototyping of a prosthetic foot obtained by additive manufacturing and performed fatigue and bending tests, except that the foot she designed is energy-returning. To our knowledge, there is no proposal for a foot made from extruded polystyrene in the case of a rigid foot like the SACH foot.

2. Materials and Methods

2.1. Materials and Equipment

In this section, we present the materials and methods of this work. We carry out compression and bending tests on the two feet shown in Figure 1 below. These are the SACH foot (left) and Alhanouna (right).



Fig. 1 Both prosthetic feet

To perform compression and bending tests, appropriate materials and equipment are required. In our case, we used a compression and bending testing machine equipped with stress and strain measuring instruments suitable for both bending and compression. The test specimens are the two feet (see Figure 1) above. Figure 2 shows the testing machine used to apply bending and compression loads to the specimens, often equipped with appropriate supports. In the case of bending, two bending supports are the elements that hold the specimen at its ends, creating a bending moment.



Fig. 2 (a) CONTROLAB brand bending/compression machine, (b) Compression device, and (c) Bending device.

To determine the weight of the two feet, we use the electronic scale in Figure 3.



Fig. 3 Electronic scale

2.2. Method: Mechanical Characterization of Prosthetic Feet

In order to assess the strength and rigidity of both feet, we perform two types of mechanical tests: the bending test and the compression test. This will allow us to measure the behavior of the materials under load. We will determine the maximum permissible stresses that each type of foot (Sach and Alhanouna) can withstand.

2.2.1. Bending Test

The bending test is carried out in our case because it is generally used on relatively flexible materials such as polymers, wood, and composites, and gives interesting information on the behavior of the materials. Figure 4 shows the positioning of the foot on the bending machine.

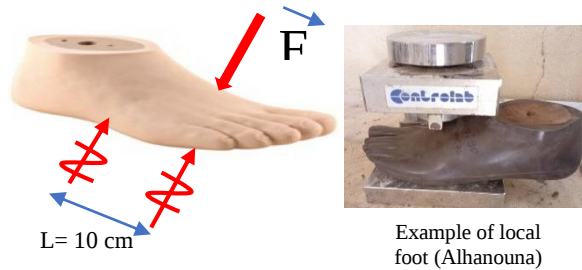


Fig. 4 Bending test

The flexural stress is determined to judge the flexural strength of the material. The flexural stress is determined using equation 1 below:

$$\sigma_F = \frac{3F_t L}{2bh^2} \quad (1)$$

With:

L: length between the two supports (L=10 cm)

b: width of the foot (b=7.5 cm)

h: height of the foot at the point of contact with the force (h=4 cm).

In the case of the bending machine used, the measured bending force is corrected with a machine calibration coefficient of 0.185 provided by the machine manufacturer.

Calculation for the Imported Foot (SACH)

The maximum bending force provided by the machine for the imported foot is 90 kN. The maximum force actually

obtained is multiplied by the machine's calibration coefficient mentioned above. This gives the maximum bending force: $F_t = 90 \times 0.185 \text{ kN}$

$\Rightarrow F_t = 16.65 \text{ kN}$. Bulleted lists may be included and should look like this:

Applying equation 1 and using the values of L, b, and h above, we obtain the value of the bending stress of the imported foot below.

$$\Rightarrow \sigma_F = 16.44 \text{ MPa}$$

Calculation for the local foot (AL-HANOUNA) :

The maximum bending force provided by the machine for the local foot is obtained using the machine calibration coefficient $F_t = 25 \times 0.185 \text{ kN}$.

$$\Rightarrow F_t = 4.63 \text{ kN}.$$

Applying equation (1) and using the values of L, b, and h above, we obtain the value of the bending stress below.

$$\Rightarrow \sigma_F = 5.78 \text{ MPa}$$

2.2.2. Compression Test

The compression test is performed on both feet to determine the behavior of each foot under compression. We believe that the foot is indeed subjected to compression due in part to the patient's weight. Figure 5 shows the positioning of the foot on the compression machine.



Fig. 5 Compression test

The compressive stress is determined using equation 2 below:

$$\sigma_C = \frac{F_C}{S} \quad (2)$$

With S, the support surface of the pressure tool is given by:

$$S = \pi \frac{r^2}{4} \quad (3)$$

With the radius of the support surface $r = 5 \text{ cm}$, we obtain $S = 1963 \text{ mm}^2$.

Calculation for the imported foot (SACH):

With the radius of the support surface $r = 5 \text{ cm}$, we obtain $S = 1963 \text{ mm}^2$.

$$\Rightarrow F_C = 75 \text{ kN}.$$

Applying Equation (2) and using the values of S above, we obtain the value of the compressive stress of the imported foot below.

$$\Rightarrow \sigma_c = 38,20 \text{ MPa}$$

Calculation for the local foot (AL-HANOUNA)

The maximum compression force provided by the machine for the local foot is: $F_c = 95 \text{ kN}$.

By applying Equation (2) and using the values of the section S obtained using Equation (3), we obtain the value of the local foot compressive stress below.

$$\Rightarrow \sigma_F = 48,40 \text{ MPa}$$

2.3. Weight Measurement Of Both Feet

To compare the two stands in terms of their overall dimensions, we decided to simply show the weight of each stand. To measure the weights, we used an electronic scale as shown in Figure 6 below.

The weight measurement given for the ALHANOUNA

foot (local), the mass MALHANOUNA = 246 g, and for the SACH foot (imported), MSACH = 521 g, i.e., practically double the mass of the imported foot.



Fig. 6 Weight measurement by electronic scale

3. Results and Discussion

In this section, we present and discuss the test results on both prosthetic feet. The test results indicate different properties for the two tested models. Figure 7 shows the results of mechanical tests performed on both feet, in compression and bending.

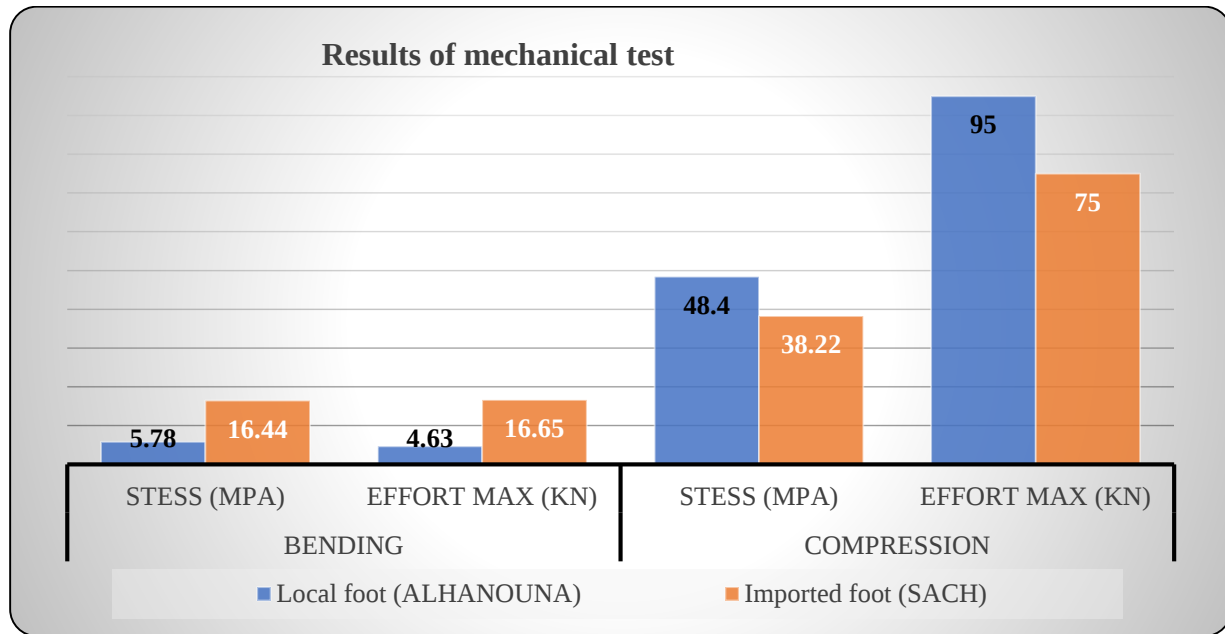


Fig. 7 Results of compression and bending tests

We found that the ALHANOUNA foot has good compressive strength, while the SACH foot has good flexion strength. The importance of one or the other foot is distinguished by the stump type. For a long stump where walking is more subject to flexion, the imported foot would be important because it offers better flexion resistance.

However, the local foot is preferred for a short stump, whereas walking is much more subject to compression. The local foot designed during this work offers a considerable

advantage for active patients with high mobility, allowing them to walk long distances.

In Abdelhakim et al. [12], an introspective study was conducted on these two prosthetic feet, conducting walking tests on the patients on both feet over a distance of three (3) kilometers, and the results showed that the prosthesis with the local foot allowed for easy walking over this distance, unlike the imported foot, which is very bulky and heavy. This is why we decided to show the weight and price of these two feet in Figure 8 below.

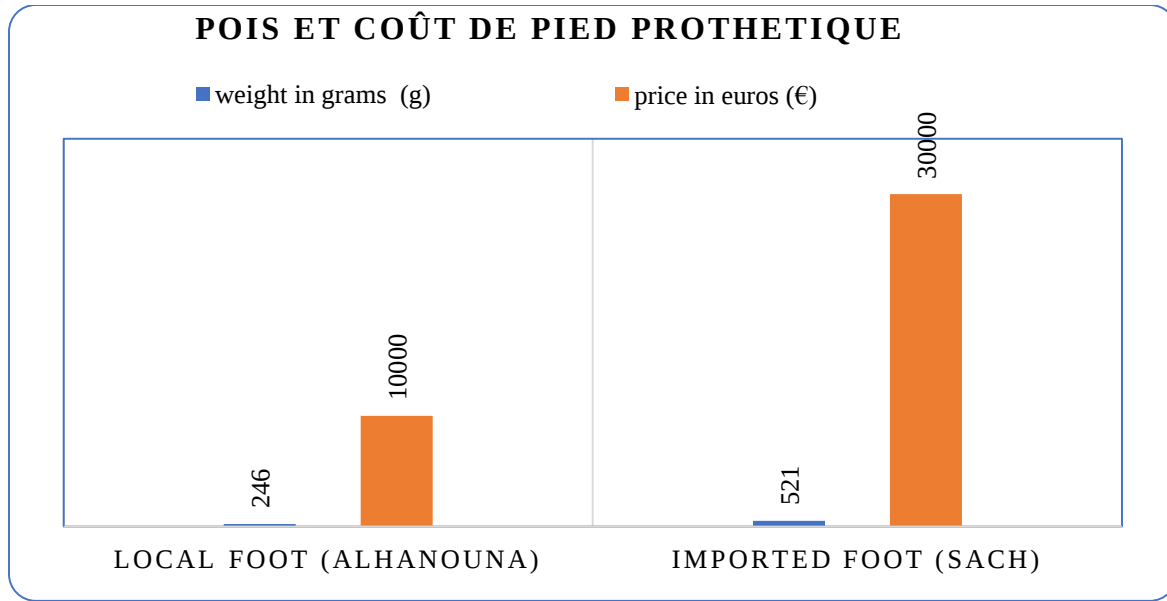


Fig. 8 Weight and cost of prosthetic foot

This weight difference raises important questions about functional performance and the level of effort required by the user during daily activities. The local foot, being lighter, could potentially offer better maneuverability and reduce fatigue during extended periods of use. Conversely, the imported foot, although heavier, could offer greater stability and better energy return when walking. It is true that the choice between these two options will depend on each patient's individual needs, lifestyle, and budget. However, in a country like Chad, which has limited resources, the majority of patients prefer the local foot, as we demonstrated in a survey conducted in [12].

4. Conclusion

As part of improving the quality of life of amputees, it is essential to have available prosthetic options. Therefore, we

designed a local prosthesis to restore functional limbs to patients for their social integration. Compression and flexion tests were conducted on both prosthetic feet, highlighting distinct characteristics that may influence user choice.

On the one hand, the local prosthetic foot (ALHANOUNA) stands out for its high compressive strength, lightness, and lower cost. On the other hand, the imported foot (SACH) offers better flexion and stability, but is heavier and more expensive.

Thus, generally speaking, the choice between the two prostheses will depend on the users' individual priorities, but for patients with moderately active lifestyles, the local foot is preferred.

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