Prosthetic Foot Design for Transtibial Prosthesis

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Abstract

The human body requires feet in order to provide stability and balance when standing or moving. Amputation of feet and that of any lower limbs significantly reduces the amputee’s ability to perform normal activities such as walking. The basic goal of prosthesis of any type is to improve or restore the function of a physically handicapped individual or amputee. The current prosthetic feet fail to accurately mimic, the characteristics exhibited by normal foot. Primarily the physical limitations of prosthesis are its inability to replicate the dynamics of Sound foot. Such dynamic Characteristics include eversion, dorsiflexion energy return impact, absorption and torsion about the ankle. The analysis prosthetic feet will be required to identify, the as well as further requirement for better ADL activities. For almost all types of lower limb Prosthesis, prosthetic foot is the most important prostheses terminal component.

1. Introduction

Current prosthetic foot designs do not replicate the exact characteristics of a normal human foot. A human foot is a multi-functional unit that can be used to perform a wide range of activities, however, a prosthetic foot is limited to only a few. More recently, manufacturers of prosthetic feet have looked into the characteristics of a prosthesis that may be adjustable. The amputee may then be able to perform a number of activities without requiring a different prosthesis.

It is important to establish the characteristics of a human foot used in its functional operations. This investigation has limited the activities to normal gait cycle in walking, the most common use of a prosthetic foot. The characteristics of a human and prosthetic foot covered in the scope of this investigation are dorsiflexion, eversion, impact absorption and the torque generated at the ankle. These are the most important characteristics in determining an appropriate prosthesis, according to requirement of an amputee. This investigation is aimed at designing a prosthetic foot that incorporates prosthetic design elements currently available, in order to design and develop a new prosthesis.

2. Prosthetic foot characteristics

One of the key factors in designing a new prosthesis is in the analysis of a amputee’s response. The characteristics deemed important by handicapped in achieving natural gait motion include:

- Energy Return
- Dorsiflexion
- Ankle Torsion
- Eversion
Impact Absorption

In order to understand the characteristics of prosthesis it is important to relate them to the mechanism of a human foot. The mechanics of the foot has been extensively studied by Klenerman, 1976. The centre of gravity of the body is continually moving up and down as we walk. The amplitude of this vertical oscillation is about 5cm. At the same time, the forward velocity of the torso is being alternately increased and decreased so that when the forefoot first reaches the ground the torso is at its lowest point and the forward velocity is at its maximum. When the opposite foot is in its swing phase, the torso is at its highest and forward velocity is at a minimum. The centre of gravity also translates 3cm to either side of the mid-line in order to bring itself more nearly over the supporting foot. These displacements of the torso and changes in the horizontal velocity are the result of the forces exerted by muscles of the leg. At heel strike, the vertical force exerted on the foot, usually measured by a force plate, exceeds body weight by 10 to 20%. The torque recorded by the force plate represents the extent to which the tissues of the foot resist the rotational forces imposed upon them by the leg. The foot exerts an internal rotation torque of between 2 and 5 Nm early in the stance phase followed by an external rotation torque between 3 and 10 Nm at the end of the stance phase.

2.1 Dorsiflexion

Once the foot has become flat, the leg rolls over the foot until it reaches a peak dorsiflexion of 8 to 10 degrees. As the heel rises off the ground the ankle plantar-flexes to a position of 18 to 23 degrees. In the later part of the stance the amount of plantar-flexion reaches up to 30 degrees.

Table 1. Dorsiflexion of normal foot at various walking speeds.

<table>
<thead>
<tr>
<th>Dorsiflexion (Degrees)</th>
<th>Walking Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 – 4°</td>
<td>1 - 3 km/h</td>
</tr>
<tr>
<td>5°</td>
<td>3 - 5 km/h</td>
</tr>
<tr>
<td>7 – 10°</td>
<td>7 - 8 km/h</td>
</tr>
</tbody>
</table>

* Acceptable walking range (3-5° dorsiflexion)

2.2 Eversion

The ability of a human foot to roll from side to side, called inversion and eversion, is important when walking on uneven surfaces. The foot must make compensations in order for the person to remain balanced, as shown in Figure 1.

Figure 1.

Inversion / Eversion caused by an obstacle
If a prosthesis is to replicate the motion of a normal foot then it must also show some inversion / eversion characteristics. If an amputee were to walk on a pebble, or any other obstruction, it would cause a displacement of the leg, as in A, and result in a fall. Instead, due to the inversion / eversion characteristics of the prosthesis, the leg remains vertical, as in B, and would cause the wearer not to lose their balance.

2.3 Energy Return
The capacity for prosthesis to store energy is very important in order to replicate the motion of a sound foot. In the operation of a sound foot, energy is stored during the stance phase of walking and is released on the transferral of weight.

![Figure 2: Normal Foot Timing](image)

Figure 2 shows the full cycle of a sound foot where HC is the heel contact, FF is the flat foot, and HO is the heel off and TO is the toe off. The ankle is in the neutral position at the moment that the heel strikes the ground. In order that the foot becomes flat on the ground the ankle must then plantar - flex 12 to 15 degrees. Therefore the foot becomes flat at 9% of the cycle and at 63% of the cycle for the other foot. Once the heel begins to leave the ground the energy stored in the foot rolls the leg over the foot. Therefore the ability for a prosthetic foot to store energy is important in order to provide enough momentum for the rest of prosthesis to roll over the foot. A sound limb releases an average of 15.74 Joules, stores an average of 14.18 Joules and therefore has an efficiency of 119.6%.

3. Component and characteristic analysis

Characteristics of prosthetic feet are not only dictated by its material properties but also by the component and orientation of such components. A prosthetic foot comprises of a heel, keel, ankle adaptor and a cosmesis. These components vary in geometry; orientation and material composition in each prosthesis are to be according to their specific function. The characteristic analysis of individual prostheses is based on the desired characteristics inherent during normal walking. The components of the prostheses were examined in order to determine the origin of the generated characteristic.
In general

- Dorsiflexion: primarily due to the deflection of the keel and any intermediate rubbers, bumpers or multi-axial joints.
- Eversion: primarily due to the distortion of the keel, and the deflection of the rubbers about the base of the keel.
- Torsion: primarily due to the distortion of the keel within the surrounding foam of the ankle block.
- Energy Return: due to the elastic properties of the keel and the rubbers.
- Impact Absorption: primarily due to the heel density.

4. Prosthetic foot design

4.1 Keel

- The function of a keel within prosthesis is to provide the energy transfer from the heel strike through to the toe off and the dorsiflexion required for natural ambulation. Depending upon the quantity of surrounding foam it also provides rotational properties such as eversion and torsion.
- The keel to be used in the new prosthesis is a modified Seattle Natural Foot design using Delrin II, nylon composite material, and intermediate polyurethane rubbers. Testing indicates that the Seattle Natural Foot keel design generates the desired characteristics more favorably than other prosthetic feet. A narrow ankle block of SACH IS51 the keel will be designed in order to provide for a larger torque. Similar design uses are found in the Otto Bock.
- Through heel impact testing, the adaptation of a section to the keel improves the impact absorption characteristics of the prosthesis. Therefore to design the section into the keel it would also increase the impact absorption of the new prosthesis.

4.2 Heel

- The function of a heel within prosthesis is to provide the impact absorption at heel strike and also provides the kinetic energy required for a smooth transition between the heel strike and the toe off.
- The heel to be used in the new prosthesis is of an Otto Bock SACH IS70 heel wedge which utilizes a low density, sponge like, polyurethane. Through impact testing, the Otto Bock wedge indicated the greatest energy storing potential which is used to increase the amount of dorsiflexion produced by prosthesis.
- The triangular wedge itself, shown below, provides for greater absorption due to the larger end being exposed to the heel strike. Used in conjunction with the section, the combined components provide extra impact absorption.
- The function of the filler is to provide a durable and aesthetically pleasing cosmesis also well as complementing the other component in performing the desired characteristics. The Seattle Natural Foot used a high grade, medium density polyurethane foam.
• The filler density and quantity is important in torsion about the ankle as the keel requires the ability to twist. The foam density and quantity either side of the keel provides the eversion properties of prosthesis.

• Excessive filler foam may alter the performance characteristics of the individual components. As a result the filler above the keel must be kept to a minimum in order to retain the elastic properties of the keel.

Figure 3
Transtibial prosthetic foot design set-up

5. Conclusion

The aim of this investigation was to design a prosthetic foot that incorporates component from currently available prosthetic feet. This investigation has limited the activities to normal ambulation, for that is the most common use of a prosthetic foot. The only characteristics of a human and prosthetic foot that this investigation has considered are dorsi / plantar flexion, inversion and eversion, torque generated at the ankle and the impact generated at heel strike. By comparing the characteristics exhibited by a prosthetic foot to those of a human foot, a selection of these prostheses was undertaken based on their favorability to the characteristics of a human foot.

References


