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PROSTHETIC FOOT DESIGN

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PROSTHETIC FOOT DESIGN

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ABSTRACT

Current prosthetic foot designs do not replicate the exact characteristics of a normal human foot. The basis of this investigation is to research current prosthetic in order to design and build a more human like prosthesis. The characteristics involved in normal walking include dorsiflexion, eversion, energy return, torsional properties and impact absorption.

Tests previously undertaken by REHABtech have determined the eversion, dorsiflexion and energy return characteristics of a selection of prosthetic feet. The additional properties of impact absorption and torsion where undertaken in this investigation. The characteristics displayed in the prosthetic feet tested were compared to those of a human foot. The characteristics exhibited by prostheses which compared favourably to those of a human foot were investigated further. Analysis of these prosthetic feet identified the componentry and material properties required to fulfil the desired characteristics.

The basis of the new prosthetic design combines current prosthetic design elements, such as materials and components. Our design incorporates a modified Seattle Natural Foot keel used in conjunction with an ankle ⊂ section. This enables the prosthesis to have better impact absorption at heel strike. The geometry of the ankle section of the keel is narrowed to enable for greater torsional properties. The heel used in the new design is a Otto Bock IS70, low density, polyurethane wedge. The filler foam selected is the Seattle Natural Foot foam which is made of high grade, medium density polyurethane. This foam provides eversion, torsion and secondary absorption properties, as well as a durable and aesthetically pleasing cosmesis.

In undertaking such a design, the new multi - function prosthesis will exhibit a greater range of characteristics than those displayed in current prosthetic feet. In doing so the new prosthesis will enable a closer representation of the functions inherent of a normal human foot.

1. INTRODUCTION

Current prosthetic feet designs make it difficult to replicate the exact characteristics of a normal human foot. A human foot is a multi - functional device 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 are looking 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. Furthermore, an understanding of joint stiffness and its variation with physiological biomechanical variables is important in the design of limb prostheses. 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 prosthetic feet patients.

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. In comparison to a normal human foot, current prosthetic feet demonstrate some of the desired characteristics effectively whilst lacking in others. Our investigation aims at combining these characteristics in order to achieve a more multi-functional prosthesis. In undertaking such a design, the new prosthesis will be exhibit a broader range of characteristics than those displayed in current prosthetic feet. In doing so, the new prosthesis will enable a closer representation of the functions inherent of a normal human foot.

2. BACKGROUND INFORMATION

Monash Rehabilitation Technology Research Unit (REHABTech) provides access to Australian and worldwide information on products, industries, suppliers and technology for the rehabilitation health professional.

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3. PROSTHETIC FOOT CHARACTERISTICS

One of the key factors in designing a new prosthesis is in the analysis of a patients response. This view is the most important because if the foot does not provide functional, practical or cosmetically acceptable characteristics the patient will not feel comfortable with the prosthesis. The characteristics deemed important by patients in achieving natural gait motion include :

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

In order to understand the characteristics of a 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 represent 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.

3.1 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.

Dorsiflexion *(Degrees)*	Walking Speed *(km/h)*
3 - 4°	1 - 3 km/h
5°	3 - 5 km/h
7 - 10°	7 - 8 km/h

*** Acceptable walking range (3 → 5° dorsiflexion)**

3.2. 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.

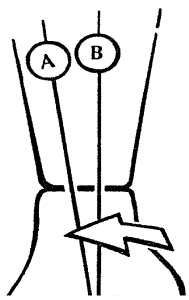

Figure 1.
Inversion / Eversion caused by an obstacle

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.

3.3. Energy Return

The capacity for a 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.

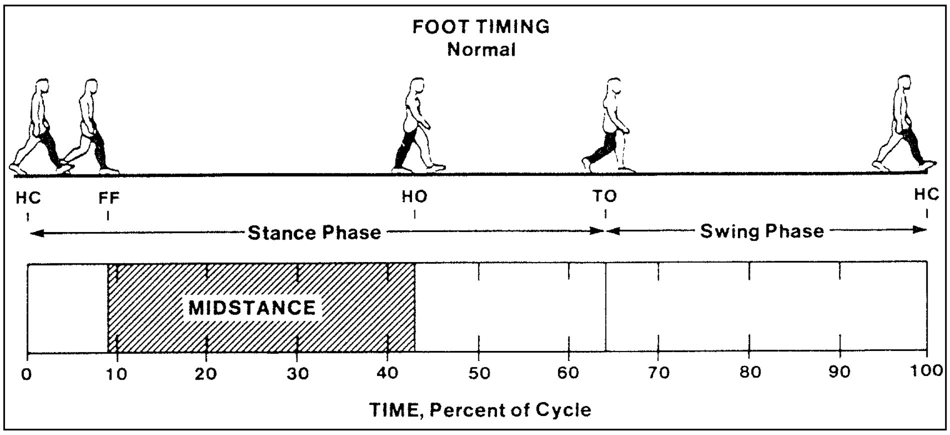

Figure 2.
Normal Foot Timing

Figure 2 shows the full cycle of a sound foot were HC is the heel contact, FF is the flat foot, 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%.

4. PROSTHETIC PROFILES

A total of 11 currently available prosthetic feet were individually analysed for their specific component and material composition, including their manufacturer performance recommendations. The 11 prostheses investigated include :

- **Carbon Copy II**
- **Otto Bock Dynamic**
- **Flex Foot Modular II**
- **Otto Bock Greissinger**
- **Blatchford Multi - Axis**
- **Vessa Quantum**
- **Kingsley SACH**
- **Campbell Childs SAFE**
- **Seattle Lite**
- **Seattle Natural**
- **Kinglsey STEN**
- **SURE FLEX**

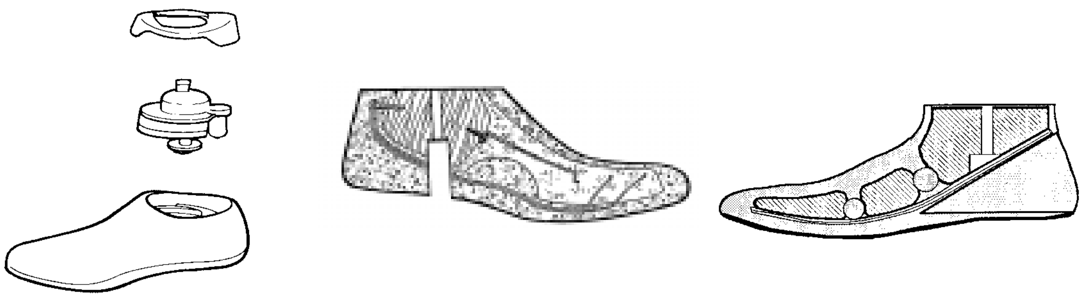

Figure 3.

Blatchford Multi - Axis **Campbell Childs SAFE** **Kingsley STEN**

5. PROSTHETIC CHARACTERISTIC ANALYSIS

Prosthetic feet are designed to perform varying functions depending on the desired application. However, most prosthetic feet only exhibit a selection of the desired characteristics needed for normal walking. The scope of this investigation incorporates the major characteristics demonstrated in walking such as eversion, dorsiflexion, energy return, torsion about the ankle and impact absorption at heel strike. Tests previously undertaken by REHABTech have determined the eversion, dorsiflexion and energy return characteristics of a selection of prosthetic feet. These where performed on size 27 cm, left, prosthetic feet. Prior research into a prostheses torsional and impact absorption characteristics has not been documented and requires further investigation.

5.1. TORSION TEST

A prosthesis is not as multi - functional as a human foot but is limited to specific movements, restricting the activity level. A prostheses torsional properties enable it to minimise the shear forces exerted inside the socket of the residual limb. The prosthesis also assists in the rotation of the knee undergoing a twisting motion.

The torsional properties of a human foot are such that for a 10° rotation angle a 10 Nm torque is generated. For the purpose of this investigation, we will be establishing a measurable torsional value, characterising the various prostheses. In addition, determining how favourably such characteristics compare to the torsional properties exhibited by a normal foot will also be studied.

Of the eleven prostheses tested results indicate that the :

- **Campbell Childs SAFE .... 9.49 Nm**
- **Otto Bock SACH IS51.. 10.84 Nm**
- **Seattle Natural .... 11.52 Nm**

were found to exhibit similar torsional properties to those of a human foot. These will be the prostheses used in the component investigation.

5.2. IMPACT TEST

The purpose of the impact absorption properties of a prosthesis is to decrease the shock exerted onto the residual stump of an amputee at heel strike. The materials in the prosthesis need to absorb and transfer this force into forward movement. Therefore the important characteristic of shock is the time over which the force is applied. For the purpose of this investigation, the shock absorption properties of the prosthesis at heel strike will be determined and an estimation of the shock generated will be made.

Results of a normal impact test indicate that the:

- **Blatchford Multi - Axis..............659.05 N**
- **Seattle Natural SNF150 ....841.2 N**
- **Sure Flex ....745.07 N**

have the greatest impact absorption properties.

An example of the impact results are indicated on Figure 4.

The Otto Bock SACH IS70 had the smallest difference between initial and secondary impacts. All of these prostheses will be used in our component analysis.

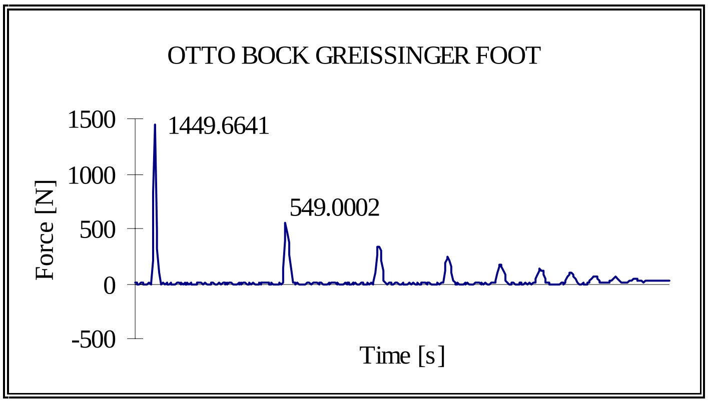

Figure 4.

The results indicate that a prosthesis with a ankle adaptor in the ⊂ configuration display a far greater impact absorption property than a prosthesis with no ankle adaptor.

5.3. PROSTHETIC CHARACTERISTIC SELECTION

The selection of prosthetic feet characteristics was undertaken on the basis on how effectively the foot reproduced the desired characteristics in reference to that of a human foot. The selection was based on the three prostheses which coincide favourably to the characteristics inherent to a human foot.

Dorsiflexion :	**Human Foot**	**5°**
	Seattle Natural	5°
	Dynamic Foot	4°
	Mutli - Axis Foot	4°

Torque :	**Human Foot**	**10 Nm**
	SACH IS51	10.84 Nm
	SAFE	9.49 Nm
	Seattle Natural	11.52 Nm

Energy Return:	**Human Foot**	**119.6 %**
	Seattle Natural	70.7 %
	Flex foot Mod.II	61.7 %
	Quantum Vessa	59.5 %

Impact :	**Human Foot**	**n/a**
	Multi - Axis	659.05 N
	Sureflex	745.07 N
	Seattle Natural	841.2 N

Eversion Angle:	**Human Foot**	**20°**
	Seattle Natural	19.5°
	Kingsley Sten	16.5°
	SAFE	16.0°

6. COMPONENT AND CHARACTERISTIC ANALYSIS

Characteristics of prosthetic feet are not only dictated by its material properties but also by the componentry 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, according to their specific function.

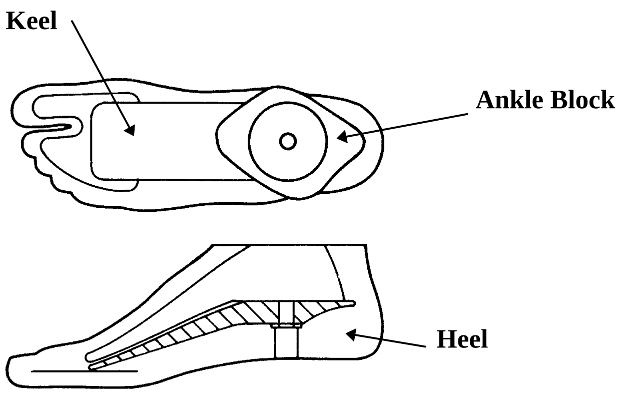

Figure 5.
Prosthetic Component Orientation

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.

7. MATERIAL ANALYSIS

A foot orthosis can be a highly effective cornerstone of treatment, or it can hamper proper outcomes. The key is selecting the proper orthotic materials and designing them into the right device. One of the easiest pitfalls to fall into is pigeonholing materials as rigid, accommodative or flexible. A thorough understanding of orthotic materials will enable the designer to combine them to the best advantage of the patient. The following list is hardly inclusive, but does provide a map of the leading materials.

- **Kevlar®, Aramid**
- **Carbon fibres**
- **Ethylene - vinyl acetate (EVA)**
- **Fibreglass / fibre epoxy**
- **Graphite composites**
- **Nylon 66**
- **Poly actetals (Delrin™)**
- **Polyethylene**
- **Polypropylene**
- **Polystyrene**
- **Polyurethane**

The performance properties of each material in its specific function are not purely quantifiable as they are subjective, varying between individuals and are dependant on the activity performed. Identifying the advantages and disadvantages of utilising such orthotic materials in prosthetic design is essential in effectively designing the components of the prostheses.

8. CONCLUSION

The aim of this investigation was to design a prosthetic foot that incorporates componentry 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.

Through testing, and tabulated data on currently available prosthetic feet, the characteristics of each prosthesis were identified. 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 favourability to the characteristics of a human foot. A material and component investigation of the selected prostheses has determined the source of the desired characteristics.

9. RECOMMENDATIONS

The ideal prosthesis should be adaptable with a custom fit for comfort and a semi - rigid or flexible construction. It should be lightweight and inexpensive with a covering to decrease shear but give control to both the forefoot and hindfoot.

The ideal prosthesis should be durable and transferable to most shoes. It should have the ability to maintain memory in its shape and be adjustable for later modifications. But most importantly, the ideal prosthesis will mimic, as close as possible, the characteristics of a human foot.

The scope of this investigation does not cover the production of an ideal prosthesis for no currently available prosthetic foot comes close to being an ideal foot. Our investigation aims at designing a multi - functional prosthesis which incorporates all of the characteristics displayed by a human foot in walking.

We have based our design on the prostheses which favourably reproduce the desired characteristics and the composition of their materials and componentry. This is shown in the following table :

CHARACTERISTIC	*PROSTHESIS*	*DESIGN*
DORSIFLEXION		
	Seattle Natural SNF150	**Delrin keel deflection and intermediate**
	Otto Bock Dynamic 1D10	**Small timber keel, and deflection of**
	Blatchford Multi - Axis	**Carbon fibre keel, rubber bumper in**
ENERGY RETURN		
	Seattle Natural SNF150	**Keel and intermediate urethane foams**
	Flex foot Modular II	**Keel Elasticity of the carbon fibre**
	Quantum Vessa	**Elastic properties of fibre glass keel.**
EVERSION ANGLE		
	Seattle Natural SNF150	**Deflection of polyurethane at the base**
	Kingsley STEN	**Twisting of the keel, bumpers and**
	SAFE	**Keel flexion and elasticity of rubbers**
TORQUE		
	SACH IS51	**Urethane surrounding ankle block**
	SAFE	**Ankle block movement in the second**
	Seattle Natural SNF150	**Distortion of keel within surrounding**
IMPACT		
	Blatchford Multi - Axis	**Very spongy soft urethane foam**
	Sureflex	**Elasticity of heel plate and density of**
	Seattle Natural SNF150	**Density of heel foam**

9.1. PROSTHETIC DESIGN

9.1.1. Keel

The function of a keel within a 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 of a modified Seattle Natural Foot design using a Delrin II, nylon composite material, and intermediate polyurethane rubbers. Testing indicates that the Seattle Natural Foot keel design generates the desired characteristics more favourably than other prosthetic feet. A narrow ankle block of the keel will be designed in order to provide for a larger torque. Similar design uses are found in the Otto Bock SACH IS51.

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 itself would also increase the impact absorption of the new prosthesis.

9.1.2. Heel

The function of a heel within a 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 a Otto Bock SACH IS70 heel wedge which utilises 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 a 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.

9.1.3. Filler Materials

The function of the filler is to provide a durable and aesthetically pleasing cosmesis also well as complementing the other componentry 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 a 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 6.
Prosthetic Foot Design

10. FURTHER DEVELOPMENTS

Further development of this investigation may comprise of performing a Finite Element Analysis Model on the keel and on the full prosthetic assembly. This will determine the stress concentration on the keel and determine if the selected materials for the components are adequate. Alternate materials identified in this investigation, such as Kevlar or Carbon Fibre, may be utilised as replacements should nylon not be appropriate as a keel material.

Further from modelling the components and analysing their endurance and performance, the next development of the project would involve the manufacturing and building of a number of prototype prostheses. The refining of the manufacturing process would involve all aspects including machining, moulding and curing.

The final stage of this investigation would involve the testing of these prototypes for the desired characteristics of dorsiflexion, energy return, eversion, impact absorption and torsion. The prototype prosthesis will exhibit more a multi - functional array of characteristic when compared to currently available prosthetic feet. In achieving the primary objective, the actual performance characteristics of the new prosthesis will be a closer representation of the functions inherent of a normal human foot.

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And finally I would like to say:
STOP ALL FRENCH NUCLEAR TESTING IN THE PACIFIC!