Prosthetic Foot Design

Daniel Rihs
Ivan Polizzi
Victorian University of Technology
REHAB Tech- Monash Rehabilitation Technology Research Unit assume no liability for any claim of adverse effects resulting from misapplication of the information presented here in. While every effort is made to ensure the accuracy of the guide no responsibility or liability will be taken for any inaccuracies.

REHABTech is finance and supported by

In collaboration with

© Copyright 2001
All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording or any information storage and retrieval system, without permission in writing from the publisher. Requests for permission to make copies of any part of the work should be addressed to:

REHAB Tech- Monash Rehabilitation Technology Research Unit
C/- C.G.M.C.
260 - 294 Kooyong Road
CAULFIELD VIC 3162
AUSTRALIA
Email rehab.tech@eng.monash.edu.au
# TABLE OF CONTENTS

SYNOPSIS...........................................................................................................................i.

BACKGROUND ....................................................................................................................1.

1.  INTRODUCTION ...........................................................................................................2.

2.  PROSTHETIC FOOT CHARACTERISTICS ................................................................3.

   2.1. Foot Flexion........................................................................................................4.

       2.1.1. Dorsiflexion..................................................................................5.

   2.2. Eversion .............................................................................................................5.

   2.3. Energy Return ..................................................................................................6.

3.0  PROSTHETIC PROFILES ...........................................................................................7.


   3.2. Dynamic Foot ....................................................................................................8.

   3.3. Flex Foot Modular II .....................................................................................8.


   3.5. Multi - Axis Foot ............................................................................................10.

   3.6. Quantum ..........................................................................................................10.

   3.7. Sach Foot .........................................................................................................11.


       3.7.2. Otto Bock Sach ...............................................................................12.

   3.8 Safe Foot ............................................................................................................13.


   3.10. Seattle Natural Foot ....................................................................................14.

   3.11. Sten .................................................................................................................14.


4.  CHARACTERISTIC ANALYSIS ...................................................................................16.

   4.1. Torsion Test ......................................................................................................16.

   4.2. Impact Test .......................................................................................................17.

   4.3. Prosthetic Characteristic Selection ....................................................................18.
5. COMPONENT AND CHARACTERISTIC ANALYSIS ........................................20.
   5.2. Otto Bock Sach IS51 - IS70 & Kingsley Sach K10...............................21.
   5.3. Otto Bock Dynamic 1D10....................................................................22.
   5.4. Kingsley Sten ......................................................................................22.
   5.5. Sure Flex ............................................................................................23.

6. MATERIAL ANALYSIS ..................................................................................27.
   6.3. Ethylene - Vinyl Acetate ....................................................................28.
   6.4. Fibreglass ...........................................................................................29.
   6.5. Graphite Composites .............................................................................29.
   6.9. Polypropylene .....................................................................................32.
   6.10. Polystyrene .......................................................................................32.
   6.11. Polyurethane .....................................................................................33.

7. CONCLUSION ...............................................................................................34.

8. RECOMMENDATIONS ..................................................................................34.
   8.1. Prosthetic Design ................................................................................36.
      8.1.1. Keel ..............................................................................................36.
      8.1.2. Heel ..............................................................................................37.
      8.1.3. Filler Materials ..........................................................................37.

ACKNOWLEDGMENTS ..................................................................................38.
SYNOPSIS

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 prosthesis 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.
BACKGROUND

The human body requires feet in order to provide stability and balance when standing or moving. Amputation of a foot significantly reduces the amputee's ability to perform normal activities such as walking. The basic goal of a prosthesis of any type is to improve or restore function to a physically handicapped individual. Current prosthetic feet fail to accurately mimic the characteristics exhibited by a normal human foot. Primarily the physical limitations of a prosthesis are its inability to replicate the dynamics of a sound foot. Such dynamic characteristics include eversion, dorsiflexion, energy return, impact absorption and torsion about the ankle. These are the major characteristics generated by a human foot during a normal walking (gait) cycle.

The basis of this investigation is to study current prosthetic feet in order to design and build a more human like prosthesis. The characteristics displayed in prosthetic feet will be tested and compared to those of a human foot. Analysis of prosthetic feet will be undertaken to identify the componentry and material properties required to optimally fulfil the desired characteristics. Through the evaluation of such prosthetic designs, an ideal prosthetic foot design can be achieved. The new prosthesis will be made up of a combination of current prosthetic design elements including materials and components, evident in current prosthetic designs. The ideal design will be able to achieve the characteristics demonstrated in current prosthetic feet and better replicate the functions of a sound foot.
1. INTRODUCTION

Current prosthetic foot designs do not 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 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 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. PROSTHETIC FOOT CHARACTERISTICS

One of the key factors in designing a new prosthesis is in the analysis of a patient's 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.

2.1. FOOT FLEXION

The flexion of a human foot can be measured about a number of planes:

- *plantar*: the ability for the foot to bend down
- *dorsi*: the ability for the foot the bend up
- *sagital*: the ability for the foot to rotate
2.1.1 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 2.

Figure 2. 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 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 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%.
3. PROSTHETIC PROFILES

3.1. CARBON COPY II

The Carbon Copy II was first introduced on the market in May 1986 by the Ohio Willow Wood Company. It was the most recent entry in the energy storing arena and has only been updated in the past few years. The CCII uses a combination of components from previous designs such as:

- Solid ankle.
- Kevlar / Nylon keel.
- Fibreglass / epoxy attachment plates.
- Low density Styrofoam fill.
- Heavy polyurethane elastomer outer shell.

The CCII has the ability to provide two levels of energy return. One level is for normal walking were the thin primary deflection plate returns a small amount of energy. The other level of energy return is for rigorous activities were the primary and secondary both act to provide a larger amount of returned energy.

The CCII offers, through its design, versatility and can be adapted to many levels of amputation including uni and bi - lateral above and below knee amputees. Overall the CCII is preferred by patients for its light weight and two levels of energy return.

The Carbon Copy II foot used in this investigation is a right foot, size 27cm.
3.2. DYNAMIC FOOT

The Dynamic Foot consists of a wooden ankle block encased by two layers of varying density foam. It is constructed so that it can produce excellent shock absorption at heel strike and provide a smooth transition from heel strike to toe off.

The Dynamic Foot is characterised by its:

- Rigid wooden keel surrounded by foams.
- Varying density foam construction

The Dynamic Foot is ideal for all patient groups and prosthesis adaptors.

The Otto Bock Dynamic foot used in this investigation is the ID10 right foot, size 27cm.

3.3. FLEX FOOT MODULAR II

The Flex Foot II consists of 2 moulded, 100% lightweight carbon - graphite, plates covered by an elastic foam which form the structure of the heel, forefoot and shank. The Flex Foot can be designed specifically for the individual and are made according to the weight of the amputee, expected activity level, stump size and the level of amputation.³

The diagram shows that the Flex Foot is not suitable for a Symes amputee or long below knee stumps that terminate less than 12.25cm from the floor. This is due to the fixed minimum length of the prosthesis.
3.4. GREISSINGER FOOT

The Greissinger Foot is a multi-axial foot that allows for rotation in all three phases:

- Flexion / extension
- Inversion / eversion
- Internal / external rotation

Multi-axis foot - ankle assemblies such as the Greissinger Foot were designed for very active below-knee amputees. They are widely used to reduce the shearing action between the stump and the socket.

The Greissinger Foot is characterised by its:

- Carbon fibre keel
- Polyurethane casing
- Multi-axis ankle

The advantage of having a multiple degree of freedom axis is that it allows for inversion / eversion that enables the patient to walk on uneven ground.

The Otto Bock Greissinger foot used in this investigation is the 1A13 right foot, size 27cm.
3.5. MULTI-AXIS FOOT

The Multi-Axis Foot consists of a carbon fibre keel encased by a polyurethane cosmesis. It is designed to allow for plantar and dorsiflexion as well as control in inversion and eversion. The heel height is adjustable and allows for torque and impact to be absorbed.

The Multi-Axis Foot is characterised by its:

- Carbon Fibre keel.
- Adjustable heel height.
- Unique ankle joint.

The Multi-Axis Foot gives a safer and more natural function and enables some patients to achieve higher levels of activity.

The Blatchford Multi-Axis foot used in this investigation is the 509153-67 left foot, size 27cm.

3.6. QUANTUM

The Quantum foot was designed and manufactured by Hanger in London and consists of three major components:

- The spring module
- The foam ankle cosmesis
- The foot cosmesis
The spring module is constructed of epoxy resin and is reinforced with layers of fibreglass. The spring module consists of a sole spring, a secondary spring and an ankle base. The sole spring gives a smooth transition from heel strike to flat foot to heel off to toe off. The secondary spring acts as an energy storing device for more vigorous activities. Selection of the module is based on the patient's weight, foot size and activity level. The Quantum foot offers a good range of eversion and inversion as well as rotational control, enabling the patient to walk on inclined surfaces.

The quantometer is a device which assists the prosthetist in determining the behaviour of the sole spring inside the cosmesis at the fitting stage.\textsuperscript{(17)} The foam ankle cosmesis is manufactured from its block form to its desired shape and attached to the foot. The foot cosmesis is a rubber cover for the spring module. Features such as toes and skin colour give it good cosmetic properties.

The VESSA Quantum foot used in this investigation is the N1562 left foot, size 26cm.

### 3.7. SACH FOOT

There are several companies that produce the Solid Ankle Cushioned Heel (SACH) prosthesis such as Otto Bock Industries Inc. and Kingsley Manufacturing Co. This is one of the most popular prosthesis due to its low maintenance and relatively low cost.

The SACH Foot is characterised by its:

- Wedge shaped heel cushions.
- Varying heel densities.
- Varying material keel.
- Rubber body and bolt attachment.
3.7.1. Kingsley SACH

Features of all Kingsley SACH Feet include:

- Eastern Hard-Rock Maple Keel.
- Single composite 3 density Medathane foot moulding.
- Reinforced sole.
- Soft, Medium and Firm Heel Densities.

The Kingsley SACH foot used in this investigation is the Wayfarer K10 right foot, size 27cm.

3.7.2. Otto Bock SACH

Features of the Otto Bock SACH foot include:

- Polyurethane body.
- Titanium Bolt
- Poplar Keel

The Otto Bock SACH feet used in this investigation are the IS51 left foot, size 27cm and the IS70 left foot, size 28cm.
3.8. SAFE FOOT

The SAFE Foot (Stationary Ankle Flexible Endoskeleton) has a solid ankle and provides large amounts of transverse rotation as well as inversion and eversion. The advantage of the SAFE Foot is that it is moisture and grit - resistant. This makes this prosthesis very low maintenance.

The SAFE foot and other soft keel designs should be viewed as offering increased shock absorption and comfort at the expense of responsiveness in a competitive situation.

The Campbell Child’s SAFE foot used in this investigation is a right foot, size 27cm.

3.9. SEATTLE LITE

The Seattle Light Foot set the standards of performance, versatility, and cosmesis for dynamic response prosthetic feet. The Delrin II patented keel affords the Light foot a unique combination of fatigue resistance, toughness, and spring-like resilience without the transmission of shock for a smooth, dynamic gait.

Features of the Seattle Lite foot include:

- Delrin II dynamic response keel
- Lightweight design
- Sculpted life-like appearance
- Available in various skin colours

The Seattle Light foot is appropriate for amputees of all ages and activity levels and can be fit on all unilateral and bilateral lower extremity amputees down to the Symes level. The light foot is available in sizes 22-30 cm and is limited to use on individuals under 135 kg.

The Seattle Lite foot used in this investigation is the SLF130 right foot, size 24cm.
3.10. SEATTLE NATURAL

The Seattle Natural Foot is the best alternative to any SACH foot on the market today. The Natural Foot has all of the performance characteristics of a compliant foot plus the additional benefits of Seattle cosmesis and less weight, all blended to perform naturally.

Features of the Seattle Natural foot include:

- Excellent roll-over during walking
- Slim, sculpted, natural-looking cosmesis
- 3/8" heel rise
- Low to medium-low activity level
- Available in various skin colours

The Seattle Natural Foot meets the requirements of amputees of all ages with low to medium-low activity levels. It is appropriate for use by unilateral and bilateral lower extremity amputees. The Seattle Natural foot is available in sizes 22-29 cm.

The Seattle Natural foot used in this investigation is the SNF150 right foot, size 27cm.

3.11. STEN

The STEN foot is one of the simplest designs in prosthetic feet for it uses the Kingsley foot moulds and rubbers. It comes in a wide variety of sizes and heel heights from a child (18cm keel) through to an adult (30cm keel). The heels also come is soft, medium or hard densities.

Although it is slightly heavier than the conventional SACH foot, it differs in its keel which allows for smooth roll-over of the prosthesis. As the name suggests the STEN, STored ENergy, has the capacity to store energy. However, the effectiveness of its ability to store energy is debatable. The structure of its keel disperses the energy rather than storing and then returning it.
The STEN Foot is characterised by its:

- Varying density heel
- Polyurethane bumpers
- Reinforcement bands

The Kingsley STEN foot used in this investigation is a right foot, size 27cm.

### 3.12. SURE FLEX

The Flex-Foot Sure-Flex is a practical, lightweight energy storage prosthesis. It is designed for patients who perform low to moderate activity levels. The carbon fibre heel provides energy storage and return which enables the patients to achieve a smooth natural gait from heel strike to toe off. It incorporates a foam sole that is available in 3 densities to allow the prosthetist to customise the fit according to the patient’s needs. The Sure-Flex offers additional ankle motion not offered in other comparable bolt-on products.

Features of the Sure-Flex include:

- 100% carbon fibre composite keel and heel.
- Polyurethane foam sole available in three densities.

The SURE FLEX foot used in this investigation is a left foot, size 26cm.
4. 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 were 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.

4.1. 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, Appendix 1, results indicate that the :
were found to exhibit similar torsional properties to those of a human foot. These will be the prostheses used in the component investigation.

### 4.2. 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, Appendix 2, indicate:

- Blatchford Multi - Axis \( \text{659.05 N} \)
- Seattle Natural SNF150 \( \text{841.2 N} \)
- Sure Flex \( \text{745.07 N} \)

have the greatest impact absorption properties.

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.

Additional testing of some prostheses with an ankle adaptor (⊂ section ) indicate:

⇒ **Ankle Configuration**
- Otto Bock SACH IS70 793.14 N
- Seattle Natural SNF150 737.48 N

**Ankle Configuration**

- Otto Bock SACH IS70 770.37 N
- Seattle Natural SNF150 689.41 N

that this addition significantly decreases impact generated at the ankle.

The results indicate that a prosthesis with an ankle adaptor in the \( \subset \) configuration display a far greater impact absorption property than a prosthesis with no ankle adaptor.

### 4.3. 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.

The selection of the prostheses and their experimentally determined characteristics are detailed in Appendix 3.

From the feet selection detailed in Appendix 3, the following feet with corresponding characteristics are:

**Dorsiflexion:**

- Human Foot 5°
- Seattle Natural 5°
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Foot</td>
<td>4°</td>
<td></td>
</tr>
<tr>
<td>Mutli - Axis Foot</td>
<td>4°</td>
<td></td>
</tr>
<tr>
<td><strong>Energy Return:</strong></td>
<td><strong>Human Foot</strong></td>
<td>119.6 %</td>
</tr>
<tr>
<td>Seattle Natural</td>
<td>70.7 %</td>
<td></td>
</tr>
<tr>
<td>Flex foot Mod.II</td>
<td>61.7 %</td>
<td></td>
</tr>
<tr>
<td>Quantum Vessa</td>
<td>59.5 %</td>
<td></td>
</tr>
<tr>
<td><strong>Eversion Angle:</strong></td>
<td><strong>Human Foot</strong></td>
<td>20°</td>
</tr>
<tr>
<td>Seattle Natural</td>
<td>19.5°</td>
<td></td>
</tr>
<tr>
<td>Kingsley Sten</td>
<td>16.5°</td>
<td></td>
</tr>
<tr>
<td>SAFE</td>
<td>16.0°</td>
<td></td>
</tr>
<tr>
<td><strong>Torque:</strong></td>
<td><strong>Human Foot</strong></td>
<td>10 Nm</td>
</tr>
<tr>
<td>SACH IS51</td>
<td>10.84 Nm</td>
<td></td>
</tr>
<tr>
<td>SAFE</td>
<td>9.49 Nm</td>
<td></td>
</tr>
<tr>
<td>Seattle Natural</td>
<td>11.52 Nm</td>
<td></td>
</tr>
<tr>
<td><strong>Impact:</strong></td>
<td><strong>Human Foot</strong></td>
<td>n/a</td>
</tr>
<tr>
<td>Multi - Axis</td>
<td>659.05 N</td>
<td></td>
</tr>
<tr>
<td>Sureflex</td>
<td>745.07 N</td>
<td></td>
</tr>
<tr>
<td>Seattle Natural</td>
<td>841.2 N</td>
<td></td>
</tr>
</tbody>
</table>
5. 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.

5.1. OTTO BOCK GREISSINGER 1A13

Characteristics:

- **Dorsiflexion** Due to multi-axis joint.
- **Eversion** Multi-axis joint, deflection of foam either side of the keel.
- **Energy Return** Multi-axis joint and rubber composites surrounding it.
- **Torsion** Deflection of rubber grommet about the bolt within the ankle.
- **Impact Absorption** Heel properties and geometry of rubber and plate within the ankle.
Components :

- **Heel**: Polyurethane Foam - Pedilan™
- **Keel**: Rigid wooden - Poplar™
- **Multi - Axis Joint**: Stainless Steel or Titanium
- **Cosmesis**: Moulded Polyurethane Foam

5.2. OTTO BOCK SACH IS51 - IS70 & KINGSLEY SACH K10

Characteristics :

- **Dorsiflexion**: Due to foam and timber keel
- **Eversion**: Large amount of foam on the underside of the keel.
- **Energy Return**: Foam surrounding keel in fore foot.
- **Torsion**: Distortion of the foam around keel on ankle base.
- **Impact Absorption**: Varying density foam of heel wedge.

Components :

- **Heel**: Polyurethane Foam - Soft Density
- **Keel**: Rigid wooden - Poplar™
- **Ankle Block**: Cosmesis surrounding keel
- **Cosmesis**: Moulded Polyurethane Foam
5.3. OTTO BOCK DYNAMIC 1D10

Characteristics:

- **Dorsiflexion**: Small timber keel, and deflection of secondary foam.
- **Eversion**: Distortion of keel and secondary foam.
- **Energy Return**: Elastic properties of the two foams.
- **Torsion**: Distortion of keel within surrounding foam of ankle block.
- **Impact Absorption**: Density of primary and secondary foams.

Components:

- **Heel**: Polyurethane Foam.
- **Keel**: Short, rigid, wooden keel with secondary polyurethane surrounding.
- **Ankle Block**: Cosmesis surrounding keel
- **Cosmesis**: Moulded Polyurethane Foam

5.4. KINGSLEY STEN

Characteristics:

- **Dorsiflexion**: Dual articulating flexible keels with bumper spacers and reinforced belting.
- **Eversion**: Twisting of the keel, bumpers and foam deflection.
- **Energy Return**: Elasticity of bumpers and reinforced keel.
- **Torsion**: Distortion of keel within surrounding foam of ankle block.
- **Impact Absorption**: Foam heel wedge.

Components:
Heel Polyurethane Foam
Keel Varying density foams between bumpers and dual keels.
Ankle Block Wooden.
Cosmesis Moulded Polyurethane Foam.

5.5. SURE FLEX

Characteristics:

Dorsiflexion Due to the Keel.
Eversion Twisting of the keel within the cosmesis and elastic properties of the cosmesis.
Energy Return Elasticity of keel.
Torsion Distortion of keel about pylon.
Impact Absorption Elasticity of heel plate and density of rubber insert.

Components:

Heel Carbon Fibre plate with Rubber insert
Keel 100% Carbon Fibre - long.
Ankle Block Foot is attached directly to pylon.
Cosmesis Kevlar reinforced foam, additional unit.
5.6. SEATTLE NATURAL

Characteristics :

- **Dorsiflexion** Due to Delrin keel deflection and intermediate rubbers.
- **Eversion** Deflection of rubbers about the base of the keel.
- **Energy Return** Keel and intermediate rubbers within keel.
- **Torsion** Distortion of keel within foam
- **Impact Absorption** Density of heel foam.

Components :

- **Heel** Polyurethane Foam.
- **Keel** Flexible, nylon-Delrin II™ with varying density foam inserts.
- **Ankle Block** Cosmesis surrounding keel.
- **Cosmesis** Moulded Polyurethane Foam - realistic.

5.7. BLATCHFORD MULTI-AXIS

Characteristics :

- **Dorsiflexion** Carbon fibre keel, rubber bumper in multi-axial joint.
- **Eversion** Orientation of carbon fibre keel and rubbers about the base.
- **Energy Return** Keel and rubber bumpers within ankle joint.
- **Torsion** Distortion of ball and snub system within ankle.
- **Impact Absorption** Density of heel foam and deflection of ankle joint.

Components :
Heel Polyurethane Foam.
Keel Rigid carbon fibre.
Ankle Block Multi-flex ankle, aluminium and rubber rings.
Cosmesis Moulded Polyurethane Foam.

5.8. CAMPBELL CHILDS SAFE

Characteristics:

Dorsiflexion Ligament bands and keel.
Eversion Keel flexion and elasticity of rubbers about the base.
Energy Return Keel flexion and elasticity of rubbers about the base.
Torsion Ankle block movement in the second urethane foam.
Impact Absorption Density of heel foam.

Components:

Heel Polyurethane Foam.
Keel Flexible urethane.
Ankle Block Maple.
Cosmesis Moulded Polyurethane Foam.

5.9. SEATTLE LITE FOOT
Characteristics:

*Dorsiflexion*  
Density of encasing foam and flexible keel.

*Eversion*  
Distortion of the foam about the keel.

*Energy Return*  
Elastic properties of keel and foam.

*Torsion*  
Rubber surrounding keel at ankle base.

*Impact Absorption*  
Density of heel foam.

Components:

*Heel*  
Polyurethane Foam.

*Keel*  
Flexible, nylon - Delrin II™

*Ankle Block*  
Hollow section.

*Cosmesis*  
Moulded Polyurethane Foam - realistic.

5.10. VESSA QUANTUM

Characteristics:

*Dorsiflexion*  
Fibre glass leave springs in two stages.

*Eversion*  
Deflection of fibre glass spring and cosmesis.

*Energy Return*  
Elastic properties of fibre glass.

*Torsion*  
Twisting of mounting block.

*Impact Absorption*  
Fibre glass spring at rear.
Components:

- Heel: Fibre glass.
- Keel: Fibre glass - epoxy.
- Ankle Block: Aluminium attachment.
- Cosmesis: Moulded Polyurethane Foam - additional unit.

6. 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.

6.1. KEVLAR®, ARAMID (polyp-phenyleneetherphthalamide)

Advantages

1. Low density.
2. High Tensile strength.
3. Low cost fibres.
4. Impact resistance.
5. Light weight.
7. Fatigue and stress resistant.
8. Creep resistance.
Disadvantages
1. Low Compressive strength
2. poor adhesion to polymers
3. Moisture Absorbent

6.2. CARBON FIBRES

Advantages
1. High Strength
2. Light Weight
3. High Stiffness
4. Chemically inert
5. Creep resistant
6. Superior bonding with resins

Disadvantages
1. Low impact strength
2. Low shear modulus
3. Brittle
4. Expensive

6.3. ETHYLENE - VINYL ACETATE (EVA)

Advantages of Polyethylene
1. Low cost to manufacture
2. Display good low temperature flexibility and toughness
3. Non Toxic
4. Excellent dielectric properties
5. Moisture resistance
6. Very good chemical resistance
7. Processable by all thermoplastic methods
Disadvantages
1. High thermal expansion
2. Poor weathering resistance
3. Subject to stress cracking
4. Difficulty in bonding
5. Flammable

6.4. FIBREGLASS / FIBRE EPOXY

Advantages
1. Wide curing latitude
2. May be used for Medical devices (artificial limbs)
3. Accept high filler levels
4. Thermosetting materials
5. Inexpensive tooling

Disadvantages
1. Upper service temperature limited to 93°C
2. Poor resistance to solvents
3. Poor bonding to resins

6.5. GRAPHITE COMPOSITES

Advantages
1. High strength to weight ratio
2. Light weight
3. Ductile

Disadvantage
1. Fail under inter - laminar shear
6.6. NYLON 66

Advantages
1. Tough, strong and impact resistant
2. Low coefficient of friction
3. Abrasion resistance
4. Processable by thermoplastic methods
5. Good solvent resistance
6. Resistant to bases

Disadvantages
1. Requires UV stabilisation
2. High shrinkage in mould
3. Subject to attack by strong acids and oxidising agents
4. High moisture absorption with related dimensional stability
5. Mechanical and electrical properties influenced by moisture content

6.7. POLY ACETALS (Delrin™)

Advantages of Acetals
1. High tensile strength with rigidity and toughness
2. Excellent dimensional stability
3. Glossy moulded surfaces
4. Moisture absorption
5. Low static and coefficient of friction
6. Low gas and vapour permeability
7. Fatigue Endurance
8. Resistance to Creep
9. Low co-efficient of friction
10. Lightweight
11. Easily fabricated
12. Abrasion resistance
Disadvantages

1. Subject to UV degradation
2. Flammable
3. Unsuitable for contact with food
4. Difficult to bond
5. Toxic, releases fumes upon degradation
6. Poor resistance to acids and bases
7. Short term failure - in particular impact resistance
8. Long term deformation such as exhibited by creep curves
9. Long term failure
10. High Cost

6.8. POLYETHYLENE

Advantages

1. Low Cost
2. Easy Processability
3. Freedom of odour and toxicity
4. Very good chemical resistance
5. Excellent insulator

Disadvantage

1. Environmental stress cracking
2. Poor scratch resistance
3. Low tensile strength
4. Lack of rigidity
6.9. POLYPROPYLENE

Advantages

1. Low density
2. Free from environmental stress cracking problems
3. Higher Brittle point
4. Processable by all thermoplastic methods
5. Low coefficient of friction
6. Good fatigue resistance
7. Excellent moisture resistance
8. First rate abrasion resistance
9. Good grade availability
10. Very good chemical resistance
11. Excellent flexural strength
12. Good Impact strength

Disadvantages

1. Degradation via exposure to UV
2. Poor weatherability
3. Flammable
4. Difficult to bond
5. Oxidative breakdown accelerated by several metals

6.10 POLYSTYRENE

Advantages

1. Hard, rigid and transparent thermoplastic
2. Free from odour and taste
3. Low cost, good mouldability
4. Low moisture absorption
5. Colourability resistance
6. Chemical resistance
Advantages
7. Light mass
8. High gloss
9. Low cost
10. Good dimensional stability
11. Good rigidity
12. Processable by all thermoplastic methods
13. Good grades available
14. Optical clarity

Disadvantages
1. Flammable
2. Poor weatherability
3. Subject to stress and environmental cracking
4. Poor thermal stability
5. Poor resistance to solvents
6. Brittleness
7. Inability to withstand the temperature of boiling water

6.11. POLYURETHANE

Advantages
1. High abrasion resistance
2. Good low temperature stability
3. Wide variability in molecular structure
4. Possibility of ambient curing
5. Comparative low cost
6. Prepolymers foam readily
7. Higher tensile strengths than any other rubber
8. Excellent tear and Abrasion resistance
9. Tend to have a high hardness
10. Low resilience
Disadvantages
  1. Poor thermal capability
  2. Toxic
  3. Poor weatherability
  4. Subject to attack by solvents
  5. Not as good as cast rubber
  6. Difficult to dye

7. 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.

8. 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:

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>PROSTHESIS</th>
<th>DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORSIFLEXION</td>
<td>Seattle Natural SNF150</td>
<td>Delrin keel deflection and intermediate urethane foams.</td>
</tr>
<tr>
<td></td>
<td>Otto Bock Dynamic 1D10</td>
<td>Small timber keel, and deflection of secondary polyurethane foam.</td>
</tr>
<tr>
<td></td>
<td>Blatchford Multi - Axis</td>
<td>Carbon fibre keel, rubber bumper in multi-axial joint.</td>
</tr>
<tr>
<td>ENERGY RETURN</td>
<td>Seattle Natural SNF150</td>
<td>Keel and intermediate urethane foams within keel.</td>
</tr>
<tr>
<td></td>
<td>Flex foot Modular II</td>
<td>Keel Elasticity of the carbon fibre composition</td>
</tr>
<tr>
<td></td>
<td>Quantum Vessa</td>
<td>Elastic properties of fibre glass keel.</td>
</tr>
<tr>
<td>EVERSION ANGLE</td>
<td>Seattle Natural SNF150</td>
<td>Deflection of polyurethane at the base of the keel.</td>
</tr>
<tr>
<td></td>
<td>Kingsley STEN</td>
<td>Twisting of the keel, bumpers and polyurethane deflection</td>
</tr>
<tr>
<td></td>
<td>SAFE</td>
<td>Keel flexion and elasticity of rubbers about the base</td>
</tr>
</tbody>
</table>
8.1. PROSTHETIC DESIGN

8.1.1. 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.

Appendix 4. - keel design.
8.1.2. 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 in Appendix 5, provides for greater absorption due to the larger end being exposed to the heel strike. Used in conjunction with the $\subset$ section, the combined components provide extra impact absorption.

8.1.3. 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.

Appendix 5 -- prosthetic foot design.
ACKNOWLEDGMENTS

The authors, would like to extend their gratitude and appreciation to the various people who volunteered their time and efforts throughout the duration of the project.

Bill Contoyannis and Ross Stewart, REHABTech Monash Hospital for their expertise and patient assistance. With an extended appreciation to John and David, REHABTech. for their technical assistance.

Dr. Christopher Mechefske, Project Supervisor, for his continued support and encouragement.

Julie Stewart, Computer Services, Department of Engineering, for her assistance in scanned images.

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.
REFERENCES

1. American Prosthetics Corporation, Concept of the Prosthetic Foot, June 29, 1992, Illinois, USA.


TORSIONAL EXPERIMENTS

Aim :

To measure the amount of torque generated around the ankle component of a prosthesis. For the purpose of this investigation, establishing a measurable torsional value characterising the various prosthesis. In addition, determining how favourably such characteristics compare to the torsional properties exhibited by a normal foot.

BACKGROUND :

The normal function of ankle torque in a sound lower limb is to provide multi-functional characteristics in understanding various activities such as walking, jumping, climbing, etc. The function that a prosthesis has is not as multi-functional as human foot but is limited to specific movements, restricting the activity level.

Though the torsional properties inherent in a prosthesis 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 in undertaking a twisting motion. Though a subjective characteristic, a true rotational value is somewhat arbitrary; dependent on the conditions and the functional requirements of the user.

The torsional properties of a human foot are such that for a $10^\circ$ rotation angle the 10 nm of torque is generated

EQUIPMENT :
* TWO PEOPLE REQUIRED TO PERFORM TORSIONAL TESTING

Torque wrench
Vice / clamping device
Slide scale protractor
Socket adapter suitable for prosthetic pyramids
Masking tape
Stabilising pylon
Additional clamp
Wooden platform

Prosthesis tested:

Gresinger - otto bock (r) size 27
Sten - kingsley (r) size 27
Safe foot campbell child's (r) size 27
Dynamic foot - otto bock (r) size 27
Seattle natural foot (r) size 27
Sach foot - otto bock 1s51 (l) size 27
Sach foot - otto bock 1s70 (l) size 28
Vessa quantum (yellow) (l) size 26
Seattle lite foot (r) size 24
Multi-axis - blatchford (l) size 27
Sure flex (l) size 26

Note: (l) left foot (r) right foot

EXPERIMENTAL SET-UP
APPENDIX 1

1. Secure the modified wrench inside the vice, ensuring the wrench is horizontal and the force indicator is facing out to the side.

2. Secure the platform to the work bench using the clamp. The platform is to be located under the socket connection of the wrench.

3. Locate the supporting arm between the socket connection of the wrench and the platform. This device is used as a counter support to the force placed on the foot.

4. Attach the prosthesis to the wrench so that the toes face up in a vertical direction.

5. Position the protractor so that the strapped arm remains vertical with the foot whilst the free arm is rested horizontally, parallel to the wrench.

Note: * It may be important to support the prosthesis on the wrench as it may be unstable.

TESTING

PREDETERMINED TORQUE

1. Standing in line with the apparatus, ensure the foot is vertical and record the initial angle of the protractor (θ₁) between the vertical arm and the horizontal arm.

2. Placing one hand near, but not on, the socket - adaptor connection and the other on the top of the foot. Maintain a vertical position of the foot and a straight horizontal positioning of the wrench. Pull down from the top of the foot, generating a twisting motion around the ankle joint.

3. The operator continues to apply the twisting force whilst the second operator indicates when 5 lb.ft is indicated on the torque wrench.
4. The device operator should maintain this position and read off the new angle indicated on the protractor (θ₂)

5. Release the applied force. Repeat steps 2 to 5 for the same foot, however, in this instance rotate the foot until the applied torque equals 10 lb.ft. Maintain this force and measure the new angle (θ₃)

**PREDETERMINED ANGLE SETTING**

Whilst the foot is still attached to the device it may be useful to undertake a secondary study into torsional properties of prosthetics.

1. Using the angle θ₁ determined in step (1) **predetermined torsional force**. Twist the foot in the same manner as in step (2) above. The device operator should move the foot so that a 10 degree angle difference from θ₁ is indicated.

2. Maintain this position. The second operator should read the wrench indicator and record the torsional value (T₁).

3. Repeat the same procedure for an angle difference of 20 degrees from θ₁ and record the new torsional value obtained (T₂).

**Repeat**

1. Remove the foot and repeat steps 1 - 2 **prosthesis preparation**.

2. Repeat steps 4 & 5 of equipment setup.

3. Undertake the testing again following the steps detailed in testing procedure following steps 1 - 5 also following Predetermined torque setting and steps 1 - 3 predetermined angle steering.

4. Once completed, reverse the setup of the apparatus so that the twisting motion placed upon the feet is now in the other direction.
5. Repeat all steps previously mentioned for this configuration.

RESULTS:

Test 1: rotation angle 10°
right feet experience outward twisting motion
left feet experience inward twisting motion

Test 2: rotation angle 10°
right feet experience inward twisting motion
left feet experience outward twisting motion

<table>
<thead>
<tr>
<th>PROSTHESIS</th>
<th>TEST 1</th>
<th>TEST 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TORQUE, Nm</td>
<td>TORQUE Nm</td>
</tr>
<tr>
<td>Greissinger</td>
<td>4.1</td>
<td>2.71</td>
</tr>
<tr>
<td>Sten</td>
<td>13.55</td>
<td>12.20</td>
</tr>
<tr>
<td>Safe</td>
<td>9.49</td>
<td>9.49</td>
</tr>
<tr>
<td>Dynamic</td>
<td>13.55</td>
<td>6.77</td>
</tr>
</tbody>
</table>
APPENDIX 1

<table>
<thead>
<tr>
<th></th>
<th>Natural</th>
<th>Otto Bock IS51</th>
<th>Otto Bock IS70</th>
<th>Quantum</th>
<th>Seattle Lite</th>
<th>Multi - Axis</th>
<th>Sure Flex</th>
<th>Sure Flex (no cosmesis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.52</td>
<td>10.84</td>
<td>14.23</td>
<td>3.39</td>
<td>14.91</td>
<td>2.71</td>
<td>2.71</td>
<td>4.06</td>
</tr>
</tbody>
</table>

Human foot 10 Nm - rotation angle 10°

A complete tabulation of results in Appendix 1A.

**OBSERVATIONS AND DISCUSSION:**

In comparing results generated from undertaking the torsional tests the best three prosthetic feet were selected. The selection was based on:

1. How favourably the prosthesis compared to the torsional properties exhibited by the sound human foot.
2. Regardless of the directional movement of the foot. The selection of any particular foot had to satisfy the parameters of the human foot in either direction.
3. The feet found to exhibit similar torsional properties to that of a human are as follows:
   - SAFE : 9.49 Nm
   - SACH IS51 : 10.84 Nm
   - Natural : 11.52 Nm
   - Sten : 12.20 Nm
APPENDIX 1

A material and component analysis of these feet will provide insight into what enables these prosthetic feet to demonstrate such torsional characteristics.
## APPENDIX 1

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>Initial Angle</th>
<th>5 lbf ft</th>
<th>10 lbf ft</th>
<th>Difference θ</th>
<th>Torque LBF FT</th>
<th>Torque Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ₁</td>
<td>θ₂</td>
<td>θ₃</td>
<td>θ₁ - θ₂</td>
<td>θ₁ - θ₃</td>
<td>T₁</td>
</tr>
<tr>
<td>Greissinger</td>
<td>156.5</td>
<td>139</td>
<td>127</td>
<td>17.5</td>
<td>29.5</td>
<td>0.0764</td>
</tr>
<tr>
<td>Sten</td>
<td>161</td>
<td>154</td>
<td>150</td>
<td>7</td>
<td>11</td>
<td>0.0305</td>
</tr>
<tr>
<td>SAFE</td>
<td>159.5</td>
<td>152</td>
<td>145</td>
<td>7.5</td>
<td>14.5</td>
<td>0.0327</td>
</tr>
<tr>
<td>Dynamic</td>
<td>165.5</td>
<td>161</td>
<td>155</td>
<td>4.5</td>
<td>10.5</td>
<td>0.0196</td>
</tr>
<tr>
<td>Natural</td>
<td>165</td>
<td>160</td>
<td>153</td>
<td>5</td>
<td>12</td>
<td>0.0218</td>
</tr>
<tr>
<td>Otto Bock IS51</td>
<td>164</td>
<td>159</td>
<td>153</td>
<td>5</td>
<td>11</td>
<td>0.0218</td>
</tr>
<tr>
<td>Otto Bock 1S70</td>
<td>159</td>
<td>152</td>
<td>148</td>
<td>7</td>
<td>11</td>
<td>0.0305</td>
</tr>
<tr>
<td>Quantum</td>
<td>168</td>
<td>151</td>
<td>139</td>
<td>17</td>
<td>29</td>
<td>0.0742</td>
</tr>
<tr>
<td>Seattle Lite</td>
<td>179</td>
<td>183</td>
<td>195</td>
<td>4</td>
<td>16</td>
<td>0.0175</td>
</tr>
<tr>
<td>Multi-Axis</td>
<td>146</td>
<td>125</td>
<td>110</td>
<td>21</td>
<td>36</td>
<td>0.0916</td>
</tr>
<tr>
<td>Sure Flex</td>
<td>135</td>
<td>116</td>
<td>109</td>
<td>19</td>
<td>26</td>
<td>0.0829</td>
</tr>
<tr>
<td>Sure Flex (no cos)</td>
<td>135</td>
<td>124</td>
<td>118</td>
<td>11</td>
<td>17</td>
<td>0.0480</td>
</tr>
</tbody>
</table>

**Test 1. Right Foot Outward - Left Foot Inward dirn.**

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>94</th>
<th>92</th>
<th>20</th>
<th>22</th>
<th>0.0873</th>
<th>0.0960</th>
<th>2</th>
<th>6.5</th>
<th>2.712</th>
<th>8.813</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greissinger</td>
<td>139</td>
<td>132</td>
<td>1</td>
<td>7</td>
<td>0.0044</td>
<td>0.0305</td>
<td>9</td>
<td>18</td>
<td>12.202</td>
<td>24.405</td>
</tr>
<tr>
<td>Sten</td>
<td>132</td>
<td>118</td>
<td>7</td>
<td>14</td>
<td>0.0305</td>
<td>0.0611</td>
<td>7</td>
<td>14</td>
<td>9.491</td>
<td>18.981</td>
</tr>
<tr>
<td>SAFE</td>
<td>121</td>
<td>106.5</td>
<td>8.5</td>
<td>14.5</td>
<td>0.0371</td>
<td>0.0633</td>
<td>5</td>
<td>14</td>
<td>6.779</td>
<td>18.981</td>
</tr>
<tr>
<td>Dynamic</td>
<td>105</td>
<td>88</td>
<td>12</td>
<td>17</td>
<td>0.0524</td>
<td>0.0742</td>
<td>2</td>
<td>12</td>
<td>2.712</td>
<td>16.270</td>
</tr>
<tr>
<td>Natural</td>
<td>126</td>
<td>103</td>
<td>14</td>
<td>23</td>
<td>0.0611</td>
<td>0.1004</td>
<td>3.5</td>
<td>8.5</td>
<td>4.745</td>
<td>11.524</td>
</tr>
<tr>
<td>Otto Bock IS51</td>
<td>124</td>
<td>111</td>
<td>5</td>
<td>13</td>
<td>0.0218</td>
<td>0.0567</td>
<td>5</td>
<td>13.5</td>
<td>6.779</td>
<td>18.304</td>
</tr>
<tr>
<td>Otto Bock 1S70</td>
<td>137</td>
<td>110</td>
<td>11</td>
<td>27</td>
<td>0.0480</td>
<td>0.1178</td>
<td>4.5</td>
<td>8</td>
<td>6.101</td>
<td>10.847</td>
</tr>
<tr>
<td>Quantum</td>
<td>108</td>
<td>93</td>
<td>10</td>
<td>15</td>
<td>0.0436</td>
<td>0.0654</td>
<td>3</td>
<td>10</td>
<td>4.067</td>
<td>13.558</td>
</tr>
<tr>
<td>Seattle Lite</td>
<td>116</td>
<td>103</td>
<td>7</td>
<td>13</td>
<td>0.0305</td>
<td>0.0567</td>
<td>6</td>
<td>15</td>
<td>8.135</td>
<td>20.337</td>
</tr>
</tbody>
</table>

**Test 2. Right Foot Inward - Left Foot Outward dirn.**
IMPACT EXPERIMENTS

AIM:

To determine the shock absorption properties of the prosthesis at heel strike and estimate the contact time of the prosthesis with the force plate. Determine which prosthesis has the best shock absorption properties at heel strike.

BACKGROUND:

In order 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. The shorter the time the larger the shock. The time over which the force is applied will depend upon the density of the material in the heel of the prosthesis. The material of most prosthesis are trademark names and the properties of these materials are not readily available. This experiment will determine the shock absorption properties of the heels material and determine the impact time.

EQUIPMENT:

TWO PEOPLE REQUIRED TO PERFORM IMPACT TEST.

180° Protractor.
Steel arm of known weight and length.
Force plate.
Data acquisition program.
Allen key set.

Prosthetic feet tested:
• Greissinger - Otto Bock (r) size 27
• Sten - Kingsley (r) size 27
• Safe Campbell Childs (r) size 27
• Dynamic - Otto Bock (r) size 27
• Seattle Natural ® size 27
• Sach - Otto Bock IS51 (l) size 27
• Sach - Otto Bock IS70 (l) size 28
• Vessa Quantum (yellow) (l) size 26
• Seattle Lite (r) size 24
• Multi - Axis - Blatchford (l) size 27
• Sure Flex (l) size 26

Note: (l) Left foot (r) Right foot

EXPERIMENTAL SETUP:

EXPERIMENTAL PROCEDURE:
PROSTHESIS PREPARATION

1. Turn on the data acquisition machine 15 minutes before the first test is performed on the force plate.

2. Attach ankle pyramids to prosthesis as required.

TESTING

1. Screw the arm to the base of the test area in order to eliminate the apparatus slipping.

2. Attach the prosthesis in the mounting.

3. Select the desired configuration in the Kisler data acquisition program. Choose eshoewalk.cfg.

4. Move the arm up to 90° using the protractor.

5. Start the data acquisition program and release the arm from its vertical position.


7. Repeat steps 4 - 6 with all the prosthetic feet.

8. For the feet that can accommodate a $\supset$ section or $\subset$ section ankle adaptor, repeat steps 4 - 6 with the adaptors on the feet.

RESULTS :
Appendix 2a shows graphically the force versus time impact of the feet on the force plate. It is possible to determine the impact time of each prosthesis and the shock absorption characteristics. A comparison on the effect of the $\supset$ section or $\subset$ section ankles can also be made.

Normal Drop Test:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Otto Bock Dynamic 1D10</td>
<td>894.34</td>
<td>494.61</td>
<td>399.73</td>
<td>0.032</td>
<td>0.064</td>
<td>0.032</td>
</tr>
<tr>
<td>Otto Bock Greissinger</td>
<td>1449.66</td>
<td>549.00</td>
<td>900.66</td>
<td>0.052</td>
<td>0.084</td>
<td>0.032</td>
</tr>
<tr>
<td>Otto Bock SACH IS51</td>
<td>974.03</td>
<td>574.30</td>
<td>399.73</td>
<td>0.092</td>
<td>0.124</td>
<td>0.032</td>
</tr>
<tr>
<td>Otto Bock SACH IS70</td>
<td>925.96</td>
<td>628.69</td>
<td>297.27</td>
<td>0.220</td>
<td>0.264</td>
<td>0.044</td>
</tr>
<tr>
<td>Seattle Lite SLF130</td>
<td>872.83</td>
<td>468.04</td>
<td>404.79</td>
<td>0.092</td>
<td>0.132</td>
<td>0.040</td>
</tr>
<tr>
<td>Blatchford Multi - Axis</td>
<td>659.05</td>
<td>187.22</td>
<td>471.84</td>
<td>0.232</td>
<td>0.264</td>
<td>0.032</td>
</tr>
<tr>
<td>Seattle Natural SNF150</td>
<td>841.21</td>
<td>457.92</td>
<td>383.29</td>
<td>0.196</td>
<td>0.228</td>
<td>0.032</td>
</tr>
<tr>
<td>Vessa Quantum No Cos.</td>
<td>2207.39</td>
<td>678.03</td>
<td>1529.36</td>
<td>0.176</td>
<td>0.196</td>
<td>0.020</td>
</tr>
<tr>
<td>Vessa Quantum With Cos.</td>
<td>1073.97</td>
<td>290.94</td>
<td>783.02</td>
<td>0.088</td>
<td>0.108</td>
<td>0.020</td>
</tr>
<tr>
<td>Campbell Childs Safe</td>
<td>917.11</td>
<td>460.45</td>
<td>456.66</td>
<td>0.012</td>
<td>0.044</td>
<td>0.032</td>
</tr>
<tr>
<td>Kingsley Sten 1027.16</td>
<td>586.95</td>
<td>440.21</td>
<td>327.63</td>
<td>0.112</td>
<td>0.144</td>
<td>0.032</td>
</tr>
<tr>
<td>Sure Flex</td>
<td>745.07</td>
<td>360.52</td>
<td>384.55</td>
<td>0.748</td>
<td>0.780</td>
<td>0.032</td>
</tr>
</tbody>
</table>

$\supset$ Section Ankle Configuration:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Otto Bock SACH IS51</td>
<td>872.83</td>
<td>545.21</td>
<td>327.63</td>
<td>0.196</td>
<td>0.228</td>
<td>0.032</td>
</tr>
<tr>
<td>Otto Bock SACH IS70</td>
<td>793.14</td>
<td>562.92</td>
<td>230.23</td>
<td>0.232</td>
<td>0.288</td>
<td>0.056</td>
</tr>
<tr>
<td>Seattle Natural SNF150</td>
<td>737.48</td>
<td>419.97</td>
<td>317.51</td>
<td>0.288</td>
<td>0.328</td>
<td>0.040</td>
</tr>
<tr>
<td>Campbell Childs Safe</td>
<td>785.55</td>
<td>417.44</td>
<td>368.11</td>
<td>0.192</td>
<td>0.224</td>
<td>0.032</td>
</tr>
<tr>
<td>Kingsley Sten</td>
<td>833.62</td>
<td>485.75</td>
<td>347.87</td>
<td>0.084</td>
<td>0.120</td>
<td>0.036</td>
</tr>
</tbody>
</table>

$\subset$ Section Ankle Configuration:
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Otto Bock Dynamic 1D10</td>
<td>783.02</td>
<td>452.86</td>
<td>330.16</td>
<td>0.292</td>
<td>0.328</td>
<td>0.036</td>
<td>0.728</td>
<td>0.772</td>
<td>0.044</td>
</tr>
<tr>
<td>Otto Bock SACH IS51</td>
<td>856.39</td>
<td>531.29</td>
<td>325.10</td>
<td>0.168</td>
<td>0.208</td>
<td>0.040</td>
<td>0.648</td>
<td>0.696</td>
<td>0.048</td>
</tr>
<tr>
<td>Otto Bock SACH IS70</td>
<td>770.37</td>
<td>556.59</td>
<td>213.78</td>
<td>0.284</td>
<td>0.332</td>
<td>0.048</td>
<td>0.868</td>
<td>0.908</td>
<td>0.040</td>
</tr>
<tr>
<td>Seattle Natural SNF150</td>
<td>689.41</td>
<td>408.59</td>
<td>280.83</td>
<td>0.100</td>
<td>0.140</td>
<td>0.040</td>
<td>0.504</td>
<td>0.552</td>
<td>0.048</td>
</tr>
<tr>
<td>Campbell Childs Safe</td>
<td>785.55</td>
<td>427.56</td>
<td>357.99</td>
<td>0.432</td>
<td>0.468</td>
<td>0.036</td>
<td>0.812</td>
<td>0.856</td>
<td>0.044</td>
</tr>
<tr>
<td>Kingsley Sten</td>
<td>841.21</td>
<td>508.52</td>
<td>332.69</td>
<td>0.380</td>
<td>0.420</td>
<td>0.040</td>
<td>0.824</td>
<td>0.864</td>
<td>0.040</td>
</tr>
</tbody>
</table>
Normal Drop Test

OTTO BOCK DYNAMIC FOOT

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.032</td>
<td>894.339</td>
</tr>
<tr>
<td>0.488</td>
<td>494.6061</td>
</tr>
<tr>
<td>0.524</td>
<td>0</td>
</tr>
</tbody>
</table>
\( y = 47.901x^3 + 134.1x^2 - 964.03x + 939.9 \)
\[ y = 672.34x^4 - 3055x^3 + 5178.1x^2 - 4256.1x + 1701.5 \]
The graph shows a plot of force against time, with the equation $y = 39.458x^3 + 94.365x^2 - 892.2x + 1064$. The x-axis represents time in seconds (0 to 1.8), and the y-axis represents force in Newtons (0 to 1200). The data points are connected by a smooth curve, indicating the relationship between force and time over the given time period.
$y = 21.295x^4 - 167.31x^3 + 486.11x^2 - 872.36x + 1107.1$
\[ y = 204.92x^4 - 767.15x^3 + 1223.8x^2 - 1451.3x + 1020.7 \]
\[ y = 679.81x^2 - 2293x + 1170.2 \]
SEATTLE NATURAL FOOT

Force [N] vs. Time [s]

- Maximum force: 841.2099 N at 0.196 s
- Second peak force: 457.9218 N at 0.596 s

Q:\PROJECTS\FEET\FEETDATA.DOC
Natrdrop.tbd

\[ y = 400.35x^3 - 544.55x^2 - 737.49x + 1018.1 \]
$y = 146.91x^3 - 107.46x^2 - 1276.7x + 1719.8$
y = 105.29x^3 + 28.069x^2 - 1017.7x + 1152.3

Time [s]

Force [N]
\[ y = 1915.9x^3 - 6293.1x^2 + 5607.8x - 723.05 \]
The graph shows the relationship between force and time. The equation representing this relationship is:

\[ y = -1658.7x^3 + 5363.9x^2 - 6949.3x + 3313.9 \]
VESSA QUANTUM
With Cosmesis

![Graph showing force versus time]
\[ y = 27225x^3 - 18191x^2 + 40.203x + 1203.3 \]
Drop test with Seattle C Stance Ankle in Forwards direction

OTTO BOCK IS51

Ankle Configuration

Force [N]

Time [s]
Ankis51.tbd

y = 107.77x^3 - 171.16x^2 - 577.86x + 1000.2

Time [s]

Force [N]
OTTO BOCK SACH IS70

Ankle Configuration

Time [s]

Force [N]

793.1408

562.915

Q:\PROJECTS\FEET\FEETDATA.DOC
Ankis70.tbd

\[ y = -4.0899x^3 + 55.515x^2 - 400.77x + 891.02 \]
SEATTLE NATURAL FOOT

Ankle Configuration

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.288</td>
<td>737.4818</td>
</tr>
<tr>
<td>0.328</td>
<td></td>
</tr>
<tr>
<td>0.704</td>
<td>419.9725</td>
</tr>
<tr>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>

Q:\PROJECTS\FEET\FEETDATA.DOC
\[ y = -179.52x^4 + 913.27x^3 - 1267.5x^2 - 97.027x + 859.36 \]
CAMBELL CHILDS SAFE FOOT

Ankle Configuration

- Force [N]
- Time [s]

- Force peaks at 785.551 N at 0.192 s
- Force peaks at 417.4425 N at 0.56 s

Q:\PROJECTS\FEET\FEETDATA.DOC
Anksafe.tbd

\[ y = 528.63x^3 - 679.57x^2 - 720.78x + 959.74 \]
KINGSLEY STEN

Ankle Configuration

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.084</td>
<td>833.6201</td>
</tr>
<tr>
<td>0.496</td>
<td>485.7513</td>
</tr>
</tbody>
</table>

Q:\PROJECTS\FEET\FEETDATA.DOC
Anksten.tbd

\[ y = 97.863x^3 + 48.536x^2 - 883.02x + 917.04 \]
Drop Test with Seattle C Stance in backwards direction

OTTO BOCK DYNAMIC FOOT
⊂ Ankle Configuration

Force [N]

Time [s]
y = 1.1965x^3 + 198.11x^2 - 937.26x + 1048

Q:\PROJECTS\FEET\FEETDATA.DOC
OTTO BOCK SACH IS51
Ankle Configuration

856.3896
531.2905

Time [s]
Force [N]
The graph shows a relationship between force and time, described by the equation:

\[ y = 64.047x^3 - 41.308x^2 - 659.85x + 976.8 \]
OTTO BOCK SACH IS70
Ankle Configuration

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.284</td>
<td>770.3712</td>
</tr>
<tr>
<td>0.332</td>
<td>556.59</td>
</tr>
<tr>
<td>0.868</td>
<td></td>
</tr>
<tr>
<td>0.908</td>
<td></td>
</tr>
</tbody>
</table>

Q:\PROJECTS\FEET\FEETDATA.DOC
y = 12.155x^4 - 90.908x^3 + 266.95x^2 - 599.42x + 932.25
The graph shows the relationship between force [N] and time [s]. The equation for the curve is:

$$y = 428.13x^4 - 925.2x^3 + 742.48x^2 - 918.92x + 784.26$$
\[ y = 531.93x^3 - 1176.5x^2 - 86.644x + 1008.7 \]
KINGSLEY STEN

Ankle Configuration

Time [s]

Force [N]

841.2099

508.5209
y = 115.9x^2 - 209.29x^2 - 575.01x + 1088.5
### Appendix 3

<table>
<thead>
<tr>
<th>FOOT TYPE</th>
<th>Dorsi - flexion ¹</th>
<th>Eversion Angle ¹</th>
<th>ENERGY RETURN ²</th>
<th>TORQUE ² (N.m)</th>
<th>IMPACT ³ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Copy II</td>
<td>3.00</td>
<td>13.50</td>
<td>35.20</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Dynamic Foot  <em>Otto Bock</em> ID10</td>
<td><strong>4.00</strong></td>
<td>11.00</td>
<td>39.20</td>
<td>13.55</td>
<td>894.34</td>
</tr>
<tr>
<td>Flex Foot Modular II</td>
<td>3.50</td>
<td>15.00</td>
<td><strong>61.70</strong></td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Greissinger Foot  <em>Otto Bock</em> 1A13</td>
<td>3.25</td>
<td>15.75</td>
<td>31.70</td>
<td>4.1</td>
<td>1449.66</td>
</tr>
<tr>
<td>Multi Axis Foot  <em>Blatchford Multiflex Foot 509153-67</em></td>
<td><strong>4.00</strong></td>
<td>15.00</td>
<td>56.70</td>
<td>6.1</td>
<td><strong>659.05</strong></td>
</tr>
<tr>
<td>Quantum VESSA  <em>Truestep 25 type A N1562</em></td>
<td>2.25</td>
<td>15.00</td>
<td><strong>59.50</strong></td>
<td>4.74</td>
<td>1073.96</td>
</tr>
<tr>
<td>SACH Foot  <em>Kingsley Wayfarer (Post Op. Flatfoot) K10</em></td>
<td>1.20</td>
<td>15.00</td>
<td>19.10</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>SACH Foot  <em>Otto Bock IS51</em></td>
<td>1.65</td>
<td>10.00</td>
<td>15.90</td>
<td><strong>10.84</strong></td>
<td>974.03</td>
</tr>
<tr>
<td>SACH Foot  <em>Otto Bock IS70</em></td>
<td>2.25</td>
<td>11.00</td>
<td>32.10</td>
<td>14.23</td>
<td>925.96</td>
</tr>
<tr>
<td>SAFE Cambell Childs</td>
<td>7.00</td>
<td>16.00</td>
<td>58.00</td>
<td><strong>9.49</strong></td>
<td>917.1</td>
</tr>
<tr>
<td>Seattle Foot  <em>M+IND, Natural SNF150</em></td>
<td><strong>5.00</strong></td>
<td>19.50</td>
<td><strong>70.70</strong></td>
<td><strong>11.52</strong></td>
<td><strong>841.2</strong></td>
</tr>
<tr>
<td>Seattle Foot  <em>M+IND, Light SLF130</em></td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>14.91</td>
<td>872.83</td>
</tr>
<tr>
<td>STEN  <em>Kingsley</em></td>
<td>1.25</td>
<td>16.50</td>
<td>15.80</td>
<td>12.2</td>
<td>1027.16</td>
</tr>
<tr>
<td>Sureflex</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>4.06</td>
<td><strong>745.07</strong></td>
</tr>
</tbody>
</table>

**Human Foot**

| | 5.00 | 20.00 | 119.60 | 10 | n/a |

**Notes:**

1. Prepared by REHABtech - all feet size 27, left
2. Test conducted at 10° rotation
3. Test conducted under uniform load
4. n/a not available at time of testing
NOTES
1. FOAM
2. KEEL
3. HEEL
4. AIR POCKET