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The Seattle Foot™

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INTRODUCTION

Traditional prosthetic feet were designed only for walking. Most amputees were unable to run, and the physical benefits of vigorous sports were lost. Even highly motivated amputees were severely limited in their activities because of a lack of appropriate prostheses and training, resulting in a significant loss of self-esteem.

The Seattle Foot™ was developed to widen the range of prosthetic alternatives for lower extremity amputees, and to allow them to seek the physical and emotional rewards of increased activity. The purpose of this paper is to discuss the research and development leading to commercial release of the Seattle Foot,™ and to review the considerations for its successful prosthetic use.

BACKGROUND

Over the course of a five year study, the Department of Kinesiology at the University of Washington used a Kistler force plate to examine the biomechanics of walking and running for normal volunteers and amputees of different abilities and amputation levels. The equipment recorded anterior, posterior, medial, lateral, and rotational ground reaction forces while slow motion cameras measured joint placement. Analysis subsequently demonstrated vast differences in the motion force vectors for walking and running; similarly, large differences were seen between normal and amputee running.

The ground reaction forces during walking were different from those during running not only because of the segment of free flight, but also because of a marked difference in the magnitude of the downward force during heel contact. In walking, this barely exceeds body weight, but in running, the downward force during heel contact exceeds body weight by two to three times. This loading can lead to injury even in non-amputees, so that provision for prosthetic mechanisms to deal with these forces became a design requirement.

In addition, amputees had a marked inability to push off after foot flat; hence the drop-off phenomenon that is so evident when amputees try to walk fast or run with conventional prostheses. Prosthetic development therefore had to incorporate a mechanism to simulate the push-off phase of normal running.

DEVELOPMENT

The Seattle Foot™ is designed to control and store energy that is available at heel strike and foot flat, releasing it during push-off to increase the forward movement of the foot and eliminate "drop-off."

Early prototypes of the foot incorporated an unusually shaped keel. Devised by Devere Lindh,[1] these keels were made of preimpregnated fiberglass acting against a rubber bumper. The fiberglass keel extended into the metatarsal area to form a spring, and as the patient walked or ran, the keel deflected and sprang back, thrusting the patient forward. These fiberglass keels functioned well for a number of patients, but excessive weight, an unacceptable failure rate, difficulties with tailoring the stiffness of the keel to the patient, and the labor requirements of the fabrication technique were drawbacks.

With the compilation of running data and experience with the fiberglass keel prototypes, Don Poggi and David Moeller[2] reevaluated the keel and suggested several design criteria. A successful foot would:

1. Be capable of deflecting 1¾ inches at the metatarsal area under a vertical load of 435 pounds. To do this reliably would require the longest possible spring.
2. Feel natural and stable in all phases of gait. This would require adequate dampening during the storage and release of energy at heel-strike and push-off.
3. Have a useful life of at least three years. This would require a durable material for the spring, to make it endure 50,000 cycles at 2.8 × body weight loading or 1,000,000 cycles at 1.4 × body weight, with a permanent set of less than .06 inches.
4. Have the lowest possible weight.
5. Have the lowest possible production cost. This implied a monolithic moldable keel rather than a composite one.
6. Have a natural cosmetic appearance.
7. Be compatible with existing prosthetic components and techniques.
8. Have a center of rotation as close to the natural ankle center as possible.

To maximize the effective length of the keel and provide a natural center of rotation, a keel shape was chosen that ran posteriorly before curving down and forward to the metatarsal area. The keel also tapered in thickness as it ran through the foot, terminating in a thin upward flare in the toe area. A wide range of synthetic structural materials were evaluated in this configuration. Only Delrin 150® provided the necessary combination of strength, lightness, moldability, and intrinsic vibration, dampening. Amputees who felt "hurried" through stance phase when wearing a foot with a fiberglass keel found the Delrin® keel foot to be more comfortable.

The keels were covered with polyurethan foam formed in conventional SACH foot molds, but as psychological demands for cosmesis increased, a range of male and female molds were taken from human feet. Prosthetic feet from these molds are quite realistic (Figure 1).

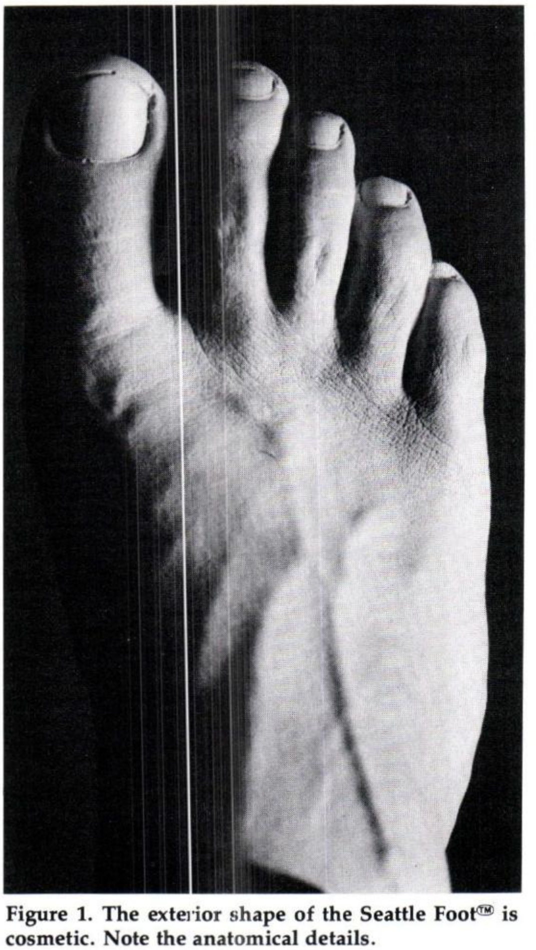

Figure 1. The exterior shape of the Seattle Foot™ is cosmetic. Note the anatomical details.

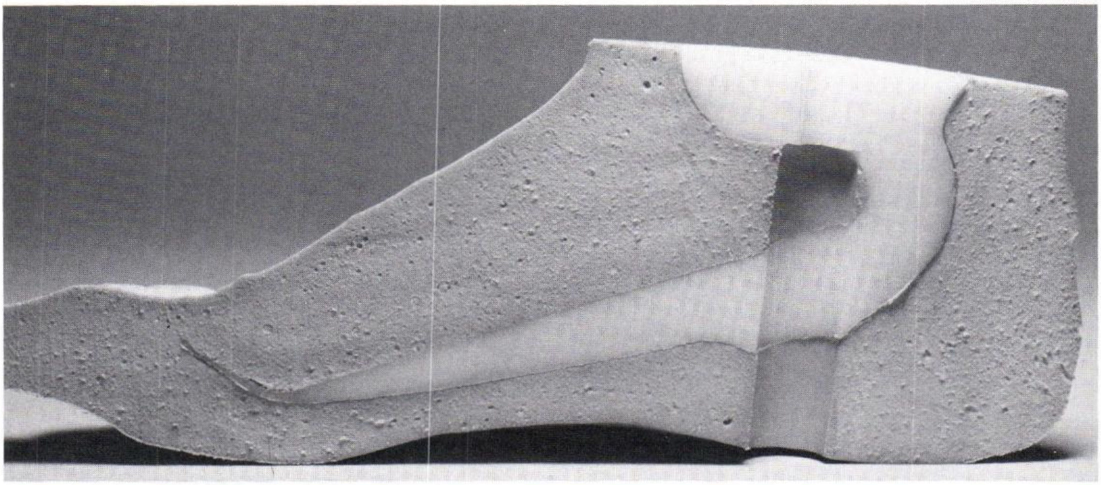

Figure 2. Initially, the Seattle Foot(TM) consisted of the keel and exterior foam. Note the toe section of the keel in the metatarsal area.

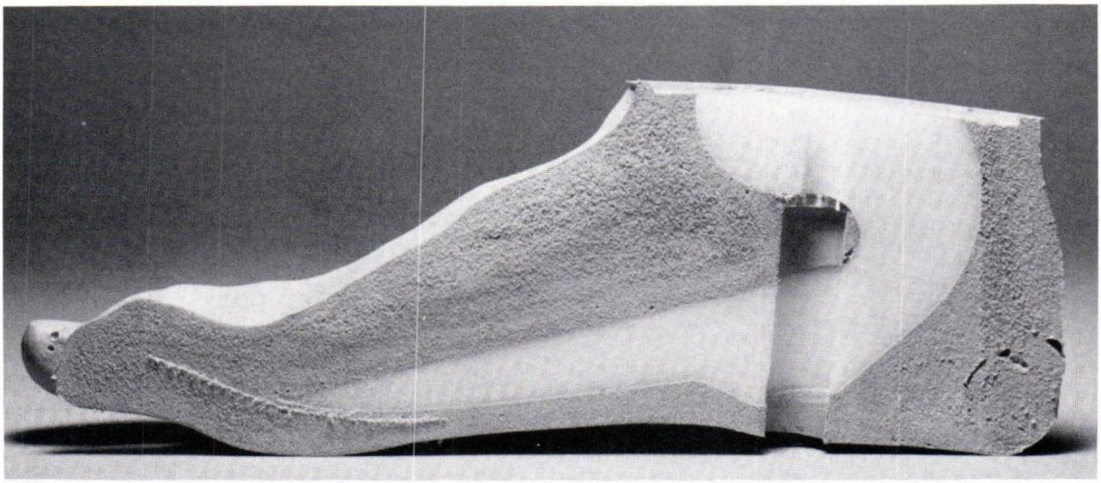

Figure 3. At present, the Seattle Foot(TM) has only three components: the keel, the external foam, and the toe reinforcement pad.

Several problems appeared during clinical evaluation and laboratory testing. Active patients were able to break the keel near the bolt hole. This problem was solved by reinforcing the keel near the bolt hole and by developing additional keel configurations designed to correspond to the weight and activity of the user. Secondly, the keel broke in the metatarsal area. This problem was met by eliminating the entire "toe" section of the keel, the thin upward flare at its anterior end (Figure 2). Also, when amputees ran without shoes on soft ground, the keel would punch through the bottom of the forefoot. This area is now reinforced with a Kevlar® pad. Currently, the Seattle Foot(TM) has only three components: the Delrin® keel, the external foam, and the Kevlar® reinforcement pad (Figure 3).

APPLICATIONS

As stated earlier, the Seattle Foot(TM) is designed to store and release energy, which it accomplishes with a specially designed keel that compresses during foot flat and extends during toe off. The keel aids the patient by thrusting the prosthesis forward, simulating the natural push-off provided by the gastrocnemius and soleus muscles.

While the Seattle Foot™ was designed to provide the push-off required during running, it can also be used for walking and is not necessarily contraindicated for people who are less active. Gait studies show that because the foot is flexible in the metatarsal area it does not limit forward rotation of the tibia over the foot, allowing the prosthesis to roll smoothly between heel-contact and toe-off. This, combined with the increased forward thrust through the spring action of the keel, makes the foot easier to use because it requires less effort. Therefore, the Seattle Foot™ is suitable for both walking and running.

The Seattle Foot™ is designed to correspond to the patient's weight and activity level. Currently, there are 11 keel configurations, fitting patients weighing between 90 to 245 pounds. These feet are available in sizes 6-12 in men and 5-8 in women. Other keels and sizes will be added as the demand increases. Each keel configuration is designed to fit a specific weight range or activity level. To avoid premature breakage, it is suggested that an active or bilateral amputee select a relatively stiffer keel.

The foot is designed to be used with shoes with a ¾ inch heel. If the patient wants to wear shoes with a lower heel, a wedge should be added inside the shoe to compensate. Because the Seattle Foot™ is a cosmetic copy of a human foot, it is wider and thinner in the metatarsal area than other prosthetic feet. Some grinding of the lateral surface may be required to fit exceptionally narrow shoes. The Seattle Foot™ weighs just over a pound (with slight variance depending on the size) which is heavier than a SACH, but lighter than a SAFE or Greissinger foot.

Patients who frequently walk on uneven ground may still prefer the Greissinger or SAFE foot to the Seattle Foot.™ Patients interested in a prosthesis for running and the greatest possible reduction in weight should consider the Flex-foot, which offers more energy storage than the Seattle Foot,™ but is not compatible with existing components and is substantially more expensive. Although the Seattle Foot™ is somewhat more expensive than conventional feet, it is compatible with most standard components. It cannot be used, however, with Hydra-Cadence units, R.O.L. rotators, or on patients with unilateral Symes or partial foot amputations. It has, however, been used successfully by many above knee and hip amputees.

ALIGNMENT

Installation of the Seattle Foot™ on an existing prosthesis requires realignment, because the amount of socket flexion, anterior-posterior, and medial-lateral position of the foot with respect to the socket, differs for each type of foot and individual patient. The alignment of the Seattle Foot™ is closer to that of the SAFE or Greissinger foot than it is to that of the SACH foot. The manufacturer provides static alignment instructions with each foot. Dynamic alignment for below-knee and above-knee applications requires additional attention to several prosthetic principles.

BELOW-KNEE ALIGNMENT

As the Seattle Foot™ is plantar-flexed (the socket extended) the patient is aware of increased push-off. This increases the hyperextension moment at the knee during midstance, and considerable effort must be exerted to walk over the forefoot. This toe-lever effect also occurs as the foot is moved anteriorly with respect to the socket. The prosthetist therefore must find a compromise between the hyperextension moment at midstance and the amount of push-off required. The knee must not be forced into hyperextension during any phase of gait, either walking or running.

Prostheses made primarily for running should be toed-out two or three degrees farther than the appropriate position for walking, as the increased pelvic rotation during running tends to internally rotate the entire lower extremity. Increasing the toe-out of the prosthetic foot will tend to compensate for this effect. An intermediate toe-out angle will usually work if the patient will be running and walking on the same prosthesis. This can be determined during the dynamic alignment.

Prosthetists have reported excessive anterior distal-tibial pressure when converting patients to a Seattle Foot.™ This is usually caused by too much socket flexion. To control excessive knee flexion, the patient needs to forcibly straighten his/her knee during foot flat, causing anterior-distal contact of the tibia inside the socket. The Seattle Foot™ should not be exchanged for an existing foot without a corresponding change in alignment.

ABOVE-KNEE DYNAMIC ALIGNMENT

When using a Berkeley alignment fixture, the pylon should be vertical during midstance. Since the keel of the Seattle Foot™ dorsi-flexes as it is loaded at stance phase, the pylon should be placed in two to three degrees of posterior tilt (plantar-flexion of the foot) during static alignment. This will allow the pylon to be vertical over the loaded foot. Since there is no plantar-flexion capacity built into the Berkeley fixture for alignment of an exoskeletal above knee prosthesis, it is suggested that the fixture be modified to allow this if the Seattle Foot™ is used. The Berkeley system also does not allow dynamic alignment using the definitive knee unit, which is suggested if optimal performance is to be evaluated. When using an Otto Bock endoskeletal system, the pylon does not need to be vertical during midstance, and no fixture modification is necessary; however, only a limited number of knee units are available.

If knee instability exists, the prosthetist may either plantar-flex the foot farther or move the knee center posterior. Too much plantar-flexion of the Seattle Foot™ may make it difficult for above knee patients to clear the toe during swing phase. This is especially a problem with Henschke-Mauch S-N-S knee units, which require a substantial toe level (plantar-flexion) to provide enough extension moment to trigger the swing mode.

AREAS OF CONCERN

The Seattle Foot™ has undergone a great deal of development and testing to ensure reliability, but there are some drawbacks.

Possibly the greatest drawback relates to the cosmesis of the foot; because the foot is natural in appearance, patients are inclined to walk and run barefoot. A number of feet have been returned (under warranty) due to foam failures on the plantar surface of the metatarsal area. In one documented case, a 40–year old amputee broke two Seattle Feet.™ This man walked barefoot, did push–ups barefoot, and had broken one of the feet by forcibly hyperextending the toes while cross-country skiing. Currently, the designers are experimenting with materials to minimize this problem. The manufacturer now includes a notice advising against barefoot ambulation.

Occasional cases of keel breakage have been reported, despite careful keel selection. In some cases, amputees have become much more active, and provision of a heavier keel is indicated. Some keel breakage is probably inevitable, since the prosthesis is designed for active patients, is light in weight, and must be flexible to function.

Wood or foam ankle blocks offer no purchase for the flat Delrin® keel when the foot is used with an exoskeletal system. The manufacturer recommends using hot melt glue to bond the foot and block, to prevent inadvertent rotation of the foot. A layer of Durite® screen between the block and foot is an alternative. Inadvertent axial rotation does not occur with endoskeletal components because of the serrated surface of the foot attachment plate.

Shaping the ankle block of an exoskeletal prosthesis can be difficult, because the contour of the lateral malleolus on some Seattle Feet™ can appear too dramatic. This is most apparent when the foot is used on an overweight or geriatric patient. Another complication may arise when the foot is attached to an exoskeletal prosthesis; the foam lip on the proximal periphery of the foot has a tendency to protrude when the foot bolt is tightened. A small amount of foam can be removed from the superior edge to avoid the undesired protrusion of the foam.

CONCLUSION

The Seattle Foot™ utilizes a special keel design and advanced materials to provide a relatively inexpensive prosthetic alternative for lower extremity amputees. It combines smooth action with increased push off, through the storage of energy, to make running and walking easier. The Seattle Foot™ can be tailored to the individual, and is compatible with standard fabrication techniques and components. It is exceptionally cosmetic in appearance, is quite durable when appropriately used, and the foot is available in a wide range of sizes for both men and women. While practitioners need to weigh all the options before choosing the Seattle Foot,™ as with any other component, it is clear that for many amputees, the Seattle Foot™ will open up a whole new range of experiences.

AUTHOR

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[1]Prosthetics Research Study, Seattle, Washington.
[2]Model and Instrument Works, Seattle, Washington.

ACKNOWLEDGMENTS

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