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Energy Storing Feet: A Clinical Comparison

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The human foot is an exceedingly complex structure. The pair contain 52 separate bones, dozens of intrinsic muscles, and scores of extrinsic ones. The feet are composed of multiple layers of ligaments, fascia, and muscle, and contain numerous interrelated articulations.

In combination with the ankle complex, the foot provides the dual functions of support and propulsion. Paradoxically, this is accomplished by combining the diametrically opposite characteristics of flexibility and rigidity as the foot adapts to the gait cycle.[15]

Despite hundreds of historical attempts to imitate this remarkable structure, very few designs have ever achieved widespread acceptance. Within the last three years, however, four new foot components have become commercially available—all in the previously unheard of class called "energy storing" designs. These intriguing new developments will be discussed in chronological order, summarizing our experience at Duke.

Seattle Foot™

In 1978, Bernice Kegal of the Prosthetics Research Study in Seattle published a paper entitled "Functional Capabilities of Lower Extremity Amputees,"[13] and noted that a major prosthetic limitation in sports activities was the inability to run. The vigorous amputee athlete was competing despite the components rather than because of them.

The Prosthetics Research Study, in cooperation with engineers from Boeing aircraft, began developing a prosthetic foot specifically designed to store energy and release it at push off: the Seattle Foot™. First introduced in 1981 at a course in modern prosthetic rehabilitation presented by the American Academy of Orthopedic Surgeons, the Seattle Foot™ was later field tested by hundreds of Veterans Administration clients. Today, it should be widely acknowledged as the stimulus for the current explosion of new concepts in this area.

The design specifics have varied over the past few years as the concept was refined. Originally, the keel was a fiberglas multi-leaf design, somewhat similar to an automobile suspension spring. The key concept was that as the patient increased his cadence, stiffer portions of the spring came into play. Various exotic materials were considered, including titanium, but were clinically impractical.[12]

The commercial version first became available in October, 1985 and consisted of a Delrin bolt block and integral keel, with Kevlar® toe pad (Figure 1). The entire structure is contained in a lifelike injection-molded polyurethane shape. To date, over 8,000 Seattle™ feet have been used in the United States.[2]

Although patient acceptance has generally been good, several technical difficulties have been noted with this design. During the VA field-testing, catastrophic failure of the plastic keel occurred in some cases. This has been greatly reduced in the commercial version, provided the proper keel configuration is selected using the manufacturer's guidelines.

Because of ongoing problems with failure of the flexible rubber toes at the keel tip, the polyurethane composition has recently been reformulated for more tear resistance.[4] About one third of our feet at Duke have failed in the forefoot, although all were replaced under manufacturer's warranty. We have experienced no catastrophic failures whatsoever in our series.

The "Life-Molds," although very natural in appearance, have presented some difficulties. The first is that the forefoot is fairly wide and

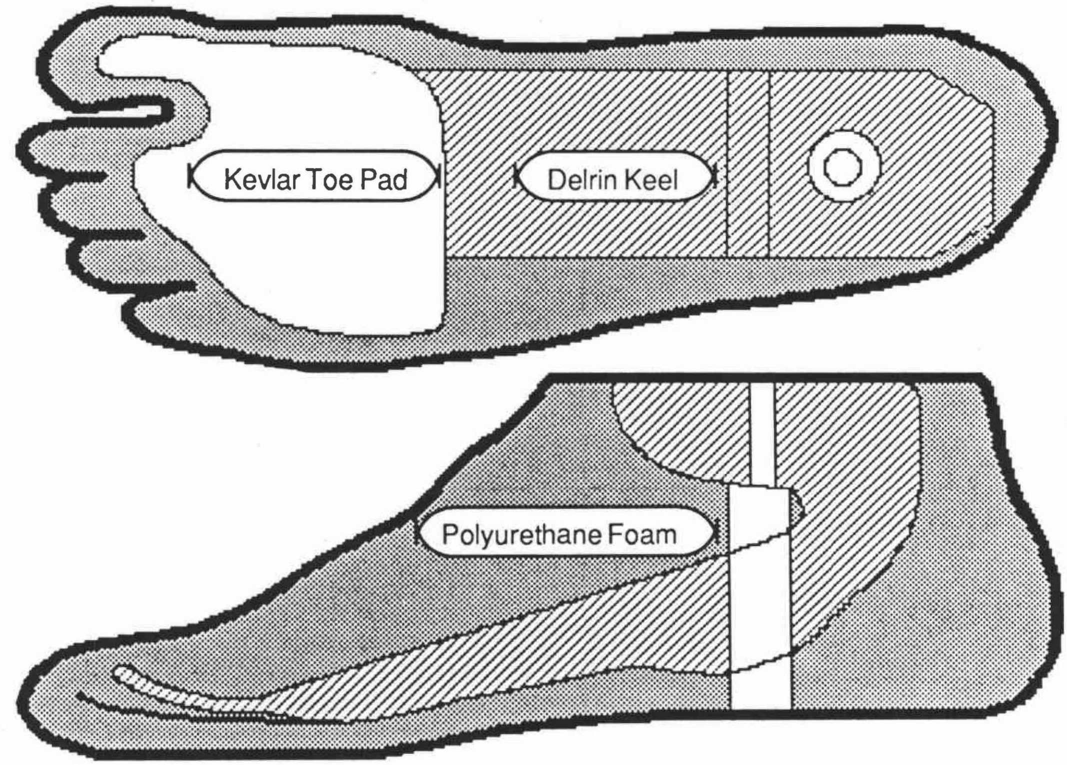

Figure 1. Seattle Foot®; note cantilevered plastic spring keel to store energy (Courtesy MIND).

often difficult to fit into dress shoes, particularly narrow widths. In addition, there is no uniformity in dimensions from size to size, or even between left and right in the same size. For example, if a patient returns requesting a foot one size smaller since purchasing tighter shoes, and a 26cm foot is substituted for a 27cm foot, the prosthesis has been inadvertently shortened by 5mm (¼″). Also, the stark contours of the original "Life-Molds" can be difficult to blend into the prosthetic ankle at the retromalleolar area, and are too muscular for some patients.

The recently available "Ladies Molds" have effectively addressed the problems noted above. Redesign of the male version is underway, and is expected to achieve similar results.

The Delrin keel has also been a source of problems. Because it is very slippery, inadvertent rotation and loss of toe out has occurred. Since drilling and pinning the bolt block would significantly increase the risk of breakage, the manufacturer recommends bonding the foot to the ankle block or endoskeletal adapter with hot-melt glue. This has eliminated problems with loss of toe out in our series at Duke, although we still experienced occasional problems with the keel "slipping" completely out of the polyurethane shell for active walkers.

Problems have also been reported with occasional bolt breakage, and speculation regarding cold creep of the plastic has been voiced. The manufacturer supplies special bolts, locktite, and torque specifications to address this issue. We have experienced no bolt problems at Duke.

Finally, this is the heaviest solid ankle design commercially available. Although most patients have no apparent difficulties, some find the weight objectionable. One volleyball player, in particular, rejected the foot for jumping activities, even though she found it excellent for jogging and similar sports.

Despite the technical difficulties noted, our experience at Duke has generally been favor-

Figure 2. Flex-Foot™, showing full-length composite strut for energy return (Photo courtesy Flex-Foot, Inc.).

able. Patients often comment on the "lively" step permitted by the cantilevered spring design. We particularly favor this component in the smaller sizes (26cm and below), as the incidence of breakage seems reduced. One unilateral hip disarticulation amputee commented that the more active push off "lets me pass someone in a crowd for the first time since I became an amputee."[21]

Flex-Foot™

At the same time the Seattle Foot™ was being developed, an independent collaboration between a plastics engineer and a young research prosthetist-amputee resulted in creation of the Flex-Foot™. This lightweight graphite composite structure offers a radically different approach. All are hand made from a computer-generated design specific to each individual patient. Data such as weight, activity level, and residual limb characteristics determine the specific orientation and thickness of reinforcement fibers.

Ultra high pressure, high temperature molding insures the greatest possible strength to weight ratio, but requires several weeks for fabrication. Although this is a very costly approach, it does permit fitting the widest range of individuals. The chief restriction is that a minimum of five inches is required from the end of the residual limb to the floor, and seven inches or greater is preferred. Thus, the Flex-Foot™ is not suitable for small children, Symes and similar amputations, and very long below-knee residual limbs.[8]

Unlike any other component currently available, Flex-Foot™ utilizes the entire distance distal to the socket for function. Since it stores energy throughout its entire length rather than just within a four inch keel, this results in a very responsive and resilient component. It also significantly improves the mass distribution of the prosthesis (Figure 2).

Most multi-functional feet bolt onto the prosthesis at the ankle block, and are heavier than a conventional SACH foot. With the weight concentrated at the distal end, the limb swings as if it were a sledgehammer. Overcoming the inertia of this mass in order to propel it through space consumes energy, and the patient perceives it as "heavy."

The Flex-Foot™, however, is more akin to an inverted sledgehammer. The bulk of the weight is in the socket and attachment cone, with the rest uniformly distributed in the pylon. This is analogous to holding the head of the sledge and swinging the handle through space. Even if the Flex-Foot™ prosthesis weighs nearly as much as the conventional limb, the patient finds it much easier to propel, and perceives it as "light." Actual weight savings of 10–15 percent are common, but patients typically perceive that the Flex-Foot™ weighs "half as much."

Another advantage unique to the Flex-Foot™ is the ability to independently adjust the anterior and posterior lever arms. Overall stiffness is fabricated in at the factory, but tilting the pylon increases the anterior flexibility. Varying the length of the heel pylon independently controls its resistance. Conventional AP linear slide adjustments affect the resistances in the conventional manner: sliding the foot forward decreases posterior leverage while increasing the anterior resistance.

Due to the complexity and magnitude of the inter-related alignment changes possible with the Flex-Foot™, we advocate use of a prototype prosthesis, at least initially. By dynamically aligning the new socket on a conventional foot using a conventional alignment fixture, mediolateral alignment and the quality of socket fitting can be easily evaluated and refined.

Once these are satisfactory, the vertical transfer fixture can be used to permit substitution of the Flex-Foot™ pylon. A secondary dynamic alignment is then performed, permitting concentration on sagittal plane characteristics without being distracted by a multitude of adjustments in other planes.

Although use of slow-motion video analysis has been of some value in refining the sagittal alignment, we strongly encourage an extended field trial prior to finishing the limb. Application of a PVC bag over the alignment fixture followed by several layers of fiberglass casting tape reinforcement will permit the patient to use the limb clinically for a week or two.

Upon return to the laboratory, the fiberglass tape can be removed and the alignment further enhanced. As the patient becomes accustomed to the function of the Flex-Foot™, he will often prefer stronger anterior resistance. A knowledgeable physical therapist can be an asset at this stage, as the person must learn to shift his weight onto the Flex-Foot™ throughout stance phase and "ride it into toe off" in order to achieve maximum benefit from its push off characteristics.

Casting tape should be reapplied and the field trial continued. Only when the patient returns, needing no additional alignment changes, can it be assumed the alignment is optimized, permitting transfer and finishing to proceed.

A comprehensive fabrication manual is provided by the manufacturer,[8] and the instructions should be followed explicitly, particularly regarding reinforcement of the attachment cone. Tremendous stresses are concentrated where the resilient pylon meets the rigid socket, and structural failures of the lamination can occur if improperly fabricated.

Cosmetic finishing is difficult and time-consuming, but results in a finished structure that is highly water resistant since the foam provided is used in life preserver construction. If immersion is anticipated, a final sealing coat of Lynadure or other flexible "skin" is recommended.

Although our series is small, we have experienced no failures with the Flex-Foot™ system, even on very large and very active individuals. One high school athlete, who destroyed SACH and SAFE feet two or three times per year, has been playing varsity football with the Flex-Foot™ for two seasons without incident.

The manufacturer reports an overall failure rate of less than four percent with over 2,500 units in the field. Most failures occurred where the heel pylon bolts attached to the anterior pylon. One common denominator has been a sudden increase in the patient's activity level after being fitted with the Flex-Foot™. A highly active individual (or one who has recently gained weight) using a pylon originally designed for standard duty applications is at risk, so the prosthetist must anticipate the ultimate stresses that will be applied.[9]

The recent announcement of a "Modular Flex-Foot™" (MFF) represents an effort to expand the usefulness of the Flex-Foot™. Available in standard configurations, these pre-made pylons can be supplied within two weeks. The heel lever arm bolts through the forefoot rather than the highly stressed ankle area, to enhance durability. A refined attachment system permits easier socket replacements, which should encourage application to more recent amputees. And, limited alignment refinements are possible even after permanent attachment to the socket, via Otto Bock "Modular" components or the "pylon connector" (Figure 3).

We believe the cost and complexity of the Flex-Foot™ can be justified due to the degree of function offered. A competitive volleyball player reported her vertical leap nearly doubled when using the Flex-Foot™, and its low inertial drag made activities less tiring.[20] A severely debilitated geriatric amputee, who ambulated with a cane due to impaired balance, claimed he could walk "twice as far before my wind gives out" after fitting with the Flex-Foot™.[1] And a 47 year old nurse completed the New York Marathon's 26 mile race on the Flex-

Foot™ one hour thirty-two minutes more quickly than with a conventional design.[16]

Hard data to buttress these anecdotal reports are very limited at this time. A motion analysis conducted at the University of Illinois suggests that the Flex-Foot™ allows a more normal range of motion than the SACH foot, even at normal cadences.[25] Several centers are reportedly conducting oxygen consumption studies in an effort to verify claims of lowered energy consumption, but none are yet published.

Although most Flex-Foot™ prostheses have been used for unilateral and bilateral below-knee amputees, a significant percentage have been applied to above-knee amputees as well, and some hip disarticulation fittings have been completed.[9] Our experience at Duke has been chiefly at the below-knee level. Although higher level amputees would benefit greatly from reduced energy consumption, the addition of a passive knee mechanism may dissipate some of the potential return and bears further study.

Carbon Copy II

The Ohio Willow Wood Company introduced the original all-plastic SACH foot a decade ago called the "Marvel" foot. After its demise due to the availability of lighter and more durable feet from other suppliers, they embarked on a research and development project for what they termed the "next generation" of solid ankle feet.

A few years ago, Mauch Laboratories approached Ohio Willow Wood to design a foot shell for Mauch's hydraulic ankle. This lead to the development of life-molds, a special microcellular polyurethane elastomer blend, and engineering of a carbon composite keel. The result was Carbon Copy I, a relatively rigid shell whose function comes primarily from the ankle mechanism.

Development continued, and in May, 1986, Carbon Copy II was introduced as the latest entry into the energy storage arena. In many ways, it represents the synthesis of some of the best attributes of previous designs. This is a conventional solid ankle design, available with three durometers of heel cushion for simulated planter flexion.

The keel, however, is a unique dual structure: a rigid posterior bolt block plus flexible anterior deflection plates. The bolt block is a special ultralight reinforced Kevlar/nylon design which recently won the plastic composite industry's "National Award of Excellence" for innovative engineering. A fiberglass/epoxy attachment plate resists deformation by both exoskeletal and endoskeletal ankle blocks, while very low density Styrofoam fills the cavities and prevents infiltration of the heavier polyurethane elastomer which forms the outer shell.

The anterior deflection plates provide two-stage resistance at heel off. In normal walking, the thin primary deflection plates (which run to the PIP joints of the toes) provide a gentle energy return. At higher cadence or during more

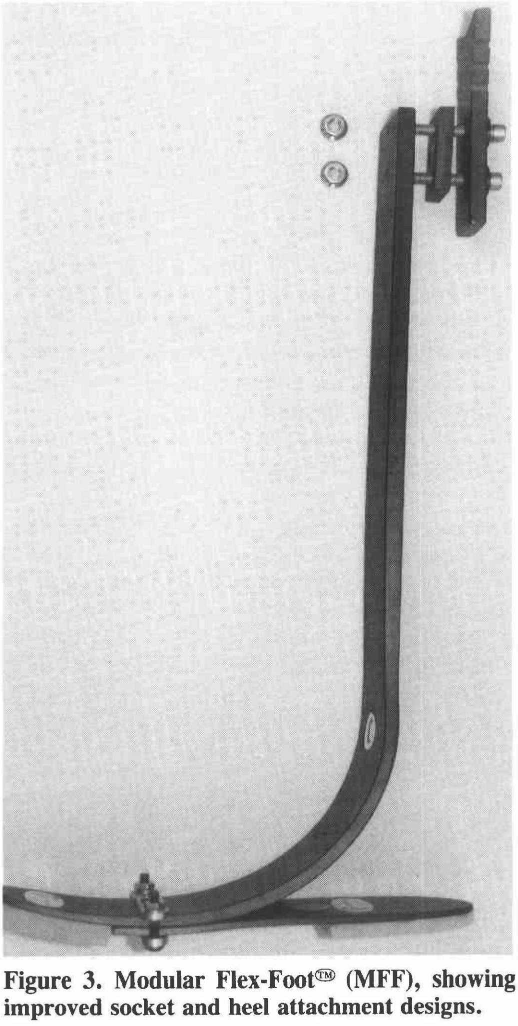

Figure 3. Modular Flex-Foot™ (MFF), showing improved socket and heel attachment designs.

Figure 4. Carbon Copy II; note rigid bolt block plus dual flexible carbon fiber deflection plates (Photo courtesy Ohio Willow Wood Co.).

vigorous activities, the auxiliary deflection plate provides additional push off. A Kevlar® glide sock prevents the plate from knifing through the elastomer shell (Figure 4).

The exterior design shows a similar attention to practical detail. The contours are lifelike, but not as starkly detailed as the Seattle Foot™. Rather, the veins and retromalleolar undercuts are softened into a more practical "humanoid" configuration. The forefoot width is a bit wider than conventional SACH feet, but less than the Seattle Foot™ version (Figure 5). Fitting narrow width shoes can sometimes be a problem.

The plantar surface is where the Carbon Copy II contour is most unique. Broad and flat (with a full-width carbon composite plate similar to Flex-Foot™), it is shaped to fit the shoe last. Analogous to a well-posted UCBL foot orthosis, this congruence between device and shoe offers maximum mediolateral stability (Figure 6).

Finally, all these practical details are contained in a package that is extremely lightweight. Significantly lighter than the conventional SACH foot, Carbon Copy II is actually slightly lighter than a geriatric "litefoot."

Currently available only in adult male sizes, Carbon Copy II should be available in female sizes in the near future. Some practitioners report that the small keel sizes are noticeably stiffer than their full-sized counterparts. In response to that observation, Ohio Willow Wood is retooling for a shorter keel block as well as narrower deflection plates for the women's style, which will initially be offered only in a 10mm (⅜″) heel height.

We have experienced no failures whatsoever with Carbon Copy II thus far, even for very vigorous applications. The manufacturer reports sales of over 2,000 feet, with known failures in nine cases. Seven were rubber tears at the tips of the toes (reportedly from one particular manufacturing run), plus one split deflection plate and one broken rivet.[17] If this early reliability continues, this may be one of the most durable prosthetic feet available.

The only other problem noted is insufficient threads on the Otto Bock titanium endoskeletal foot bolt, which can be identified by its bright blue color. Placing one or two spacer washers under the head of the bolt allows it to be tightened firmly without running out of threads.

One of the key design criteria for this foot was versatility, and we have found it suitable for many levels of amputation—including unilateral and bilateral below-knee, unilateral above-knee, hip disarticulation and hemipelvectomy, as well as above-knee/below-knee bilaterals.

Overall, the Carbon Copy II and Seattle Foot™ seem to offer similar function to the patient, and the wholesale cost is comparable. At least in the larger keel sizes, most patients have preferred the Carbon Copy over the Seattle Foot™, due to lighter weight and the two-stage resistance. In the smaller keel sizes, the difference is less pronounced, and many prefer the responsiveness of the Seattle design. In general, we consider both Carbon Copy and the

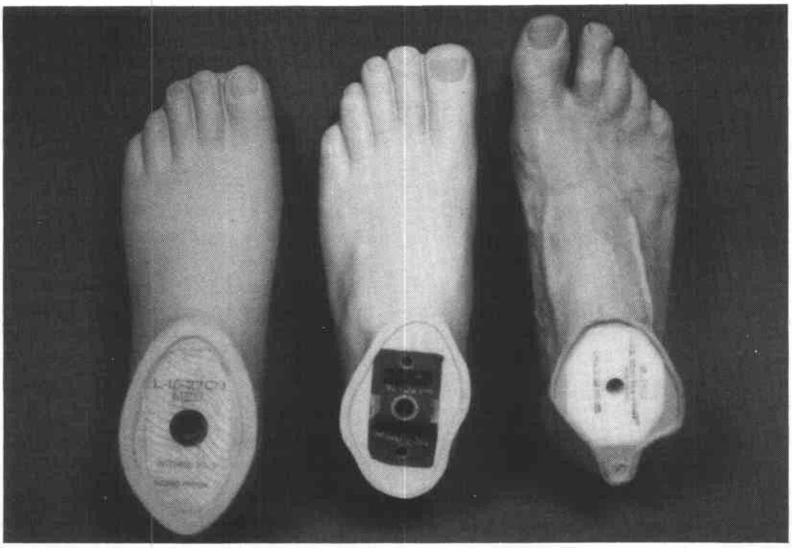

Figure 5. (Dorsal view, L to R) STEN foot, Carbon Copy II, Seattle Foot™; note retromalleolar contours and forefoot width.

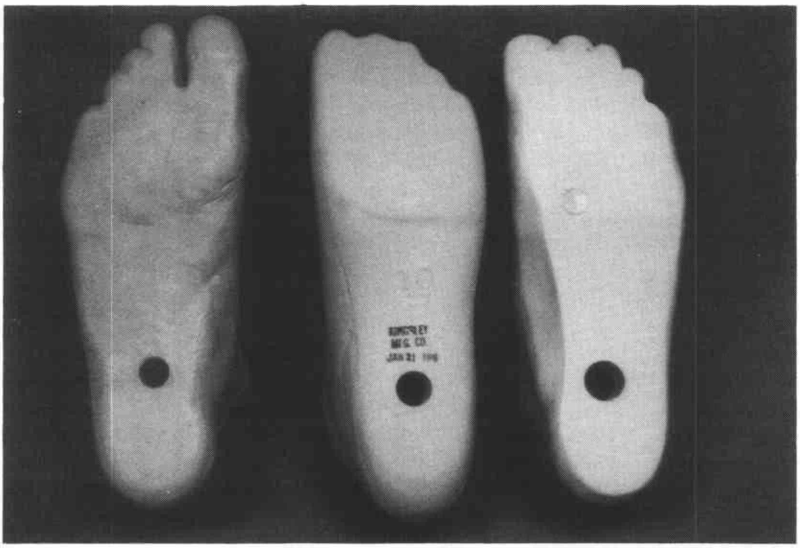

Figure 6. (Plantar view, L to R) Seattle Foot™, STEN foot, Carbon Copy II; the flatter configuration enhances mediolateral stability within the shoe.

Seattle Foot™ design to be good, moderately responsive energy storing designs.

STEN Foot

STEN Foot is one of the simplest designs in prosthetic feet. Externally, it uses the familiar Kingsley foot molds and rubber. This means it is the easiest design to fit in a variety of shoe styles, and comes in the greatest selection of sizes and heel heights: from a child's 18cm keel to an adult's 30cm, including women's widths as well. Soft, medium, or firm heel durometers are available as well.[24]

Slightly heavier than a conventional SACH foot, the STEN Foot differs in its dual articulated keel. In addition to a metatarsal-phalangeal articulation, it also features a tarsal-metatarsal articulation, thus permitting a smoother,

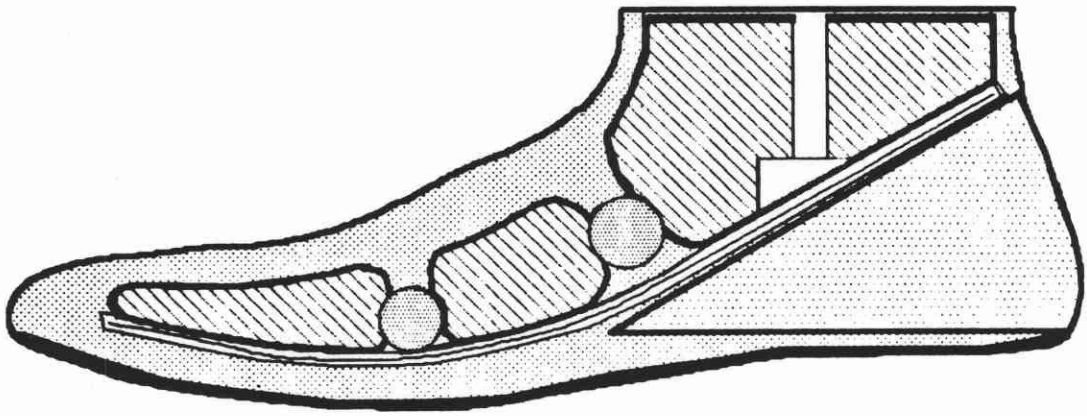

Figure 7. STEN foot; note dual keel articulations and double reinforced belting (Illustration courtesy Kingsley Manufacturing).

more gradual roll-over than a solid SACH keel (Figure 7).

Although the name stands for "STored ENergy" foot, it is our clinical impression that it does not accomplish this goal as effectively as the previous designs. The "keel bumpers" are directly analogous to the toe bumper in an old-fashioned wooden foot; both seem more to dissipate than to return energy.

We view the STEN Foot as an additional flexible keel design, similar to the SAFE foot, permitting a smoother roll-over and somewhat greater forefoot supination and pronation than the more rigid SACH design. Since it is lighter than the SAFE foot, fits the shoe more readily, and is available in a broad range of heel heights and sizes, it may offer some advantages.

Compared to a SACH foot, patient response has been predominantly favorable. Most preferred the smoother, "softer" roll-over it offers. Some higher level amputees complained of a slight increase in the tendency for the prosthetic knee to "buckle," although this could usually be minimized by plantarflexing or moving the foot more anteriorly.

Reliability was a significant problem with early versions of this design, which sometimes failed catastrophically due to rupture of the plantar belting beneath the midfoot articulation. This resulted in a sudden loss of forefoot resistance, causing the amputee to stumble. When three of our initial seven STEN Feet failed in this fashion, we stopped using this component.

It has since been redesigned with double belting reinforcements. The manufacturer reports that 3,000 feet have been sold, with no belting failures whatsoever since the reinforcement was added. With the new design, the overall failure rate from all causes is currently under one percent.[24]

At a recent Academy conference, Richard Carey, C.P. reported on over 80 successful applications of the reinforced version of the STEN Foot, and suggested it is particularly appropriate for the new amputee as the softer roll-over may facilitate gait training.[6] This also might allow an easier transition to a more sophisticated design later, since the flexible keel is a common characteristic of all current "energy storing" feet.

Other Designs

Although not a brand new design, the SAFE foot (Stationary Ankle Flexible Endoskeleton) has recently been advertised as "the original energy storing foot." In our view, this may be stretching the point, since we believe the flexible keel serves primarily to dissipate energy as it accommodates to irregular surfaces.

The SAFE foot can be viewed as a solid ankle version of the multi-axis concept, and we consider it an alternate to the well-known Greissinger foot. Both provide significant transverse rotation as well as inversion and eversion, in addition to some degree of plantar flexion and dorsiflexion.[5] The SAFE foot has the advantage of requiring no maintenance and being moisture and grit-resistant, while the Greissinger permits independent selection of the plantar flexion and other resistances.

We summarize the SAFE foot as an "accommodative" design. It is probably unparalleled for use on uneven surfaces, and many amputees report an increase in residual limb comfort because it absorbs much of the shock of everyday walking. But aggressive racquet sportsmen have complained that it takes a fraction of a second to "wind up" before permitting push off, thus lowering their score. Perhaps 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.

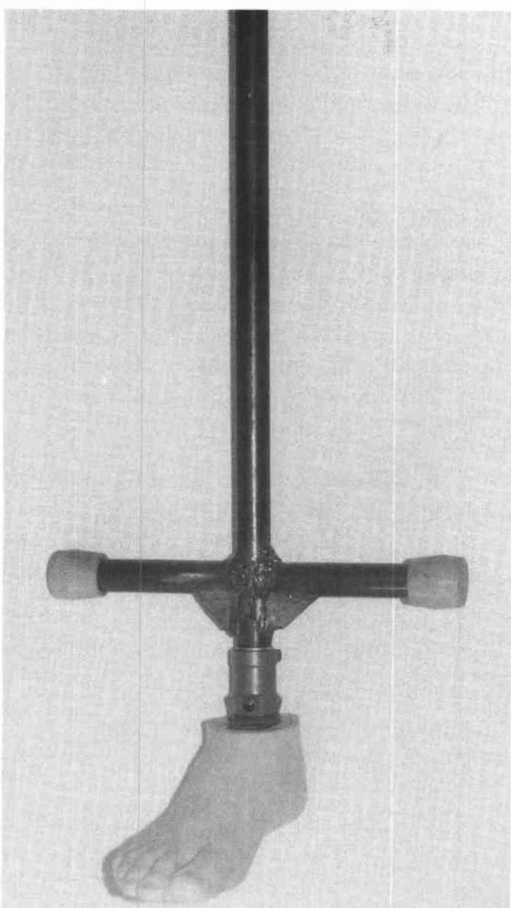

Figure 8. Pogo stick device used to test vertical spring capabilities of various feet.

Clinical Ranking

There are currently no accepted definitions of what constitutes an "energy storing" prosthetic foot. In fact, there is currently no hard data to demonstrate any energy savings at all, despite numerous anecdotal reports. Yet, there is a need to have some means of evaluating and ranking the various designs, to add some measure of rational justification for clinical use of a given component.

In reviewing slides of a unilateral below-knee amputee playing competitive volleyball, it was noted that her vertical leap appeared to be noticeably higher with the Flex-Foot™ than with the Seattle Foot™. This difference is likely due to the amount of "spring return" inherent in the components, and may represent one plausible criterion to rank their effectiveness.

To test this hypothesis, a simple "pogo stick" apparatus was constructed which permitted interchange of various prosthetic feet (Figure 8). A non-amputee subject was in-

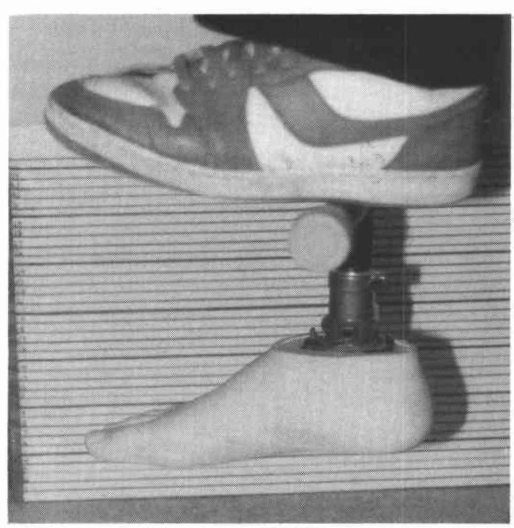

Figure 9. Frame-by-frame video analysis of ground clearance in centimeter increments.

structed to jump on the pogo stick for ten hops, trying to attain as much altitude as possible. It is believed that this measures the spring potential of the component as if it were loaded by body weight at midstance. Since the subject's feet both remained firmly on the foot pegs and did not contact the ground, this was felt to be more accurate than measuring unilateral amputees jumping, where the sound limb could partially compensate for the component's deficits.

Using frame-by-frame slow motion video analysis, the amount of ground clearance was measured to the nearest centimeter (Figure 9). This was not intended to be a controlled study, but rather a simple preliminary investigation; no quantitative judgments should be drawn from this data. Nevertheless, the trends were consistant over multiple trials, and are summarized in Figure 10.

It is interesting to note that Figure 10 coincides with our subjective clinical ranking of the effectiveness of these designs. Patients given the choice between the SACH and STEN foot, for example, generally chose the more flexible STEN, but patients perferred the Carbon Copy II or Seattle Foot™ to the STEN, because the spring keels "felt more natural." Given the choice between Flex-Foot™ and other designs, the choice was generally for the more responsive composite system.

Furthermore, the ranking also reflects the degree of sophistication of the design, and the relative wholesale cost from the manufacturer (Figure 11). The weight of the components was less straightforward. The inexpensive designs increased in weight as they increased in complexity, weighing progressively more than a conventional SACH foot. However, the two most expensive energy storing designs—Flex-Foot™ and Carbon Copy II—resulted in a lighter prosthesis than a SACH configuration (Figure 12).

Summary

Thanks to the efforts of the Prosthetics Research Study in Seattle, the concept of energy storing prosthetic feet has been widely dissemi-

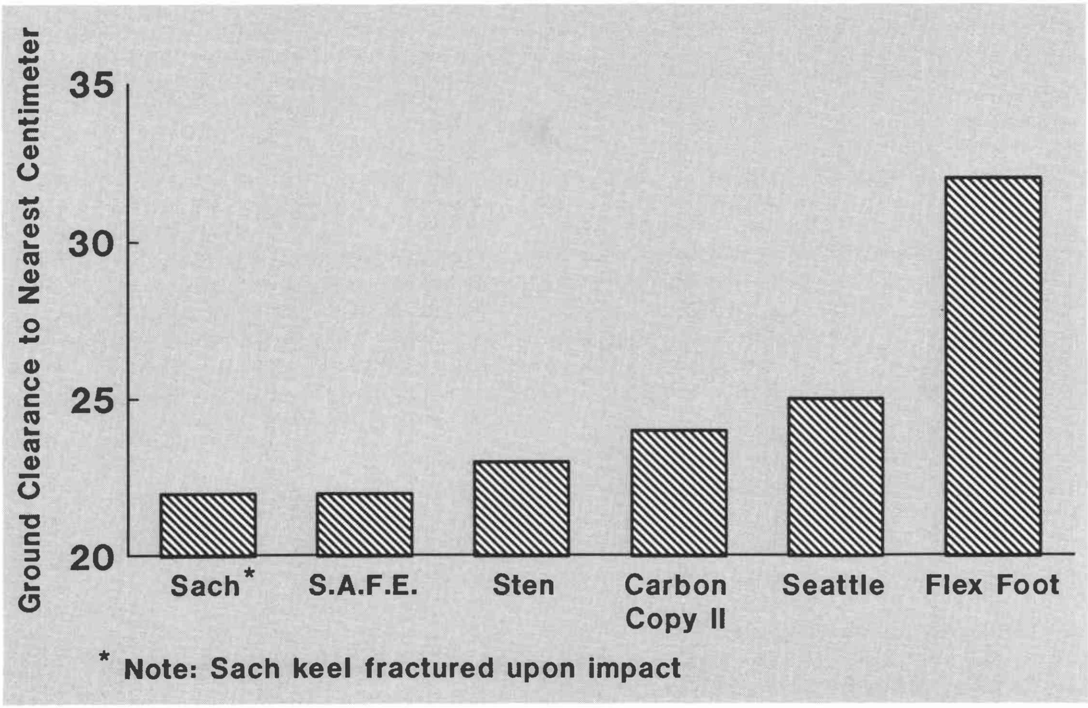

Figure 10. Ground clearance after vertical leap using pogo stick apparatus; 175 pound male subject, men's size 10 feet.

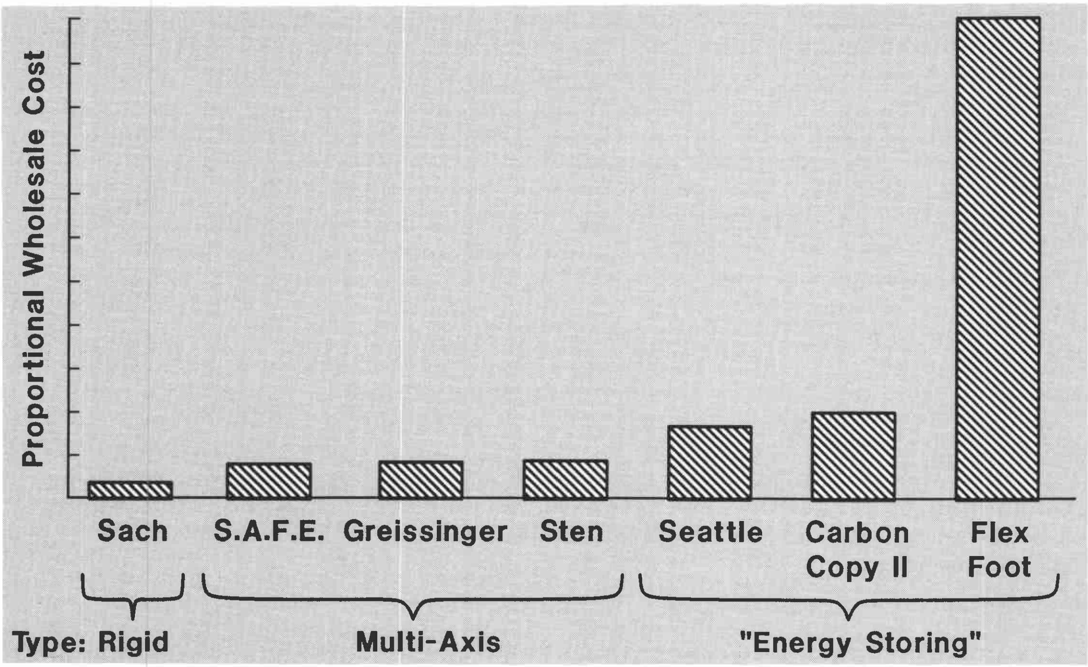

Figure 11. Relative wholesale costs for prosthetic foot mechanisms.

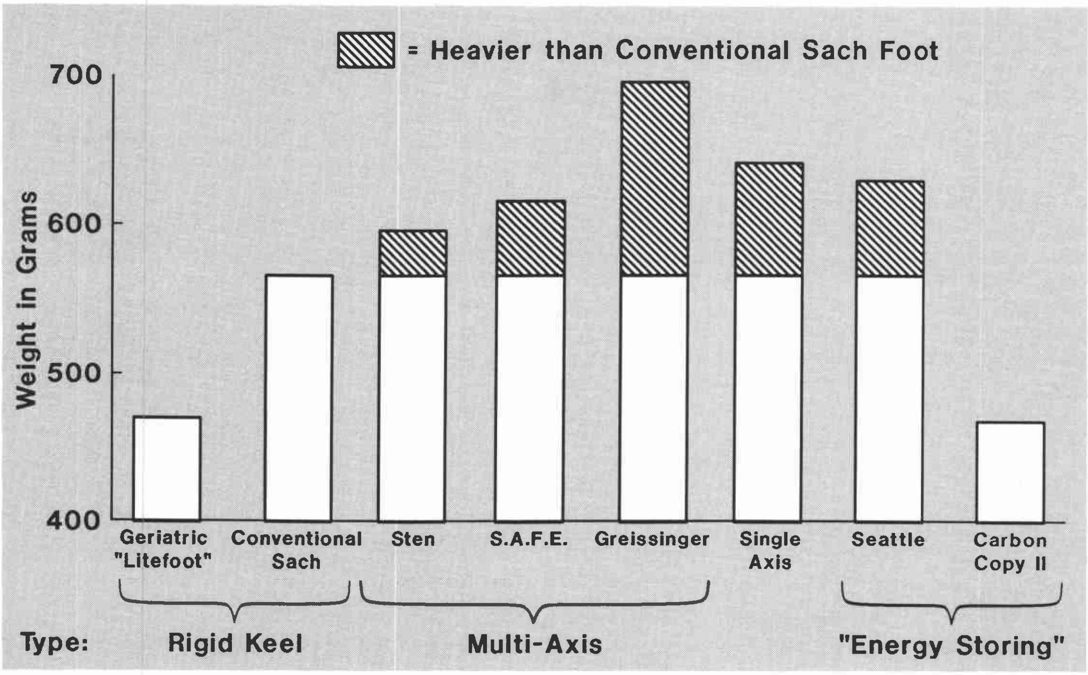

Figure 12. Weight of men's size 10 foot components, not including ankle block.

Component	Levels	Quantity	Component Failures	
			Number	Percent
Sten Foot	BK, BIL BK, KD	7	3	43%*
Seattle Foot™	BK, BIL BK, AK, HD	16	5	31%*
Carbon Copy II	SYMES, PFFD, BK, BIL BK, AK, HD, HP	35	0	0%
Flex-Foot™	BK, AK	7	0	0%

* Initial Version; Current designs are significantly more reliable

Figure 13. "Energy storing" feet through April 1987, Duke University experience.

nated.[19] Although it is fashionable to claim such benefits, no clear definition of the characteristics required has been established. The author suggests that the ability to leap vertically is one simple measurement of the "springiness" of a component, while reduced oxygen consumption during a measured task would be a more precise definition of an energy-conserving component.

All current designs seem to have merit, and have been successfully utilized clinically (Figure 13). Although limited, the Duke experience has been summarized as a first step toward more clearly delineating the indications and contraindications for each design (Figure 14).

The conventional SACH foot remains the most widely used design in North America, due to its low cost and reliability. In sports applications, it is particularly well suited for sprinting, since the rigid keel digs into the track, permitting rapid acceleration.[20]

Multi-axis feet (Greissinger and SAFE) accommodate uneven terrain and dissipate some of the shocks of ambulation, thereby increasing skin comfort. They have been widely used by amputee athletes, although the softer keel resistance may increase the lag between sudden movements. Except for limiting transverse rotation, the STEN foot offers similar function, and may be worth considering for the novice amputee in particular.

The Seattle Foot™ and Carbon Copy II are solid ankle devices that attempt to store energy via a spring keel design. They have been well received for a variety of amputation levels, and seem particularly well suited for joggers and weekend athletes.

Flex-Foot™ represents the maximum in energy storage potential, and can be individualized for a wide range of applications. It is by far the best design for vertical jumping, thereby lending itself to such sports as volleyball. It has also performed well for long distance running, as well as vigorous sports in general.

Finally, all these components have more widespread application than originally assumed. A more flexible forefoot permits an easier roll-over. For the geriatric individual, even a modest decrease in the effort required for walking can offer a substantial improvement in ambulatory potential. The more debilitated the person, the more important the weight and responsiveness of the foot component become. Virtually any lower limb amputee could benefit from the enhanced functioning that a sophisticated prosthetic foot can offer.

Although none of these designs will turn the amputee into Superman, each can add a significant dimension to the degree of restoration that can be offered. Jan Stokosa, C.P., has noted that although conventional prosthetic limbs restore mobility rather effectively, many patients feel their *function* has not been restored, so long as vigorous activities remain difficult or impossible to achieve.[23]

By increasing our collective experience with the components under discussion and pooling our impressions in forums such as this, it is hoped that we can more closely approach that elusive goal: complete functional prosthetic restoration for every amputee.

Component	Cost/Weight	Indication	Advantages
Sach	Low/medium	General use	Reliable, inexpensive, accommodates numerous shoe styles
Single axis	Mod/heavy	To enhance knee stability	Adds stability to prosthetic knees
Greissinger	Mod/heavy	Accommodate uneven surfaces, absorb rotary torques	Multi-directional motion
Safe	Mod/heavy	Accommodate uneven surfaces, absorb rotary torques, smooth roll-over	Multi-directional motion, moisture & grit resistant
Sten-Foot	Mod/medium	Smooth roll over	Moderate cost & weight; accommodates numerous shoe styles; ML stability similar to Sach
Seattle Foot™	High/heavy	Jogging, general sports, ''conserve energy''	''Energy storing'' smooth roll-over
Carbon Copy II	High/light	Jogging, general sports, ''conserve energy''	''Energy storing'', smooth roll-over, very stable ML, highest solid ankle foot
Flex-Foot™	Very high/ very light	Running, jumping, vigorous sports, ''conserve energy''	Most ''energy storing'', most stable ML, lowest inertia, wide range of applications

Figure 14. Clinical comparison of prosthetic feet.

Disadvantages	Typical Sports Applications	Ankle Mechanism	Permits Forefoot Pro/Supination	Permits Hindfoot in/ Eversion/Rotation
Fairly rigid, limited range of motion	Sprinting	Fixed	No	No
Slightly increased cost, weight, maintenance	Limited	Articulated	No	No
Slightly increased cost, weight, maintenance less ML stability	General, to absorb stresses		Yes	Yes
Slightly increased cost, weight, less ML stability	General, to absorb stresses	←---------- Fixed ----------→	Yes	Yes
Slightly increased cost, weight	General, for smoother roll-over		Yes	No
Increased cost, weight, difficult to fit in shoes	General, jogging		No	No
Increased cost, difficult to fit in shoes	General, jogging		No	No
High cost, complex fabrication & alignment, not feasible for very long residual limbs	Vigorous sports jumping, running	Flexible	No	No

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Appendix

SAFE Foot, Campbell-Childs, Inc., 105 East First Street, P.O. Box 120, Phoenix, Oregon 97535.

Flex-Foot™, Flex-Foot, Inc., 14 Hughes, B-201, Irvine, California 92714.

STEN Foot, Litefoot, SACH, and Single Axis Feet, Kingsley Manufacturing Company, P.O. Box CSN 5010, Costa Mesa, California 92628.

Carbon Copy II, Ohio Willow Wood Company, 15441 Scioto Darby Road, P.O. Box 192, Mount Sterling, Ohio 43134.

Greissinger, Single Axis, & SACH Feet, Otto Bock Industries, Inc., 4130 Highway 55, Minneapolis, Minnesota 55422.

Seattle Foot™, Model & Instrument Development, 861 Poplar Place South, Seattle, Washington 98144.