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Transtibial energy-storage-and-return prosthetic devices: A review of energy concepts and a proposed nomenclature

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Abstract—Prosthetic devices that can store and return energy during gait enhance the mobility and functionality of lower-limb amputees (1–4). The process of selecting and fitting such devices is complicated, partly because of confusing literature on the topic. Gait analysis methods for measuring energy characteristics are often incomplete, leading to inconsistencies in the energy classifications of different products. These inconsistencies are part of the reason for the lack of universally accurate terminology in the field. Inaccurate terminology perpetuates misunderstanding. In this paper, important prosthetic energy concepts and methods for measuring energy characteristics are reviewed. Then a technically accurate nomenclature and a method of functional classification are proposed. This review and proposed classification scheme should help to alleviate confusion and should facilitate enhancement of the design, selection, and fitting of prosthetic limbs for amputee patients.

Key words: *gait analysis, lower-limb amputee, prosthetic feet.*

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INTRODUCTION

Prosthetic feet that can store and release energy during gait can be beneficial to lower-limb amputees (1–4). Current foot designs provide a wide range of performance choices and, when fit appropriately, can improve the comfort and performance of a prosthetic limb. However, current designs also place additional demand on the rehabilitation team. The team must be familiar with the spectrum of available components, as well as how each component might alter patient function. There are thus two requirements of clinicians for effective prosthetic selection and for fitting of advanced prosthetic feet: understanding the principles of energy transfer, and understanding how these devices differ.

Unfortunately, the literature related to energy transfer and prosthetic componentry is confusing. One problem is the variation in the methods used to measure the energy-storage and the energy-return features. Most methods measure only part of the total energy characteristics. A second problem, one that stems from the first, is the lack of a universally common and technically accurate terminology. The result is a confusing literature that confounds component selection and fitting.

The purpose of this review is to:

1. Clearly explain the energy concepts and terms relevant to energy transfer in prosthetics,

2. Review methods for measurement of prosthesis energy storage and energy return and discuss which parts of the energy capabilities they measure, and
3. Propose a technically accurate nomenclature and method of functional classification for prosthetic devices that can store and release energy.

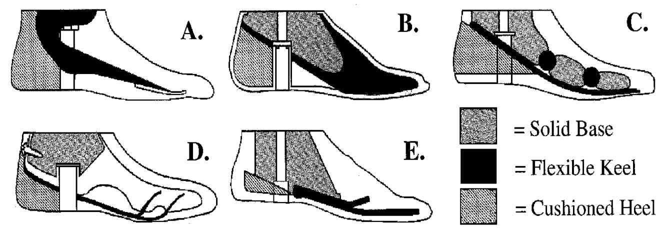

Figure 1.
Crosssections of various energy-storing feet. Each foot is composed of a compressible heel and flexible keel spring. **A.** Seattle Foot, **B**. Dynamic Foot, **C**. STEN Foot, **D**. SAFE Foot, **E.** Carbon Copy II Foot. Image based on the images of Wing DC, Hittenberg DA. Arch Phys Med Rehabil 1989;70(4):330–5.

BACKGROUND

One of the most important goals of rehabilitation following a transtibial amputation is to return an individual to the highest functional level of ambulation possible. A successful rehabilitation involves a comprehensive process of obtaining an optimum socket design, alignment, and choice of prosthetic componentry. Prior to the early 1980s, most prosthetic feet were designed with the goal of restoring basic walking and simple occupational tasks. Active or athletic amputees, however, demand more than this minimum "functional level" of ambulation from their prostheses. These individuals have the additional goals of being able to run, jump, and participate in sports. The demand for prostheses capable of higher levels of performance shaped the design and manufacture of the so-called "energy storing" foot, a foot capable of storing energy during stance and returning it to the amputee to assist in forward propulsion in late stance. This foot design was met with great clinical success and soon became a driving force in the design of prosthetic feet.

The introduction of the Seattle Foot™ in 1981 brought about the inception of the first so-called "energy-storing" prosthetic foot (ESPF). The Seattle Foot (Seattle Limb Systems, Poulsbo, WA) incorporates a flexible Delrin® (DuPont, Wilmington, DE) keel inside a polyurethane shell. It is this Delrin keel that flexes during loading, acting as an elastic spring, returning a portion of the input energy to the amputee later in gait.

Other feet followed a pattern similar to the Seattle Foot and incorporated a flexible keel(s) surrounded by foam and/or a polyurethane cosmesis. Such feet include the Dynamic (Otto Bock Industries, Minneapolis, MN), STEN (Kingsley Manufacturing Co., Costa Mesa, CA), SAFE (Campbell-Childs, Inc., White City, OR), Carbon Copy II (Ohio Willow Wood Co., Mount Sterling, OH), TruStep® (College Park Industries, Inc., Fraser, MI), Quantum (Hanger Orthopedic Group, Bethesda, MD), and others (**Figure 1**). Specific construction differences and clinical applications for each of the above feet have received prior attention and publication (5–7).

In 1987, a radically different type of prosthetic device was introduced into the market. The Flex-Foot (Flex-Foot, Inc., Aliso Viejo, CA; **Figure 2A**) prosthesis includes both a flexible carbon fiber shank and a heel spring, which allow the entire length of the prosthesis, rather than solely the foot, to flex, absorb, and return energy to the amputee. This unconventional design is considered by many to be the most "advanced" energy-storing prosthetic device available. Newer and more sophisticated prosthetic designs such as the Reflex VSP® (Flex-Foot, Inc.; **Figure 2B**) may continue to improve on the performance of the Flex-Foot, but have received little attention in the literature thus far (8,9). In 1988, another design similar to the Flex-Foot, was developed by Springlite (Salt Lake City, UT). The Springlite Advantage DP foot (**Figure 2C**) utilizes a carbon/epoxy pylon that flexes under the weight of the amputee but is a unique one-piece design (the heel spring is fused to the pylon spring with a compressible urethane elastomer heel web). The Springlite foot, while a commonly used clinical device, has received little attention in the literature. In 2000, another energy-storing foot was introduced. The Ohio Willow Wood Pathfinder® is similar in concept to the Flex-Foot Reflex VSP but adds an adjustable heel shock absorber to a composite keel spring system (**Figure 2D**). Such a design allows the foot to be specifically "tailored" to the activity level and task of the amputee.

As prosthetic devices become more complex, the need for understanding the mechanical performance of prostheses becomes ever more critical. Ultimately, both ESPF and conventional prosthetic feet are passive devices

Figure 2.
Advanced energy-storing prostheses: **A.** Modular III, **B.** Reflex VSP, **C.** Advantage DP, and **D.** Pathfinder.

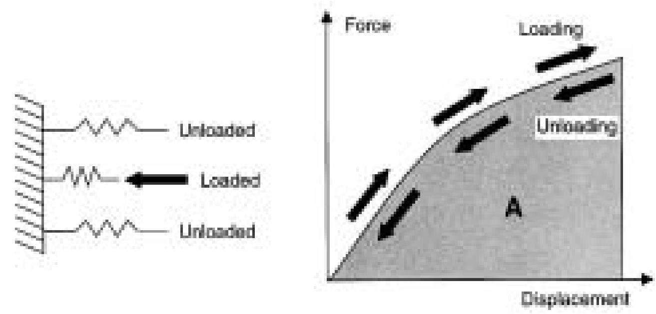

Figure 3.
Potential energy derived from a spring in compression corresponds to area **A**.

and, as such, will never fully attain the performance of the unamputated limb (an active system with muscular forces and sensory feedback). Despite this limitation, there have been significant advances in the devices themselves that may greatly improve the performance and the activity level of the amputee. To better evaluate and analyze the performance of such devices, one must understand the basic principles upon which they have been designed and engineered.

Energy Concepts

Principles of Energy Storage

The relationship between work and energy is a fairly simple one, yet the two terms are many times used interchangeably in the literature surrounding ESPF. Energy is the capability of a material to do work. In the ideal case, the energy and the work of an object are identical, but in reality, the work an object performs is always less than the stored energy it possesses because of heat, sound, and other losses. For simplicity, consider the prosthesis as a simple mechanical spring (in reality, it is more accurately described as a system of springs and other mechanical components). During gait, work is provided by the weight of the body to load the spring into compression. The material of the prosthesis (i.e., the spring) then stores this work as potential energy and can release it as work to act upon another object when the compressive force is released. Work is calculated by integration of the force-deformation curve generated by compression of the spring (**Figure 3**). The potential energy of the compressed spring corresponds to area **A** under the curve.

Elasticity vs. Viscoelasticity

A compressed (theoretical) elastic spring will return 100 percent of the potential energy as work when it is released. This theoretical energy is called the elastic potential energy of the spring. An elastic spring will return to its original shape via the same path that was used to compress it, as shown in **Figure 3**. In reality, no spring is 100 percent efficient. Rather than return to its original state via the same path on the force-deformation curve as when it was compressed, a real spring will return via a different path because of friction in the spring and energy lost as heat and/or sound. This behavior, called viscoelasticity, is identified by hysteresis, the difference between the loading and unloading portions of the load-deformation curve (**Figure 4**).

The energy lost in this system as a result of friction is equivalent to area **B** between the two curves (i.e., the area under the loading curve minus the area under the unloading curve) and is dissipated as heat and sound. This area between the input and output curves is also known as the dissipated energy and is equivalent to the input energy minus the output energy:

$$\int_{x0}^{x1} F_{Loading} \cdot dx - \int_{x0}^{x1} F_{Unloading} \cdot dx$$

Energy, as denoted by many prosthetics researchers when describing an ESPF, is simply the work input to the prosthesis during different phases of gait. The energy stored and returned by a prosthesis is typically calculated by integrating under the ankle power-time curve measured with gait analysis equipment, a quantity that approximates the energy measurement derived from a force-deformation curve. These joint powers are calculated across each

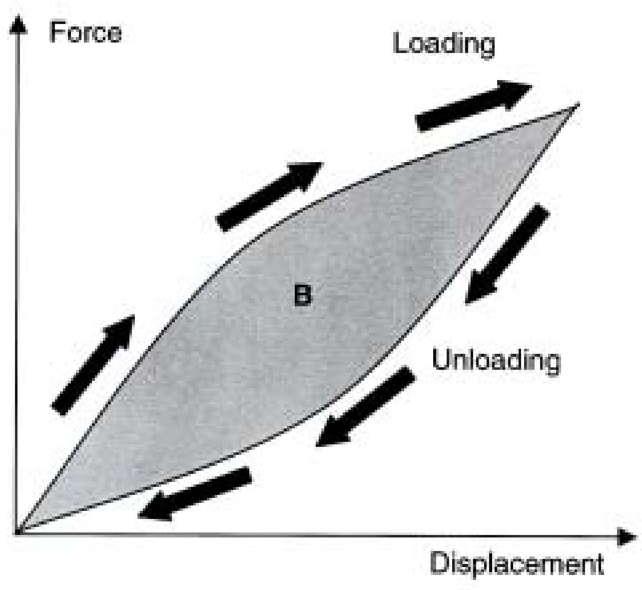

Figure 4.
Simulated load-deformation curve of a viscoelastic material. **B** = energy lost as a result of friction.

joint by motion analysis software with force plate and kinematic data because the total deformation of the spring cannot be measured directly.

Energy in Intact Ankle Joint

The ankle complex provides most of the work produced during gait (10). The ankle joint is formed by a highly sophisticated system of bones, muscles, tendons, and ligaments. The predominant motion of the ankle joint in walking gait is in the sagittal plane, and the majority of gait analysis techniques developed (and those discussed in this paper) are focused on that plane of motion. For simplicity, the ankle joint is often analyzed with the use of the link-segment model that represents the leg bones and the foot as two rigid segments on either side of an articulating joint (11). The two primary muscle groups of the ankle, the plantarflexors and dorsiflexors, govern the relative motion between these rigid bodies. This model, while technically inaccurate (the foot is actually composed of 26 individual bones), sufficiently represents the gross motion of the ankle joint for most analysts' purposes.

In the function of the intact ankle, the muscles of the leg provide the majority of shock absorption, controlled motion, and power generation (**Figure 5**). Upon ground contact, the primary dorsiflexors (tibialis anterior, extensor hallicus longus, and extensor digitorum longus) eccentrically contract to absorb shock and provide controlled plantarflexion of the foot. This action continues until the foot is flat on the ground at the end of the loading response. The plantarflexors (soleus, gastrocnemius, flexor digitorum longus, flexor hallucis longus, and peroneus longus and brevis) then eccentrically contract during controlled rotation of the tibia over the foot before concentrically contracting to propel the limb forward and initiate heel-rise. This final concentric action provides the primary power in the ankle during gait.

In quantitative gait analysis evaluations, the ankle has been shown to produce substantially more work than any other joint in the lower limb (10,12). In a study of nine normal subjects at self-selected walking velocity, the ankle joint muscles produced an average of 540 percent more work than they absorbed during gait (10). This active generation of power is critical to the production of natural gait. Effective replacement of this power generation is one of the major barriers to total gait replication with a prosthetic system.

Energy in Lower-Limb Prosthesis

The goal of complete physiological replacement of an amputated foot and ankle with a prosthetic device is an ambitious and, as of yet, unattained aim. Because the musculoskeletal complex of the foot and ankle not only absorbs energy but also generates more energy than it absorbs, active prosthetic components would be required to completely replace the lower limb. However, current commercial prostheses are composed of passive materials, and thus can at best only partially replace the missing physiological system. This leads to marked asymmetries in the temporal (13–20), kinetic (2,17,20–24), and kinematic (14,19,21,23–25) gait parameters between each limb of an amputee during walking gait.

The prosthetic foot-ankle complex achieves its partial replacement of the energy features of the normal physiological system through two main components, the heel and the keel. Both components can absorb shock and store and release energy. However, in general, the heel functions primarily as an energy-absorbing mechanism when the limb strikes the ground at initial contact. The keel functions as a stable surface for stance and, in some prostheses, such as the Seattle or Flex-Foot, as a propelling mechanism to push the amputee into the next step of gait. Together, the heel and keel both absorb and return energy, in an attempt to replicate normal ambulation in the amputee.

The prosthetic heel is the primary area of impact loading in the prosthesis. As the foot contacts the ground, the heel is loaded in compression and unloaded slowly as the amputee moves into mid-stance and the keel loading begins (**Figure 6**). In most prostheses, the heel consists of a compressible foam material that simulates controlled plantarflexion as it compresses and brings the keel into contact with the ground. The foam heel uses a viscoelastic material that dissipates energy as it compresses and expands. Other types of heels include the heel spring found in the Flex-Foot prosthetic system. The spring acts like the compressible foam, but with much greater energy-storage and energy-return capability, initially compressing and then slowly releasing energy as the foot moves into mid-stance. Thus, for this design, the heel is an important energy-storage and energy-return part of the prosthesis. As the stiffness of the heel increases, the duration of impact absorption decreases and less energy is dissipated. The remaining energy is then passed on to the more proximal sites, such as the socket-residual limb interface, or to the musculoskeletal system itself. Therefore, the higher efficiency of the spring-heel comes at a cost of increased impact absorption by the musculoskeletal system.

Once the body passes over the foot in mid-stance, loading of the keel begins. In the case of the SACH foot, the rigid wooden keel deforms minimally to store energy, though the soft foam cosmesis compresses and a larger amount of energy is dissipated there as stance continues (26). However, in an ESPF with a flexible keel, the keel begins to compress and energy is stored as the foot moves into dorsiflexion. As the tibial advancement occurs, the keel spring is compressed and energy stored

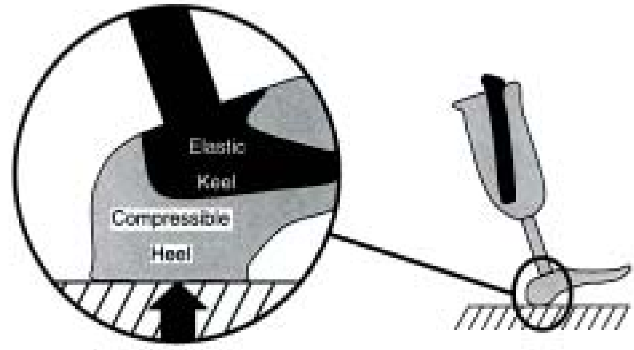

Figure 6.
Heel compression of a prosthesis during loading response.

until the amputee moves forward through stance phase and begins unloading the prosthesis. As the foot is unloaded in terminal stance, the keel spring returns a portion of the stored energy and assists in propelling the limb forward into preswing (**Figure 7**).

Energy Measurement. Energy measurement and analysis include five interrelated concepts that are used to describe the energy performance of a prosthesis: energy storage, energy return, total energy, dissipated energy, and efficiency. These concepts are most easily understood by examining the ankle power-time curve generated during kinetic gait analysis (**Figure 8**). The areas of stored and returned energy are identified as the integrated values of the power-time curve, areas **A** and **B** for the heel and areas **C** and **D** for the keel. The last two concepts, dissipated energy (area **A** minus area **B** for the heel; area **C** minus area **D** for the keel), and efficiency

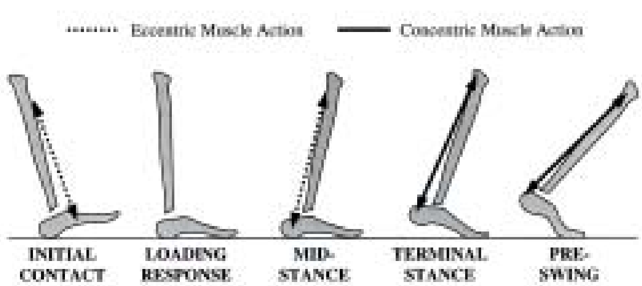

Figure 5.
Motion and net muscle action of the foot-ankle complex in walking gait.

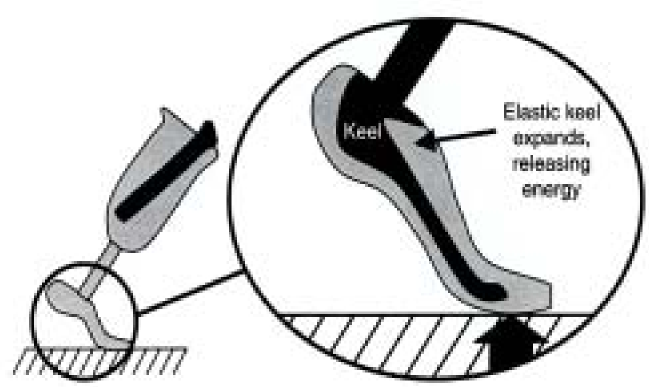

Figure 7.
Keel loading of a prosthesis during terminal stance.

(**B**/**A** for the heel; **D**/**C** for the keel) are simply functions of these variables. Since both the heel and the keel can store and release energy, their performance features must be separated as done here, though in many literature reports, they are not. There are various methods used to calculate or measure these variables (as discussed in the following paragraphs), but the principles remain the same for any method used.

The various methods developed to measure energy storage capacity of a prosthesis are often used to classify or categorize these prostheses into functional groups. Unfortunately, the classification systems currently used do not always agree, and a single foot can be placed in entirely different categories, depending on the analysis method used. Each of the reviewed methods measures or calculates one or more of the energy concepts listed previously. The four primary methods of energy analysis of prosthetic feet include functional, mechanical, kinetic, and mathematical analyses.

Functional Analysis. The easiest technique that can be used to characterize or classify the energy characteristics of prosthetic devices is a functional method. Such techniques use a simple performance test with little computational analysis. One such method, used by Michael, involved attaching each device to a pogo stick and performing a hopping experiment on each foot (27). The mean maximum vertical displacement of the pogo stick was measured (ten trials), a feature most closely related to return energy of the keel (area **D** in **Figure 8**). With this criterion, the feet were ranked in order of displacement produced during the hop: SACH, SAFE, STEN, Carbon Copy II, Seattle, and Flex-Foot (from lesser to greater displacement). This same ranking corresponded to subjective clinical evaluations made by the researchers. This method does not consider dissipated energy. A device that requires much energy to deform and has a low efficiency (but still returns a large amount of energy compared to similar devices) might still be ranked highly, although functionally it might be very difficult for an amputee to use.

Mechanical Analysis. Mechanical analyses are used to determine the energy characteristics of the prosthesis in a method similar to that used for standard engineering materials. The prosthesis is loaded in a mechanical press (e.g., an Instron® Testing Machine) while force and deformation are recorded. Hysteresis is proportional to the dissipated energy, calculated as area **C** minus area **D**, the energy "lost" during gait (**Figure 8**). A prosthesis that dissipates energy during terminal stance requires additional energy generation by the amputee's musculoskeletal system to achieve the same propulsion, because this energy is not conserved. With this evaluation method, in terminal stance the Quantum foot dissipated less energy (was better) than the SACH, while the Dynamic foot dissipated more energy (was worse) than the SACH (28). Thus, though the Dynamic foot is an energy-storage-and return device and the SACH foot is not, the Dynamic foot rated less favorably in this energy analysis.

Kinetic Analysis. Kinetic methods are typically the most common method for evaluating the energy-storage-and return capabilities of a prosthetic device. Most motion analysis software packages automatically generate the joint powers from the collected kinetic and kinematic data. Integration of the joint power (ankle moment times angular acceleration) versus time curve can be used to determine the energy absorbed and released by the device. The total energy is calculated as the sum of areas under the ankle power-time curve (the sum of areas **A**, **B,** **C**, and **D** in **Figure 8**). Using a total energy calculation, Ehara grouped the STEN, SACH, Quantum, and Seattle LiteFoot as "low energy"; the Dynamic, Carbon Copy II, Seattle, and SAFE as "intermediate energy"; and the SAFE II and Flex-Walk as "high energy" (29,30). Thus, the analysis conducted by Ehara ranks the Dynamic foot higher than the SACH, yet Van Jaarsveld reverses this ranking (28–30). While Michael ranks the SAFE foot as

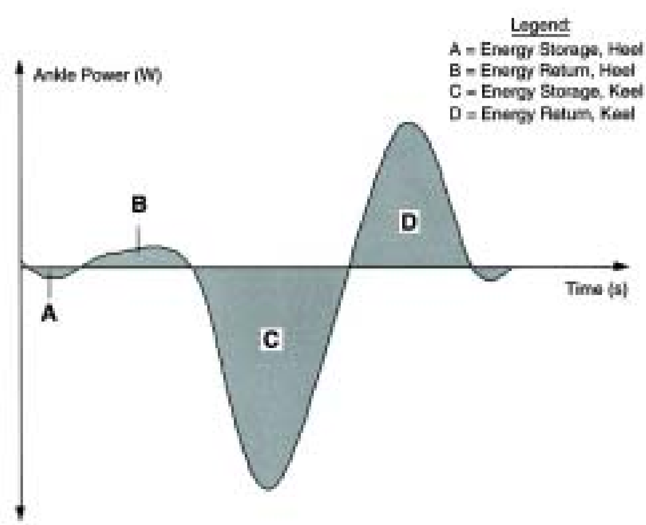

Figure 8.
Representative ankle power-time curve.

the lowest performing foot (nearly equivalent to the SACH, which fractured during testing), Ehara places the SAFE as one of the highest performing feet. Similarly, Michael's test placed the STEN foot as a moderate performer, while Ehara ranked it as the very lowest energy-storing foot, below even the "conventional" SACH foot (27,29,30). Clearly, comparison among these types of energy transfer analyses results in confusion.

The total energy, by definition, incorporates both the stored and returned energy and therefore might be a better measure of performance than either alone. However, high total energy derived through the cost of high stored energy might not be beneficial to the amputee. As the conservation of energy dictates, large stored energy can only be accomplished through an energy loss in the amputee-prosthesis system. Using significant amounts of energy from the musculoskeletal system to produce large amounts of energy in the prosthesis might be metabolically detrimental for the amputee or could negatively affect hip or knee wear. The question yet remains as to what amount of energy storage in the prosthesis is ideal. Further, the total energy does not differentiate between the heel and keel sections of the foot. Thus, engineers redesigning a foot would have little information on where to concentrate design enhancements if only the total energy, as opposed to the keel energy and heel energy, were given. Though Ehara's methods did allow separation of heel and keel energies in analysis, the separation was not included in the measure for prosthesis ranking (29,30).

Others have used similar methods to calculate many of the energy variables discussed (12,31,32). Czerniecki used the joint power method to analyze the total work and efficiency of running amputees using the SACH, Seattle, and Flex-Foot (12). Efficiency is the ratio of the returned energy to the stored energy (**B/A** for the heel and **D/C** for the keel in **Figure 8**). A device with a large dissipated energy would therefore have a relatively low efficiency. Efficiency is usually obtained at the cost of an increase in stiffness of the spring material. Since efficiency is a calculated ratio, a high efficiency may be obtained at any magnitude of energy storage or return so long as the ratio approaches unity. Czerniecki avoids this limitation by reporting both the efficiency and the total energy. In that study, the Flex-Foot produced higher total energy (70.0 percent of the normal control) and spring efficiency (84.0 percent efficiency) than either the Seattle (63.0 percent of normal total energy; 52.0 percent efficiency) or SACH (49.5 percent of normal total energy; 31.0 percent efficiency). Czerniecki's results were only calculated for the keel section of the foot; performance of the heel section was not included. However, Czerniecki's rankings of the Flex-Foot better than the Seattle and the Seattle better than the SACH are consistent with the ranking from Ehara (29,30).

Mathematical Analysis. One research group developed an alternative method for analysis of the energy-storage-and-return characteristics of prostheses. The instantaneous net power was calculated as the sum of the translational (force times velocity) and rotational (moment times angular velocity) joint power components throughout gait (33,34). The energy stored and returned in the prosthesis was calculated as the time integral of the net power flowing into and out of a fixed point on the prosthesis. The method augments the kinematics methods (inverse dynamics model) in order to evaluate the energy stored and released in the heel/keel springs, as well as that stored and released by the cosmesis material. Prince (33) demonstrated that the heel stored and returned a significant portion of the total stored and returned energy in the foot (46.6 percent stored energy and 19.3 percent returned energy for the Flex-Foot, 67.5 percent and 55.7 percent for the SACH foot, and 60.2 percent and 50.0 percent for the Seattle Foot, respectively). Thus the contribution of the heel-to-energy transfer was significant. Independent analysis of the heel portion of the foot should thus be part of an energy analysis.

Nomenclature and Functional Classification

Confusion in Literature

The limitations in the completeness of energy characterization of prosthetic feet, particularly early on, led to an inaccurate nomenclature. Two terms have been used to describe prosthetic feet that can store and return energy, ESPF and "dynamic elastic response" (DER) foot. The term "ESPF" was first adopted in the late 1980s to differentiate feet with a flexible keel design from those without (typically the SACH foot) (6,27). However, the term ESPF is an inadequate description, because it considers only areas **A** and **C** in the ankle power-time curve (**Figure 8**). The term "DER" foot or "dynamic response" foot was developed in the early 1990s (2). DER, while signifying perhaps the flexing action of the prosthetic foot, does not describe the loss of energy, but merely the transfer of potential energy to kinetic energy. This

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terminology disregards the dissipated energy in the heel (area **B** minus area **A, Figure 8**) and in the keel (area **D** minus area **C, Figure 8**). Further, the term "elastic" suggests equivalent areas of energy storage and return in the prosthesis. In order to be accurate, a terminology should address all four areas of energy storage or return represented in the power-time curve (areas **A, B, C,** and **D** in **Figure 8**).

A Revised Terminology

In order to adequately describe the function and performance of lower-limb prosthetics, a modified convention for the description of these devices is proposed. Extending from the original ESPF terminology, the term energy-storage and energy-return prosthetic foot is suggested. This term signifies not only that the device can store, but also can return energy to the amputee during gait.

It is further suggested that to accurately classify an energy-storage-and return device, at least four attributes are required: two for the heel and two for the keel. Two of each of the following must be reported for both the heel and keel: either energy storage or energy return and either energy efficiency, energy dissipation, or total energy. Energy storage and energy efficiency are preferred. The energy efficiency of the device corresponds to the response, while the energy storage corresponds to accommodation (7). From these two parameters, the three additional parameters may be calculated easily for each section of the foot (**Figure 9**).

With the use of this convention, a single quantity can be used to describe both the heel and keel behavior. The heel-keel (HK) system is derived from the efficiency and energy storage capacity of each section of the foot (**Figure 10**). A heel with low energy storage (accommodation) is not clinically functional to amputees; therefore categories H3 and H4 have been eliminated from the metric. With the use of this metric, there are eight remaining possible device descriptions corresponding to the characteristics of accommodation and response of the heel and keel (**Table**). Of the eight, only five clinically functional combinations remain. This improved HK categorization process will provide clarification of usage in the literature and convey the proper action and application of these devices. For example, a high-energy (accommodation), high-efficiency (response) heel and a high-energy, high-efficiency keel (H1K1) might be prescribed for a very active patient who runs and plays sports. Adopting a universal and technically accurate terminology will lead to a greater general understanding and consistency in measurement techniques of prosthetics technology.

1) Energy Stored = E_{Store} } Experimentally Determined
2) Efficiency = E_{eff} }
3) Energy Returned = $E_{Ret} = E_{Store} \cdot E_{eff}$
4) Energy Dissipated = $E_{Disp} = E_{Store} \cdot (1 - E_{eff})$
5) Total Energy = $E_{Tot} = E_{Store} \cdot (1 + E_{eff})$

Figure 9.
Typical energy determinants used for analysis of prosthetic devices.

DISCUSSION

This paper examines the modern "energy-storing" prosthetic device through a presentation of energy concepts, a recommendation for a revised and technically consistent nomenclature, and a new technique for analysis and categorization based on performance for energy-storage-and return prostheses. A review and critical analysis of the relevant literature reveals key issues to be addressed in order to adequately understand and investigate amputee performance and the fundamental design of advanced energy-storage-and return prosthetic devices.

Knowledge of the mechanisms of energy transfer in the energy-storing foot is necessary to understand the

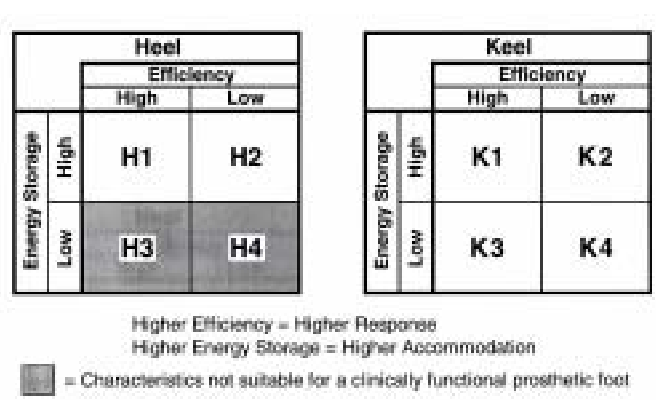

Figure 10.
Proposed heel-keel (HK) functional energy-storage-and return prosthesis evaluation system.

Table.
HK categorization chart and associated activity level.

Categorization	Heel Accommodation (Energy Stg)	Heel Response (Efficiency)	Keel Accommodation (Energy Stg)	Keel Response (Efficiency)	Walking Speed			Sports Activity		Other Properties	
					Slow	Moderate	High	Running	Uneven Terrain	Shock Absorption	Increased Simulated ROM
H1K1	High	High	High	High	—	•	•	•	—	—	•
H2K1	High	Low	High	High	—	•	•	•	—	•	•
H2K3	High	Low	Low	High	•	•	—	—	—	•	—
H2K2	High	Low	High	Low	•	•	—	—	•	•	•
H2K4	High	Low	Low	Low	•	•	—	—	—	•	—
H1K2	High	High	High	Low	—	—	—	—	—	—	—
H1K3	High	High	Low	High	—	—	—	—	—	—	—
H1K4	High	High	Low	High	—	—	—	—	—	—	—

□ = Characteristics not suitable for a clinically functional prosthetic foot.

performance and application of advanced prosthetic devices. Although implicitly understood, the literature often fails to designate and differentiate the two energy-storing components of a prosthetic foot—the heel and the keel. Since the major function of an energy-storage-and return device is to propel the amputee during gait, the keel performance is often the focus of analysis while the heel is often overlooked. One reason for this oversight might be that the heel's returned energy often is not utilized as an input energy for the keel, but rather simply dissipated. A future area of research might be examining energy transfer between these two areas of the foot. The question of whether the energy stored in the foot during loading response (heel energy storage) can be transferred into the terminal stance energy release (keel energy release) or whether it can only be dissipated needs to be answered. If prosthetic designs can be modified to more efficiently utilize input energy rather than to dissipate it, then amputee performance might be enhanced.

A revised terminology, dubbed energy-storage-and return, is proposed to accurately describe the function and performance of advanced prosthetic devices. While this terminology does not necessarily distinguish the types of prostheses by definition alone, the measured magnitudes of the energy transfer parameters can be used to categorize the devices by functional performance. This categorization will then provide a clinical tool for aligning amputee activity level and device performance in a way currently only indirectly discussed in the literature. A proposed classification system is suggested in order to rank and categorize energy-storage-and return and conventional feet based upon the accommodation and response of each section of the foot. This HK classification provides a total of five functional foot categories and is tabulated according to functional capacity for future use. This metric is designed not to be a complete replacement, but an augmentation to existing clinical evaluation systems, adding a measure of performance that is both functional and technically precise. More extensive research and clinical evaluation are now required to complete and augment the proposed HK classification system. While classical engineering methods and gait analysis can be used to analyze the accommodation and response of these devices, clinical input is required to determine the functional application and recommended usage of each level of the scale.

Finally, one must understand that the tools of engineering methods and gait analysis, while helpful, are only a part of the whole design of a successful rehabilitation. A performance analysis of the prosthesis may help predict the behavior of the device when used by the individual, but is not entirely sufficient to analyze the performance of an amputee. Future research must concentrate not on analyzing which devices work, but on analyzing why the devices that do work are successful for the particular amputee. A vital component to analyzing prosthesis energy transfer should now be to understand how much energy absorption and release is appropriate for the individual, as well as understand how that transfer of energy affects the individual. Questions such as, "Is it better for the amputee to absorb more or less energy in the prosthetic limb than the sound limb (or that of a normal limb)?" must be answered to further develop advanced prosthetic designs. While the performance of the prosthesis will always be a vital component of prosthetic design, the ultimate goal will always be the optimum performance and health of the amputee.

Toward this end, analysis of energy transfer mechanisms in an energy-storage-and return prosthesis has been examined and the fundamental characteristics explained. A revised nomenclature and a system for categorization based upon functional performance have been suggested for energy-storage-and return prosthetic devices. Further input is required from researchers and clinicians at large to expand upon the ideas presented here and to further evaluate both amputee and energy-storage-and return prosthesis performance. By maintaining an understanding of the energy principles of the prosthesis, a consistent and technically accurate nomenclature, and a method to categorize the energy-storage-and return devices according to functional performance, we achieve a better position from which to provide greater care for the amputee and an increased ability to improve upon prosthetic designs.

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