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Mechanical efficiency during gait of adults with transtibial amputation: A pilot study comparing the SACH, Seattle, and Golden-Ankle prosthetic feet

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Abstract—As more and more prosthetic feet become commercially available, the selection of the appropriate device is a more difficult task for clinical team members. To date, ranking prosthetic feet based on biomechanical parameters has been done using the spring efficiency. The current analytical technique for calculating spring efficiency has two flaws: first, prosthetic feet with a bendable flexible keel are analyzed the same way as those with an articulated ankle and a rigid foot, and second, there is no accounting for the energy losses in the viscoelastic cosmetic material surrounding the keel. This paper develops a rigorous technique to calculate the net energy stored or dissipated and then recovered during the stance phase of gait. Five adults with transtibial amputation were tested with three different prosthetic feet: SACH, Seattle, and Golden-Ankle. The subjects walked at self-selected cadence and stepped on a force plate while two-dimensional segmental kinematic and kinetic data were collected. The results showed that the Golden-Ankle stored or dissipated and then recovered significantly more energy than either the SACH or Seattle. The time to reach foot flat was also significantly reduced for the Golden-Ankle in comparison to both the others. Because the cosmetic material of the SACH foot can store or dissipate and then recover as much energy as the Seattle foot, the SACH foot should be considered an energy-storing foot. Finally, the net efficiency alone can not discriminate adequately among different types of prosthetic feet; therefore, one should consider the time to reach foot flat and the amount of energy recovered as additional objective criteria (weight, maintenance, and cosmesis) for selection of a prosthetic foot device.

Key words: *efficiency, energy, gait, prosthetic foot, transtibial amputation.*

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INTRODUCTION

More than 30,000 lower limb amputations (LLA) are performed every year in North America (1). Over three-quarters are done on men over the age of 60, who are affected by peripheral vascular diseases with or without diabetes mellitus (2,3). Before 1960, a majority of these LLAs were performed at the transfemoral level instead of the transtibial. Subsequently, this tendency has reversed, principally due to improvements in preoperative modalities (4,5), surgical procedures (6,7), and postoperative management (8). Today, almost all persons with LLA are fitted with a prosthesis, receive

gait training, and return to community living (9,10). The role of a prosthetic foot is to replace as much as possible the distal shank, ankle, and foot functions and appearance. In locomotion, these functions provide the rest of the body a stable interface and support with the ground as well as aid propulsion to the limb. The gait of subjects with LLA has been described as requiring higher oxygen consumption than that of the nondisabled, and this metabolic energy cost increases with the level of amputation (11,12).

The last decade has shown tremendous improvement in prosthetic foot devices. Energy-storing prosthetic feet have been designed to store mechanical energy during early and mid-stance and to release this energy during late stance to assist the push-off, leading to a functional improvement of gait (13,14). Recently, the efficiency of energy-storing prosthetic feet has been questioned (15–17), because those fitted with these sophisticated devices did not show a significant decrease in oxygen consumption (metabolic energy) during walking, compared with that of non-energy-storing prosthetic feet.

With more prosthetic feet on the market, it becomes difficult for clinical team members to select the optimal prosthetic foot for a given client. Comparison between energy-storing feet has been done using questionnaires (18,19), kinematics (16–18), and ground reaction forces (18,19–21). Clinical assessment of them has been done by measuring the height of the ground clearance after vertical leap using a pogo stick (13), quasi-static loading (22), foot compliance (23,24), forward impulsion (24,25), and other factors such as weight, maintenance, and cosmetic appearance (13,14).

Calculation of the ankle moment of force has been reported using an inverse dynamic analysis (26–29) or the projection of vertical vector approach (17,23,24,30). In the latter technique, inertial properties, and angular accelerations of the foot are negligible. A decade earlier, Wells (31) reported only small contributions by these parameters to the ankle moment of force, and recommended avoiding this method in the calculation of the knee and hip moments, because it can lead to significant errors. Classically, the muscle power absorbed or generated at the ankle joint during nonimpaired gait has been calculated as:

$$P_a = M_a \cdot \omega_a \qquad \text{Watt} \qquad [1]$$

where: M_a is the ankle moment of force and ω_a is the ankle angular velocity. If M_a and ω_a have the same polarity, the product is positive, indicating a concentric contraction. In nonimpaired walking, this is interpreted as being indicative of energy generation by the muscles, and in a prosthetic foot, it is interpreted as energy recovery from a spring mechanism. If M_a and ω_a have different polarity, the power indicated an energy absorption from an eccentric muscle contraction or energy storage/dissipation in the spring mechanism of a prosthetic foot. The time integral of the ankle power at the ankle gives the work absorbed and generated by the ankle muscles as:

$$W_a = \int P_a \; dt \qquad \text{Joules} \qquad [2]$$

Then the spring efficiency can be calculated as follows:

$$\text{Spring Efficiency} = \frac{W_a \text{ (recovered)}}{W_a \text{ (stored or dissipated)}} \cdot 100 \quad \% \qquad [3]$$

The same muscle power calculation technique has been used in research dealing with both control and LLA populations. Ranking of prosthetic feet based on their mechanical spring efficiency has been reported for walking (26–30). Unfortunately, two flaws exist in the spring analysis technique. First, the model assumes a rigid foot along the line defined between the ankle and metatarsal joints as well as a hinge joint articulation around the ankle. The bending of the flexible keel, the deformation within the cosmetic forefoot material, and the presence of an immobile ankle violate these assumptions. Second, the energy stored or dissipated and recovered in the viscoelastic material surrounding the keel of the prosthesis was not taken into account. The purpose of this study is to discriminate among three prosthetic feet for the net energy stored or dissipated and then recovered, as well as for the spring efficiency, using a more rigorous technique. Five adults with transtibial amputation (ATTA) were fitted with three different prosthetic feet: one non-energy-storing device, the Solid Ankle Cushion Heel—or SACH foot (Otto Bock Orthopedic Industry of Canada, Oakville, ON) and two energy-storing prostheses, the Seattle foot (M+IND, Seattle, WA) and the Golden-Ankle (MMG Prosthetics, Decatur, GA). The Seattle foot is equipped with a flexible keel in Delrin (acetyl polymer), acting as a leaf spring that can bend and store energy, while the Golden-Ankle is an ankle designed with two helical springs with a hinge joint above the rear spring, attached to a Syme SACH foot.

METHODS

Subjects

Five ATTAs were fitted in a random order with the SACH, Seattle foot, and Golden-Ankle. All subjects were fitted by the same prosthetist (G.S.) who was certified by the Canadian Board for Certification in Prosthetics and Orthotics. He has been in clinical practice for 13 years and instructs in a clinical program. Each subject has had a prosthesis for more than 2 years, and wore the same socket while interchanging the prosthetic feet; each was realigned using standard alignment criteria. When the subjects wore a different foot from that normally worn, there was a 15-min training period for adapting. The anthropometric characteristics of the subjects are reported in **Table 1.**

Motion and Force Recording Systems

Seven reflective markers were attached on the acromion, greater trochanter, lateral knee condyle, the distal part of the prosthetic leg (at the level of the sound limb ankle), the metatarsal break, heel, and toe. The ATTA's gait was recorded at 60 Hz using a CCD video camera while the subject walked at self-selected cadence over a 13-m walkway with an embedded AMTI force plate (Advanced Mechanical Technology Incorporated, Watertown, MA).

Two trials per prosthetic foot were collected and processed in a two-dimensional (2-D) inverse dynamic analysis (32). Statistical analysis including a MANOVA procedure; Scheffé post-hoc comparisons were used, and alpha error was set at 5 percent.

Calculation of Work and Net Efficiency

The technique used to calculate the energy stored or dissipated and then recovered has been previously reported (33) and will be summarized in the next two sections.

Table 1.
Anthropometric characteristics of the five persons with transtibial amputation.

Subject code	Age (yrs)	Height (cm)	Weight (kg)	Side	Cause
WQ21	44	164.5	81.5	left	vascular
WQ22	32	180.3	78.1	left	trauma
WQ23	43	177.8	81.0	left	vascular
WQ24	28	171.5	76.3	right	trauma
WQ25	64	182.9	81.7	right	vascular
mean	42.2	175.4	79.7		
SD	14.0	7.4	2.4		

A point located on the distal end of the rigid part of the prosthetic leg (at the level of the sound limb ankle) was chosen to track all the flow of energy entering and leaving the ankle and foot device. At the defined ankle joint at the distal end of the leg, there are two kinds of energy flow: the translational power calculated as the force-velocity product in the horizontal and vertical directions and the rotational power calculated from the moment-angular velocity product. The summation of the translational and rotational powers leads to the total power that flows into or out of the distal end of the leg as:

$$P_{dist} = F_a \cdot V_a + M_a \cdot \omega_{leg} \qquad \text{Watt} \qquad [4]$$

where F_a, V_a are, respectively, the reaction forces and the linear velocities acting on the distal end of the leg, M_a is the moment at that point and ω_{leg} is the leg angular velocity. The time integral of P_{dist} over the stance phase yields the net work, either stored or dissipated (negative) and that which is recovered (positive), from the prosthesis.

$$W_d = \int P_{dist} \; dt \qquad \text{Joules} \qquad [5]$$

The net efficiency is calculated by the ratio of the net work done during recovery phase over the net work done during the storage or dissipation phases and is expressed as a percentage as follows:

$$\text{Net Efficiency} = \frac{W_d \text{ (recovered)}}{W_d \text{ (stored or dissipated)}} \cdot 100 \quad \% \qquad [6]$$

The net efficiency calculated from Equation 6 takes into account not only the rotational power contribution due to any spring mechanism but also the translational power due to compression and recovery from the compliant foot structures.

Foot Power Balance Analysis

The portion of energy that has been stored or dissipated and then recovered from the cosmetic material surrounding the keel of different prosthetic feet can be calculated using the following procedure. The total mechanical energy of the foot at time t_i can be defined as the sum of the potential, translational, and rotational kinetic energies:

$$E_{(f,t_1)} = mgh_{(f,t_1)} + \frac{1}{2} m \left[v_{(f,t_1)}\right]^2 + \frac{1}{2} I \left[\omega_{(f,t_1)}\right]^2 \quad \text{Joules} \qquad [7]$$

where m is the mass, g the gravitational constant, h the height of the center of mass, v the linear velocity, I the mass moment of inertia, and ω the angular velocity. The time derivative of the total mechanical energy yields the rate of change of energy (instantaneous power) of the "rigid" foot segment at a given time (t_1) as:

$$\dot{E}_{(f,t_1)} = \frac{E_{f,t_2)} - E_{f,t_0)}}{2\Delta t} \quad \text{Watt} \qquad [8]$$

In a perfect rigid segment, the mathematical model assumes that the rate of change of foot mechanical energy will equal the sum of the translational and rotational powers entering or leaving the segment:

$$\dot{E}_{foot} = F_a \cdot V_a + M_a \cdot \omega_{foot} \quad \text{Watt} \qquad [9]$$

where ω_{foot} is the foot angular velocity. Any residual of this equation reflects the fact that the prosthetic foot is not perfectly rigid (the keel flexes and the cosmetic material compresses). The residual power due to the compliant foot (P_c) is calculated as:

$$P_c = \dot{E}_{foot} - (F_a \cdot V_a + M_a \cdot \omega_{foot}) \quad \text{Watt} \qquad [10]$$

When P_c is negative this means that energy is being stored or dissipated in the compliant material, and when P_c is positive, energy is being recovered.

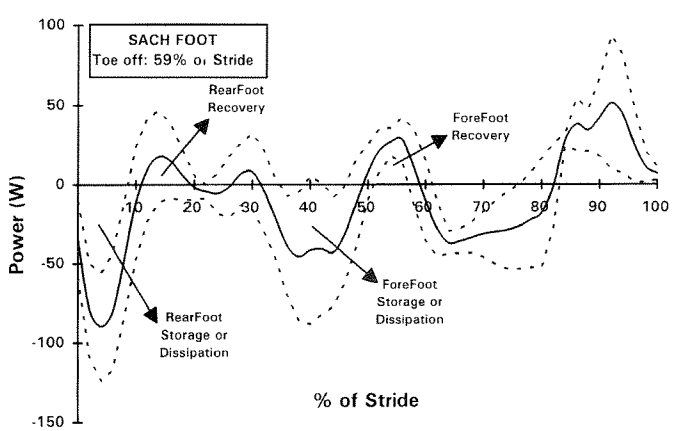

Figure 1.
Ensemble average ±1 SD for the power flow at the distal end of the leg in five adults with transtibial amputation fitted with a SACH foot and walking at self-selected cadence. Periods of energy storage/dissipation and recovery are indicated with arrows.

RESULTS

Gait velocity of all subjects ranged from 0.9 to 1.4 m/s. **Figure 1** shows the average ± one standard deviation (SD) of the power flowing into or out of the distal end of the leg for five ATTA fitted with a SACH foot. At initial loading (0–11 percent of stride), the rearfoot material displays storage or dissipation of energy that flows from the leg to the foot and is being absorbed by the cushioned heel material of the SACH foot. All three prostheses showed the same bursts of energy and polarity.

Figure 2a sketches the average SACH foot power balance for the five ATTA during initial loading phase and shows that all of the power from P_{dist} (113 W) was stored or dissipated in the rearfoot material of the prosthesis and resulted in the compliant power (P_c=120 W). Some of this energy is recovered between 11 and 32 percent of stride (**Figure 1**) by the rearfoot material. This accounts for the plantigrade foot position. **Figure 2b** shows that at a given time in the foot flat phase, 29 W was being recovered by rearfoot decompression (P_c), and all of this energy is flowing back to the leg (P_{dist}=29 W). During that period, no rate of change of mechanical energy of the foot ($\dot{E}_{foot}$) is recorded, because the foot is not moving.

During late stance, between 32 to 47 percent of stride, another period of storage or dissipation occurs mainly in the forefoot section (**Figure 1**). **Figure 2c** shows that some rotational energy is flowing from the leg (P_{leg}=160 W) to the foot (P_{foot}=151 W), indicating that a negligible amount of energy (3 W) was being stored in the spring-like unit of the SACH. Thus, some energy has also been stored within the forefoot material (P_c=36 W). Finally, during push-off (47 to 59 percent of stride), some energy is being recovered by the forefoot section. **Figure 2d** shows that 61 W has been recovered by the compliant power (P_c) in forefoot material, adding to the spring energy recovery (P_{sp}=7 W) and flowing back into the leg (P_{dist}=52 W).

Table 2 summarizes the work done (area under the P_{dist} curve) during the stance phase of five ATTAs fitted with the SACH, Seattle, and Golden-Ankle. At initial loading, the rearfoot section of all prosthetic feet shows a large energy storage within the heel material or in the spring unit of the Golden (7–11 J). Later in stance, the heel recovers a consistent amount of energy (≅1.9 J) across all prosthetic feet and suggests similar heel construction and mechanical characteristics between the feet. Efficiency of the rearfoot section shows

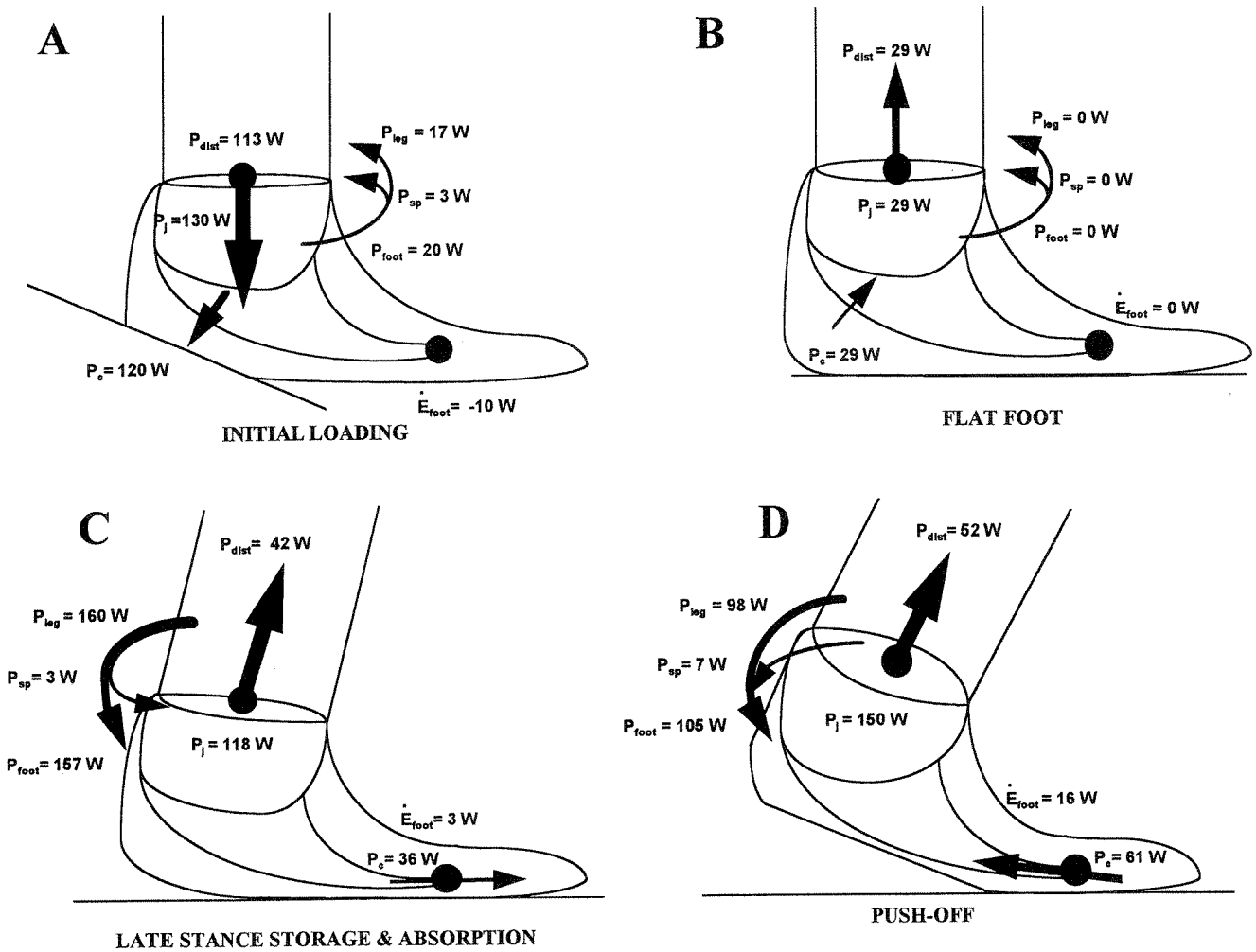

Figure 2.
Typical power balance of an adult with transtibial amputation fitted with a SACH foot during initial loading (a), flat foot (b), late stance (c), and push-off (d) phases. Rotational powers are shown with curved arrows: power of the leg (P_{leg}), spring power (P_{sp}), foot power (P_{foot}); while translational powers are shown with linear arrows: power at the distal end of the leg (P_{dist}), joint power (P_j), and compliant power (P_c). $\dot{E}_{foot}$ is the rate of change of mechanical energy of the foot. The thick arrows are larger power flows, the thinner are small power flows.

low and variable results across prosthetic feet (14–24 percent).

The forefoot section of the Golden-Ankle is capable of storing or dissipating significantly more energy (11 J) than either the Seattle (6.2 J) or the SACH (5.1 J). The Golden-Ankle also recovered significantly more energy (6.9 J) than either the Seattle (3.3 J) or the SACH (2.7 J). This energy flowing back through the distal end of the leg will assist the forward propulsion of the prosthetic limb to the next step. The forefoot section is more efficient (54–67 percent) than the rearfoot section (14–24 percent) across all three feet (**Table 2**).

When expressed as a total foot (rearfoot+forefoot), the Golden-Ankle shows significantly greater ability to store or dissipate energy (21.9 J) compared to the Seattle (13.4 J) or the SACH (12.1 J). The Golden-Ankle also recovers significantly more energy (8.8 J) than either a Seattle (5.1 J) or SACH (4.5 J). All prosthetic feet have about the same low efficiency (around 37–41 percent).

Because all moment of force curves look the same across all subjects and walking trials, a trial of an

Table 2.
Average net energy stored or dissipated and then recovered, and energy efficiency in five persons with transtibial amputation during walking at self-selected cadence.

	Golden-Ankle		Seattle		SACH	
	mean	(SD)	mean	(SD)	mean	(SD)
Rearfoot						
Stored/Dissipated (J)	10.9	(4.9)	7.2	(2.4)	7.0	(3.1)
Recovered (J)	1.9	(2.0)	1.8	(1.7)	1.9	(2.0)
Efficiency (%)	13.7	(13.0)	23.6	(20.2)	21.2	(18.0)
Forefoot						
Stored/Dissipated (J)	11.0	(4.5)*	6.2	(0.6)	5.1	(1.8)
Recovered (J)	6.9	(1.9)*	3.3	(1.3)	2.7	(0.3)
Efficiency (%)	66.7	(18.0)	54.4	(25.6)	58.6	(23.6)
Total Foot						
Stored/Dissipated (J)	21.9	(5.7)*	13.4	(2.4)	12.1	(2.9)
Recovered (J)	8.8	(2.6)*	5.1	(2.6)	4.5	(2.2)
Net efficiency (%)	40.9	(9.0)	38.7	(21.0)	36.6	(10.3)

*Golden-ankle significantly different from either the Seattle or SACH prosthetic feet, $p<0.05$.

ATTA fitted with a SACH foot (long dashed line) was chosen and overlaid by the mean ±1 SD (solid line) of 19 controls (34). **Figure 3** shows a typical internal ankle moment of force profile of an ATTA fitted with a SACH foot. At initial loading, a dorsiflexor moment is internally created at the ankle level, and later the polarity changes to plantarflexor moment. In controls, this zero crossing occurs earlier in the gait cycle (7 percent of stride) compared to the ATTA fitted with a SACH foot (20 percent of stride). When the moment of force profile changes polarity, the resultant forces acting under the foot pass the ankle. At that time, the ATTA reaches a foot-flat position and the prosthetic shank is perpendicular to the ground level.

Figure 4 shows that the five ATTAs fitted with the Golden-Ankle reached foot flat significantly earlier in the gait cycle (14 percent of stride) compared with those fitted with either the Seattle (21 percent of stride) or SACH feet (20 percent of stride). The Golden-Ankle showed a more natural gait pattern, probably because its ankle articulation more closely mimics anatomical function.

DISCUSSION

The cushioned heel of the SACH was designed to compress at initial contact to cause plantar flexion (14). In persons with lower limb amputations fitted with solid ankle prosthetic feet, this movement is almost impossible to achieve. In this case, the lowering of the foot on the ground is not a plantar flexion. Because the prosthetic shank is rigidly fixed on the foot, a dorsiflexion moment of long duration is created, and lowering of the foot to the ground can be achieved by two strategies. First, by allowing the rotation of the shank over the heel, the ATTA will attempt to collapse the knee, and this is resisted by eccentric quadriceps activity. Only ATTAs with adequate residual knee function and residual stump length are able to perform such a task. Second, the ATTA may lock the knee with a co-contraction between the hamstrings and quadriceps muscles (28) and then vault over the prosthetic foot. Both strategies will delay the time to achieve foot flat.

Edelstein (14) recognizes the energy-storage capability with the compression of the heel in prosthetic feet but states that during stance, no significant energy can be stored and released in the compressed heel material of the SACH at late stance when propulsion is needed. The present study suggests that a great amount of energy (7–11 J) is effectively stored or dissipated in the heel material of the SACH, Seattle, and Golden-Ankle prosthetic feet. During the initial loading, the energy storage or dissipation (7–11 J) is as great or greater than the amount of energy stored or dissipated later in stance (5–11 J). All three prosthetic feet recovered about the same amount of energy (≅1.9 J); this suggests the same heel function. Because energy recovery is mostly

oriented along the long axis of the prosthesis, it appears that the heel may rebound off the ground and also may increase the height of the center of mass of the subject during midstance. This will increase the potential energy that can be transferred later into kinetic energy to assist forward progression. The rearfoot cosmetic material and spring mechanism of the Golden-Ankle should also be considered as a system able to store and recover energy in early stance. Nevertheless, for the rearfoot section, energy efficiency remains low across the three feet tested.

The forefoot section of the Golden-Ankle showed a period of storage or dissipation of energy superior to the SACH or Seattle feet. The spring unit of the Golden-Ankle seems to be appropriate for storing energy that can be used later to assist the propulsion.

When expressed as a total foot, the amount of energy stored or dissipated reveals that the Golden-Ankle has the potential of returning almost 22 J. The lack of significant difference between the SACH and Seattle feet suggests that the viscoelastic material around the keel of the Seattle foot limits the recovery of energy and results in an important dissipation. The SACH foot should now be considered as an energy-storing prosthetic foot, since its cosmetic material is capable of storing and recovering energy in late stance.

Comparing data from the current study regarding the amount of energy stored or dissipated and then

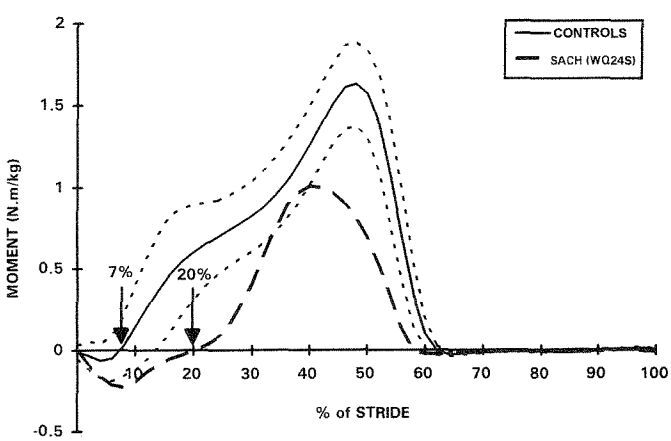

Figure 3.
Ensemble average ±1 SD deviation for controls (N=19) ankle moment of force (thin line) compared with the ankle prosthetic moment of force profile (thick dashed line) for an adult with transtibial amputation fitted with a SACH foot while walking at self-selected cadence. Time where flat foot occurs is indicated with arrows.

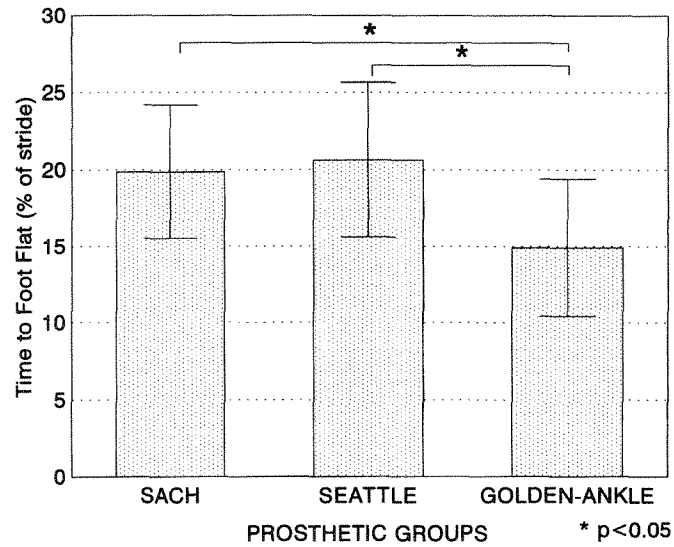

Figure 4.
Average time ±1 SD of foot flat in five adults with transtibial amputation fitted with a SACH, Seattle, and Golden-Ankle prosthetic components.

recovered with data from literature reveals important discrepancies. **Figure 5** summarizes different studies reporting the work stored and recovered (using moment times ankle angular velocity) in ATTA fitted with the SACH foot. The amount of energy stored or dissipated is underestimated by all but Ehara et al. (27). For the amount of energy recovered, the present study is consistently above the results from other authors. This can be the direct result of adding the portion of energy from the force-velocity product at the distal end of the leg that is absent in the previous studies. One should also appreciate fluctuation in efficiency from study to study. For example, Barr et al. (30) reported an efficiency of 30 percent, but the amount of energy stored or dissipated and recovered is minimal compared to the present study, which reports a slightly higher net energy efficiency.

Figure 6 shows a comparison of the energy stored or dissipated and then recovered during normal walking of an ATTA fitted with an energy-storing prosthetic foot, the Seattle foot. Ehara et al. (27) show a very low efficiency (14 percent) compared with the present study, despite the fact that the amounts of energy stored or dissipated and recovered were similar. Gitter et al. (26), show an efficiency (71 percent) about twice that reported in the present study (37 percent), using a more rigorous technique for energy calculation. The ankle

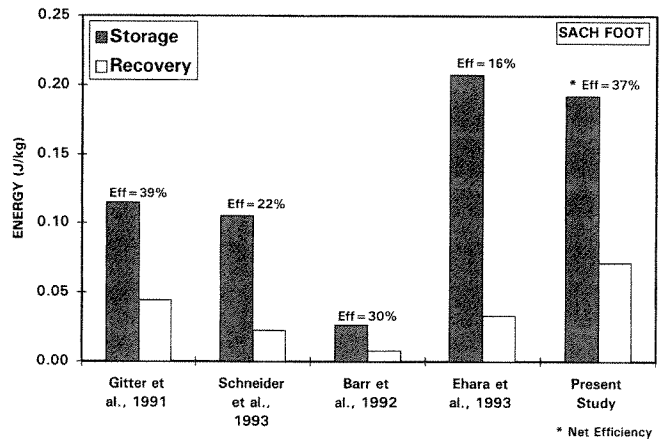

Figure 5.
Comparison of the energy storage and recovery as well as the efficiency in percentage when people with lower limb amputation walked with a SACH foot.

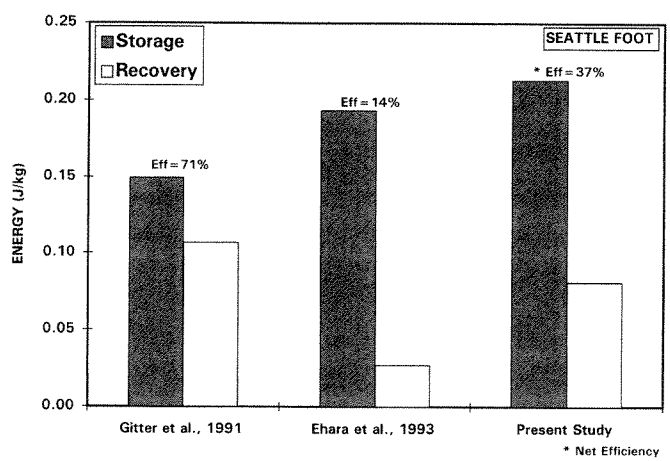

Figure 6.
Comparison of the energy storage and recovery as well as the efficiency in percentage when people with lower limb amputation walked with a Seattle foot.

joint of the Golden-Ankle significantly reduces the time to reach foot-flat position compared to the SACH or Seattle feet. Edelstein (14) reported the difficulty for ATTAs fitted with a SACH foot to reach the foot-flat position. The energy-storing and ankle mobility functions should be incorporated in future design of prosthetic feet. Based on the five ATTAs tested in the present study, the spring mechanism of the Golden-Ankle seems to be superior to the flexible keel of the Seattle for energy storage and release. Even in the best case, the Golden-Ankle recovered only 30 percent of the work reported in control subjects (≅24 J) during walking (35).

CONCLUSIONS

Energy calculation and efficiency were assessed in the gait of five adults with transtibial amputation fitted with the SACH, Seattle, and Golden-Ankle prosthetic feet. The following conclusions can be drawn.

1. The translational power makes a significant contribution to the total amount of energy that enters or leaves the distal end of the leg and should be considered in prosthetic feet energy assessment.
2. Net energy efficiency during walking is about the same (≅40 percent) across all prosthetic feet tested and suggests that this variable alone can not discriminate among prosthetic feet.
3. Because of its ankle joint and spring mechanism, the Golden-Ankle allows a significantly higher net energy storage or dissipation and then recovery compared with either SACH or Seattle prosthetic feet.
4. The time to reach a foot-flat position was significantly reduced in the Golden-Ankle compared with either the SACH or Seattle prosthetic feet. This variable should be considered in the criteria with the net energy recovered for selecting a particular prosthetic foot.

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