Energy expenditure during ambulation in dysvascular and traumatic below-knee amputees: A comparison of five prosthetic feet

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Abstract—Recent advancement in prosthetic technology has led to the development of dynamic elastic response feet (DER), which are reported to store and release energy to facilitate gait. To date, there has been no objective evidence to suggest energy conservation while using these foot designs. The purpose of this study was to compare the energy expenditure of five commercially available prosthetic feet (SACH and four DER feet) in both the traumatic and dysvascular populations during level walking. Seventeen male subjects with below-knee amputation (nine traumatic and seven dysvascular) were tested for energy expenditure (Douglas Bag technique) during a 20-min walk while wearing each of the prosthetic feet. The DER prosthetic foot designs were not shown to reduce the energy cost (ml O₂/kg·m) or rate of energy expenditure (ml O₂/kg·min) compared to the SACH foot. Overall, the traumatic amputees had a similar oxygen consumption per meter traveled compared to the dysvascular amputees; however, the rate of energy consumption was much higher in the traumatic group. This increased rate was a function of the greater walking velocity employed by the traumatic subjects, made possible by their better physical fitness.

Key words: amputees, energy cost, prosthetics.

INTRODUCTION

Advancement in prosthetic technology during the last decade has led to the development of new prosthetic foot designs which have been termed Dynamic Elastic Response or DER feet. Compared to the traditional solid configuration of the SACH foot, the DER feet are reported to store and release energy in a manner that facilitates ambulation (1,2). The internal keel of these feet is designed to elastically deform under load bearing (thus storing energy) and then release when the amputee advances over the foot (3). This supposedly reproduces the energy absorption and generation characteristics of the normal foot and ankle in addition to providing better mobility. Theoretically, this would reduce the high energy cost of ambulation associated with this population.

Despite the reported energy storing and releasing properties of the DER feet, previous studies have failed to show statistically significant reductions in energy expenditure (i.e., oxygen consumption) when compared to the conventional SACH foot (4–7). To date, there has been only one report as to how the energy expenditure of the two primary populations of persons with below-knee (BK) amputation, due to trauma or vascular dysfunction, compares while walking with different prosthetic feet (7). In addition, biomechanical analysis during level walking has demonstrated that the SACH and DER feet have knee and hip power curves of comparable magnitude, implying that the metabolic energy consumption should be similar (8).
These studies have been limited in sample size and have been inconsistent regarding the amputee population under investigation.

Compared to traumatic amputees, the dysvascular population tends to be less physically active, with a greater incidence of health-related problems (9). Thus, the traumatic amputee is more likely able to effectively compensate for the biomechanical limitations imposed by using a prosthesis than is the dysvascular amputee.

Studies have demonstrated that the energy expenditure per minute (O₂ rate) when walking at a self-selected comfortable speed, is equal between the traumatic amputees, dysvascular amputees, and subjects without amputation (10,11). Differences in walking velocity between these groups was responsible for the consistent O₂ rate. The energy cost (ml O₂/kg-m) for dysvascular amputees, however, has been reported to be greater when compared to traumatic amputees, with both groups having a greater energy cost than non-amputees because of a decrease in ambulation efficiency (11).

Little evidence exists that the energy “stored” in the DER feet is actually utilized to spare metabolic energy expenditure for either the dysvascular or traumatic amputee. The purpose of this study was to compare the effects of five different commercially available prosthetic feet (SACH and four DER feet) on the energy expenditure of walking in both the traumatic and dysvascular populations. This information could assist in providing a basis for prosthetic foot prescription for a patient with BK amputation (BKA), and would be beneficial in determining whether any of the DER feet provide the capacity for energy conservation.

METHODS

Subjects

Seventeen males with BKA, 10 traumatic and 7 dysvascular, participated in this study. The etiology of the dysvascular group was related to vascular disease secondary to diabetes. Subjects were recruited from the Long Beach Department of Veterans Affairs Medical Center (LBVA) STAMP program and from Rancho Los Amigos Medical Center Prosthetic Service.

Criteria for participation included independent community ambulation without use of an assistive device, and a history of compliance. All subjects consented to participate following explanation of the testing procedures and review of the informed consent form (approved by the LBVA Subcommittee for Human Studies). Following completion of the study, the subjects were able to choose one of the five feet tested to retain on a permanent basis.

Prosthetic Management

Five prosthetic feet were tested in random order for each subject: SACH,1 Carbon Copy II,2 Seattle Lite,3 Quantum,4 and Flex-Foot.5 To ensure the fitting of appropriate foot components and keel, each manufacturer was provided with each subject’s age, weight, height, contralateral shoe size, activity level, amputation level, and length of residual limb. The selection of the SACH foot heel wedge was based on the weight of the subject according to the guidelines of the developer. The appropriateness of each foot component/keel selection was then confirmed or modified at the time of prosthetic fitting.

The fit of each prosthesis was clinically optimized and reviewed by a team of three certified prosthetists. Alignment of the first foot followed established prosthetic principles. The Vertical Fabrication Jig6 was used for subsequent alignments when more than the interchange of a foot-bolt was required.

Instrumentation

Each subject was fitted with three precordial electrocardiograph electrodes to monitor heart rate, a compression closing switch taped to the bottom of one shoe to record stride frequency (converted to cadence), and a harness with a telemetry system (Figure 1). A nose clip was placed on the subject to prevent nasal breathing. The harness was equipped with a mouthpiece attached to a T-segment with two one-way valves which allowed inspiration of ambient air and expiration into the collection bags (modified Douglas bags). A multiported system allowed attachment of multiple collection bags. A thermistor placed in the T-segment detected difference in temperature between the ambient air and expired air, allowing recording of respiration rate.

A level, 60.5 m outdoor track was used for the walking trials. Each meter of the track was marked for monitoring the distance traveled.

Respiration rate, heart rate, and stride frequency were recorded via telemetry on a strip chart recorder.7 Gas analyzers were used to determine the carbon dioxide and oxygen content of the collected sample of expired air.8 The temperature of the sampled air was monitored by a thermistor placed in the sample flow line. The volume of the collected expired air was measured by evacuating the col-
Selection bag through a gas flow meter. A mercury barometer was used to determine the atmospheric pressure at the time of testing.

Procedures
Subjects were given an accommodation period of 1 month to adjust to each prosthetic foot. Testing with the five prosthetic feet occurred at approximately 1-month intervals over a 5-month period. The testing procedures were identical for each session.

Body weight was recorded prior to each trial. Energy expenditure at rest was recorded after the subject had been seated for 30 min and fully instrumented for 5 min. Following the rest period, a self-selected free walk was completed. The duration of the walk was a minimum of 5 min and a maximum of 20 min. After the minimum 5 min, the subjects were allowed to terminate the testing when they felt unable to walk any longer.

Individual gas samples, heart rate, and respiration rate were recorded during the last 2 min of the 5 min rest period and at minutes 4 to 5, 9 to 10, 14 to 15, and 19 to 20 during walking. Stride frequency was also recorded during the walking trial. Distance traveled during each collection period, and the total distance walked were monitored by one of the investigators. Barometric pressure at the time of testing was recorded for use in calculating gas volumes.

Data Management
To calculate energy expenditure at rest and during walking, carbon dioxide content, oxygen content, temperature, and volume of the collected samples of expired air were used. Oxygen consumption values were converted to standard temperature, pressure, dry (STPD). Body weight (kg) was used to convert the oxygen consumption to ml of O2 consumed per kg-min (rate of energy expenditure). For the walking data, body weight and velocity (m/min) were used to determine the ml of O2 consumed per kg-m (energy cost per unit distance).

Cadence was calculated as twice the stride frequency. Stride length was calculated from the cadence and distance walked per minute.

The carbon dioxide produced and the oxygen consumed, as measured from the gas analyses, were used to calculate the respiratory exchange quotient (RQ) at rest, and the respiratory exchange ratio (RER) during walking.

Data Analysis
The data from the last collection period of each walking trial were used for comparisons between groups and prosthetic feet. Statistical analyses were performed using BMDP statistical software. All data were analyzed for normality of distribution using the Shapiro and Wilk’s W-statistic. Differences between prosthetic feet and groups for each parameter measured were determined either by a two-way analysis of variance (ANOVA) with repeated measures, or a Friedman’s two-way ANOVA with repeated measures for those data not normally distributed. A 95 percent confidence level was used to determine statistical significance. A post-hoc Tukey test was used to find the significantly different comparisons.

RESULTS
Of the 17 subjects tested, 1 (a traumatic BKA) moved out of the area after completing four of the five sessions, and was therefore dropped from the analysis. Thus, the following data are from the remaining 16 subjects. The two groups were of similar age, height, and weight (Table 1).
As shown on Table 2, the heart rate (HR) during rest of the dysvascular group was significantly greater than that for the traumatic group (79 vs. 65 bpm; p<0.05). However, there was no significant difference in energy rate (oxygen consumption per min) at rest between groups or test days for all subjects. In addition, the RQ at rest did not vary between trials, days, or between the groups of amputees.

Eight of the nine traumatic amputees were able to complete the full 20-min test protocol. Only one of the dysvascular amputees was able to complete the 20-min trial. Failure to complete the 20-min walk was secondary to complaints of calf and/or anterior leg pain in the sound limb, or complaints of generalized fatigue. The traumatic group demonstrated a significantly greater average total walking time than the dysvascular group (18.8 vs. 10.3 min) as well as a significant increase (1.5 vs. 0.65 km) in distance traveled (Table 3).

During the walking trials, there was no statistical difference in velocity of ambulation between the five feet tested. However, the velocity of the traumatic group was significantly greater (82.3 vs. 61.7 m/min; p<0.01) than that of the dysvascular group when averaged across all foot conditions (Figure 2). Stride length did not vary with foot type, however, the traumatic group had a greater stride length (1.48 vs. 1.22 m; p<0.01) compared to the dysvascular group (Figure 3). Cadence was not significantly altered by the type of foot worn, nor by the etiology of the BKA. A trend toward decreased cadence in the dysvascular group was exhibited (100 vs. 110 steps/min) compared to the traumatic group (Figure 4).

During the last minute of the walking trials, the traumatic group had a lower heart rate than the dysvascular group; however, this was not statistically significant (113 vs. 116 beats/min), and respiratory rate (24 vs. 29 breaths/min) showed a similar response (Table 4). Heart rate and respiratory rate did not vary with the type of foot worn.

Among the prosthetic feet used, no significant changes in the rate of energy consumption were identified; however, the traumatic group had an energy rate (17.7 vs. 13.2 ml O2/kg-min; p<0.01) that was statistically greater than the dysvascular group when averaged across all conditions (Figure 5, Table 5). The net energy cost (oxygen consumption per distance traveled) was not statistically different between the types of feet tested or between the groups of amputees (Figure 6, Table 6).

The walking data revealed a slightly higher, but not statistically significant, RER for the dysvascular group compared to the traumatic group (0.91 vs. 0.86), and the oxygen pulse (oxygen rate to heart rate ratio) was significantly greater (0.16 vs. 0.11 ml/kg-beat; p<0.01) in the traumatic group compared to the dysvascular group (Table 4). Foot type did not affect RER or the oxygen pulse ratio for either group.

### DISCUSSION

The altered mechanics of BKA gait has been well documented in the literature (4,8,12,13). To regain lost walking capability, the amputee exerts additional effort which is reflected in the increased oxygen consumption per meter traveled during gait (Figure 6, Table 6). Waters (11) reported this increased energy consumption to be 167 and 129 percent of normal for dysvascular and traumatic BKAs respectively. Comparable values were found in the current study. These increases reflect the demands on the remaining musculature. The lack of normal ankle mobility in loading response and single limb support necessitates compensatory gait patterns and muscle activity to provide stability and advancement over the foot (14). In the amputated limb, the large muscles controlling the hip and knee demonstrate more intense and prolonged elec-
Table 3.
Stride characteristics during energy cost testing, averaged for all feet tested*: mean (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traumatic</th>
<th>Dysvascular</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>1.5 (0.43)</td>
<td>0.65 (0.41)</td>
<td>0.0009**</td>
</tr>
<tr>
<td>Time (min)</td>
<td>18.8 (3.3)</td>
<td>10.3 (5.8)</td>
<td>0.0015**</td>
</tr>
<tr>
<td>Velocity (m/min)</td>
<td>82.3 (16.9)</td>
<td>61.7 (8.7)</td>
<td>0.0065**</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.49 (0.20)</td>
<td>1.22 (0.14)</td>
<td>0.0068**</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>110.3 (12.1)</td>
<td>100.8 (6.7)</td>
<td>0.0545</td>
</tr>
</tbody>
</table>

* No significant differences were found between feet for these variables.
** Traumatic group significantly greater than the dysvascular group (p<0.50).

Figure 2.
Walking velocity (m/min) for both dysvascular and traumatic amputees for each foot tested. Flex=Flex-Foot, CCII=Carbon Copy II, Seat=Seattle Lite, Quan=Quantum. Normal data from (14).

Figure 3.
Stride length (m) for both dysvascular and traumatic amputees for each foot tested. Flex=Flex-Foot, CCII=Carbon Copy II, Seat=Seattle Lite, Quan=Quantum. Normal data from (14).

tromyographic activity compared to those of persons without amputation and is consistent with the increased energy cost (4).

The recent designs of the DER prosthetic feet have focused on providing increased ankle mobility and reported energy return via a flexible internal keel to improve “push-off” mechanics. In addition to previous kinematic analyses that have found increased dorsiflexion mobility with the DER prosthetic feet compared to the SACH foot (4,15), indirect power calculations have implied energy conservation by these new prosthetic designs (8). The results of this study of direct energetics demonstrate that the energy cost and the rate of oxygen consumption were not influenced by prosthetic foot design, regardless of the etiology of amputation. This finding is in agreement with the work of Barth, Shumacher, and Sienko-Thomas (7) who also found no energy cost differences between six prosthetic feet in a much smaller population (N=6).

Given the small differences found in the current investigation for both energy cost and rate of energy expenditure between the five feet, combined with a relatively modest population (N=17), the statistical power of this analysis was quite low (0.13). Sample size determination found, however, that it would take approximately 70 subjects to show a statistical difference between prosthetic feet. This finding implies that the small difference detected in such an analysis would probably not be considered clinically significant.
Previously reported data have indicated that BKAs have a slower gait velocity, decreased stride length, and decreased cadence compared to persons without amputations (4,6—8,11—13). Compared to the earlier data of Waters (11), both amputee groups in this study walked at greater unrestrained velocities (dysvascular: 64 vs. 45 m/min; traumatic: 82 vs. 71 m/min). Velocity for the traumatic group was close to the value of 86 m/min established by Perry (14) for male subjects without amputation. Foot type had no influence on velocity in either group.

The dysvascular amputees’ slower velocity related to their less than normal stride length, as cadence, was not significantly different between groups (Figures 3 and 4). Since stride length was not affected by foot design, the shorter stride length in the dysvascular group suggests decreased strength compared to the traumatic amputees.

While the values for energy cost per meter traveled were similar between groups (Figure 6, Table 6), the near normal stride characteristics of the traumatic group were achieved at a greater rate of energy expenditure compared to their dysvascular counterparts (Figure 5, Table 5). This high rate of energy expenditure combined with a normal velocity, resulted in an energy cost (0.217 vs. 0.214 ml O₂/kg-min) similar to the more slowly ambulating dysvascular amputees (Figure 6, Table 6).

In contrast, Barth, Shumacher, and Sienko-Thomas (7) reported a significant difference in energy cost between their traumatic and dysvascular groups. While the energy cost values for the traumatic group in this study were similar to that of our data, their energy cost data for their dysvascular amputees were considerably less (0.214 vs. 0.130 ml O₂/kg-m). This was a function of the decreased velocity which was more pronounced in their dysvascular group. On the average, the dysvascular amputees in our study had a greater walking velocity compared to these previous results using a treadmill (45.0 vs. 61.7 m/min). This would account for the variability in energy cost results, as walking velocity has been shown to increase the rate and magnitude of loading, thus requiring increased muscular demand during loading response (16).

The increase in the rate of energy expenditure by the traumatic BKAs represents their capacity to walk faster, and reflects a higher level of physiological fitness. Despite the similar net energy cost between the two groups, the traumatic BKAs were able to cover a larger distance at a greater velocity, while the dysvascular amputees required more time to cover a comparable distance.

After 20 min of ambulation, the traumatic BKA subjects had a 147 percent greater rate of energy expenditure than normal (Figure 5). Compared to the traumatic amputee data of Pagliarulo (13), there was an increased rate of oxygen consumption in our traumatic group (17.7 vs. 15.5 ml O₂/kg-min). This is reflective of the relatively faster walking velocities that were evident in the current investigation (82.3 vs. 71.0 m/min). As expected, the mean net energy cost values for the traumatic amputees between these two studies was similar (0.217 vs. 0.218 ml O₂/kg-m).

The dysvascular group maintained a nearly normal energy rate (112 percent of normal) by walking at a slower velocity (83 percent of normal). This decrease in velocity in combination with a normal energy rate, however, resulted in a relatively high energy expenditure per meter traveled (136 percent of normal). The rate of energy expenditure for the dysvascular group also was higher than the rate previously reported by Waters (11) for this population (13.7 vs. 11.7 ml O₂/kg-min). As with the traumatic group, the difference between these values was a function of the increased walking velocity exhibited in this investigation (61.7 vs. 45.0 m/min).

The poor endurance of the dysvascular group was demonstrated by their inability to complete 20 minutes of walking, even at an energy expenditure rate only 12 percent greater than normal. Respiratory exchange ratios of 0.91 indicate the dysvascular subjects were working at anaerobic levels and support the subjective complaints of fatigue (17). Pain reported in the sound limb suggests systemic vascular compromise in these subjects. The similar, but slightly lower RER (0.86) of the traumatic group in-
Table 4.
Energy cost parameters collected during last minute of walking averaged across all feet tested*: mean (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traumatic</th>
<th>Dysvascular</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (beats/min)</td>
<td>113.7 (19.1)</td>
<td>116.4 (17.8)</td>
<td>0.749</td>
</tr>
<tr>
<td>Respiratory rate (breaths/min)</td>
<td>23.8 (6.8)</td>
<td>29.1 (7.7)</td>
<td>0.137</td>
</tr>
<tr>
<td>Oxygen pulse (ml/kg-beat)</td>
<td>0.16 (0.03)</td>
<td>0.11 (0.02)</td>
<td>0.002**</td>
</tr>
<tr>
<td>Respiratory Exchange Ratio (RER)</td>
<td>0.86 (0.06)</td>
<td>0.91 (0.07)</td>
<td>0.086</td>
</tr>
</tbody>
</table>

*No significant differences were found between prosthetic foot type for these variables.
**Traumatic group significantly greater than the dysvascular group (p<0.01).

Table 5.
Energy consumption rate (ml O2/kg-min): Mean (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traumatic</th>
<th>Dysvascular</th>
</tr>
</thead>
<tbody>
<tr>
<td>SACH</td>
<td>18.48 (3.0)</td>
<td>13.41 (2.8)</td>
</tr>
<tr>
<td>Flex</td>
<td>18.04 (3.6)</td>
<td>13.61 (1.7)</td>
</tr>
<tr>
<td>Carbon Copy II</td>
<td>17.18 (3.6)</td>
<td>13.66 (2.7)</td>
</tr>
<tr>
<td>Seattle</td>
<td>17.08 (2.7)</td>
<td>13.10 (2.2)</td>
</tr>
<tr>
<td>Quantum</td>
<td>17.79 (3.5)</td>
<td>12.41 (2.3)</td>
</tr>
<tr>
<td>Average*</td>
<td>17.72**</td>
<td>13.23</td>
</tr>
</tbody>
</table>

*Averaged across all feet tested.
**Traumatic > Dysvascular (p<0.01).

Figure 5.
Energy consumption rate (ml of oxygen per kg-min) for both dysvascular and traumatic amputees for each foot tested. Flex=Flex-Foot, CCII=Carbon Copy II, Seat=Seattle Lite, Quan=Quantum. Normal data from (11).

TRAAUTICIC DYSVASCULAR

ml O2/kg-min
20
15
10
5
0
SACH FLEX CCII SEAT QUAN

The DER feet were designed for the more vigorous amputees to facilitate running. Their emphasis was improved forward progression through greater ankle dorsiflexion. It was assumed that improved progression and push-off conserved energy. The findings of this study and others, imply that progression over the prosthesis and the initiation of swing limb advancement are not the prime causes of energy cost. Rather, peak energy cost mechanics occur elsewhere in the gait cycle.

Endurance for walking at self-selected comfortable speeds was not improved with use of DER feet compared to the SACH foot. While the DER feet are reported to assist with energy return to the amputee to help reduce the physical demand of walking, neither group demonstrated changes in energy expenditure as a result of varying the type of prosthetic foot.
Figure 6. Energy cost per distance traveled (ml of oxygen per kg-m) for both dysvascular and traumatic amputees for each foot tested. Flex=Flex-Foot, CCII=Carbon Copy II, Seat=Seattle Lite, Quan=Quantum.

Table 6. Energy cost per distance traveled (ml O2/kg-m): Mean (SD).

<table>
<thead>
<tr>
<th></th>
<th>Traumatic</th>
<th>Dysvascular</th>
</tr>
</thead>
<tbody>
<tr>
<td>SACH</td>
<td>0.227 (0.03)</td>
<td>0.223 (0.04)</td>
</tr>
<tr>
<td>Flex</td>
<td>0.219 (0.02)</td>
<td>0.215 (0.03)</td>
</tr>
<tr>
<td>Carbon Copy II</td>
<td>0.207 (0.03)</td>
<td>0.221 (0.02)</td>
</tr>
<tr>
<td>Seattle</td>
<td>0.215 (0.04)</td>
<td>0.211 (0.04)</td>
</tr>
<tr>
<td>Quantum</td>
<td>0.220 (0.03)</td>
<td>0.206 (0.03)</td>
</tr>
<tr>
<td>Average*</td>
<td>0.217</td>
<td>0.214</td>
</tr>
</tbody>
</table>

*Averaged across all feet tested.

CONCLUSION

The DER prosthetic foot designs were not shown to reduce the physiologic demand of walking compared to the SACH foot. This was true for both the dysvascular group, for whom walking has been demonstrated to be a nearly anaerobic activity, and the traumatic amputees, who were working at a higher rate of energy expenditure. These data imply that the maximum muscular effort occurs at a time in the gait cycle which is not influenced by the DER foot mechanics. Future studies may incorporate a higher demand activity (other than free walking) to determine if energy conservation would be more evident.

ENDNOTES

2. The Ohio Willow Wood Co., Mount Sterling, OH.
3. Model and Instrument Development, Seattle, WA.
4. Hosmer-Dorrance Corp., Campbell, CA.
5. Flex-Foot Inc., Laguna Hills, CA.
6. Hosmer-Dorrance Corp., Campbell, CA.
7. Model 302, Astro-med, West Warwick, RI.
10. BMDP Statistical Software Inc., Los Angeles, CA.

REFERENCES