Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol 32 No. 4, November 1995
Pages 309–315

# The effect of five prosthetic feet on the gait and loading of the sound limb in dysvascular below-knee amputees

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**Abstract**—The purpose of this study was to determine the effects of prosthetic foot design on the vertical ground reaction forces experienced by the sound and amputated limbs in a group of persons with dysvascular below-knee amputations. Stride characteristics, joint motion, and ground reaction forces were recorded simultaneously during a self-selected free walking velocity in seven subjects wearing five different prosthetic feet (SACH, Flex-Foot, Carbon Copy II, Seattle, Quantum). Subjects used each foot for one month prior to testing. Results indicated that the sound limb was exposed to higher vertical ground reaction forces than normal despite a reduced walking velocity. Use of the Flex-Foot resulted in the lowest sound limb vertical forces, which appears to be related to its large arc of dorsiflexion motion. In addition, there was increased loading response knee flexion of the sound limb indicating an attempt by these subjects to modulate floor impact. These results suggest that the intact lower extremity is susceptible to excessive floor impact, and that prosthetic foot design can have an effect on the magnitude of the vertical forces experienced by the limb.

**Key words:** *amputees, gait, ground reaction force, kinematics, prosthetics.*

## INTRODUCTION

Peripheral vascular disease has become the leading cause of lower limb amputation since World War II (1). With improvement in medical and surgical care of diabetic amputees, the number of persons with below-knee (BK) amputation in relation to persons with above-knee (AK) amputation has significantly increased (2). Successful preservation of the knee joint in these patients has lead to improved function through a more normal gait pattern and decreased energy consumption (3). Despite this improved ability, persons with dysvascular BK amputation have up to a 33 percent chance of having their contralateral limb amputated within 5 years (4).

The effects of BK amputee gait on the contralateral limb have been previously discussed. Two reports have demonstrated that persons with BK amputation are susceptible to developing osteoarthritis in the contralateral limb with prosthetic use of at least 5 years (5,6). Although both reports concluded that degenerative changes may be due to increased joint loading, these clinical findings conflicted with gait studies by Hurley et al. (7), and Lewallen et al. (8), who demonstrated that persons with BK amputation decreased their contralateral limb loading by walking at a slower gait velocity. This suggests that persons with dysvascular amputation may employ a strategy of decreasing gait speed to protect their sound limbs from excessive forces.

Long-term prosthetic use may be a predisposing factor to early degenerative joint changes, but a greater implication for patients with vascular disease is whether increased sound limb loading can be a precursor to early amputation. Although it has been documented that persons with amputation experience greater peak ground reaction forces, and spend a greater proportion of their

**This material is based upon work supported by the Rehabilitation Research and Development Programs, Department of Veterans Affairs, Washington, DC.**

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gait cycle on their sound limb, Pinzur et al. (9) found no increases in plantar pressures in the sound foot of a group of persons with dysvascular amputation which would explain complications of the contralateral limb. Whether repetitive loading forces across the sound limb results in cumulative microtrauma remains unclear.

Among a group of persons with traumatic BK amputation, Powers et al. (10) demonstrated that prosthetic foot design had a significant influence on sound limb loading. These authors postulated that in persons with BK amputation whose gait velocities approached normal values, the design of the prosthetic foot had a significant effect on the vertical excursion of the center of gravity; thus, potentially affecting the amount of loading force imparted to the sound limb during loading. While this finding was evident in the vigorous person with traumatic BK amputation, the effects of prosthetic foot design on the loading characteristics of the more fragile person with dysvascular amputation has yet to be discerned.

The purpose of this study was to study the loading patterns of a group of persons with dysvascular amputation while they were wearing five different prosthetic feet. This information may have significant implications for this population, since it has been hypothesized that asymmetric loading may contribute to the development of contralateral limb problems.

## METHODS

### Subjects

Seven males with diabetic BK amputation resulting from vascular insufficiency participated in this study. Their mean age was 62.1 years, ranging from 45 to 70 years of age (**Table 1**). Subjects were recruited from the Long Beach VA Medical Center (VAMC) STAMP program. All participants were community ambulators and none used assistive devices. At the time of testing, each subject demonstrated residual limb volume stability of at least 6-months duration. All subjects were free from complications associated with residual limb breakdown or resting limb pain. Following the completion of the study, each subject was able to choose one of the prosthetic feet for permanent use. Prior to participation, informed consent was obtained from all subjects.

### Foot Selection

Five prosthetic feet were tested in random order: Flex-Foot[1], Carbon Copy II[2], Seattle Lite-foot[3], Quantum[4], and SACH[5]. Each manufacturer was provided with the age, weight, height, contralateral shoe size, activity level, amputation level, and residual limb length of each subject to ensure proper fitting of the prosthesis. The manufacturers' guidelines for appropriateness of each foot component was verified and, if necessary, modified. The fit of each foot was reviewed and clinically optimized by a team of three certified prosthetists from the Long Beach VAMC. The Vertical Fabrication Jig[4] was utilized to reproduce precise alignments when more than one interchange of a foot-bolt was required.

**Table 1**
Subject characteristics.

| Subject # | Age (yrs) | Height (cm) | Weight (kg) |
|---|---|---|---|
| 1 | 68 | 188 | 87 |
| 2 | 45 | 188 | 78 |
| 3 | 63 | 152 | 60 |
| 4 | 60 | 183 | 101 |
| 5 | 70 | 180 | 84 |
| 6 | 64 | 183 | 84 |
| 7 | 65 | 175 | 90 |
| Mean | 62.1 | 178.4 | 83.4 |

### Procedures

After each prosthetic fitting, subjects were given an accommodation period of one month. After this adjustment time, the prosthesis and foot alignment were rechecked and the subjects were sent to the Rancho Los Amigos Pathokinesiology Laboratory for instrumented gait analysis. Each subject was tested once a month for a total period of 5 months. The testing procedure was identical during each session.

Compression closing footswitches (Stride Analyzer System)[6] were taped to the shoe soles of each subject and were used to calculate stride characteristics and foot-floor contact patterns. Motion analysis was performed using a six camera VICON motion system[7]. Reflective markers placed at specific anatomic positions were used to identify the sagittal plane motion of the pelvis, thigh, knee, and ankle. The markers placed on the prosthesis were estimated from the sound side. Motion data were collected at 50 Hz.

Vertical ground reaction force was measured by a Kistler force plate[8] concealed in the middle of the walkway. The force plate position was not revealed to the patient in order to prevent targeting.

Gait analysis was performed during a self-selected free walking speed while walking along a 10-meter walkway with the middle 6 meters used for data collection. A successful trial was completed when the foot of interest landed fully on the force plate. Repeated trials were necessary to obtain data on both the amputated and sound limbs. Two trials of data were collected for each side. All gait data were collected simultaneously.

### Data Management

All motion data were normalized to a 62 percent stance phase in order to average data from multiple strides and different subjects. Motion data were then analyzed to identify the maximum and minimum degree of motion in each phase of gait and the point (percentage of the gait cycle) at which it occurred. Foot switch data were used to determine the phases of gait and to calculate the stride characteristics of each subject.

Vertical ground reaction forces were analyzed to determine the magnitude and timing of the first peak, valley, and second peak. To facilitate comparison, all forces were reported as a percentage of body weight.

### Data Analysis

Statistical analyses were performed using BMDP statistical software[9]. All data were analyzed for normality using the Shapiro and Wilk's W statistic. Differences between the five prosthetic feet were determined by repeated measures analysis of variance (ANOVA). A post hoc Tukey test was used to delineate the significantly different comparisons. Significance level was set at $p<0.05$.

## RESULTS

### Stride Characteristics

Significant differences were found in both velocity and stride length (**Table 2**). For free walking velocity, the only significant difference was found with the Flex-Foot, which was statistically greater than that of the SACH foot (71.6 vs. 63.3 m/min; $p<0.05$). The stride length, while using the Flex-Foot, was significantly greater than that of the SACH, Carbon Copy II, and Seattle Lite-foot (1.35 vs. 1.25, 1.27, and 1.26 m respectively; $p<0.05$). There was no statistical difference between the subjects' cadence using any of the five feet.

**Table 2**
Free walking stride characteristics.

| Foot Type | Mean (standard deviation) Velocity (m/min) | Stride length (m) | Cadence (step/min) |
|---|---|---|---|
| SACH | 63.3 (10.0) | 1.25 (0.16) | 101.4 (7.9) |
| Flex-Foot | 71.6 (12.6)* | 1.35 (0.19)** | 106.0 (6.5) |
| Carbon Copy II | 65.0 (13.0) | 1.27 (0.17) | 101.7 (11.3) |
| Seattle-Lite | 65.0 (8.0) | 1.25 (0.13) | 103.1 (5.6) |
| Quantum | 67.7 (11.3) | 1.28 (0.15) | 105.1 (7.8) |
| Normal[11] | 81.6 (9.4) | 1.51 (0.14) | 108.2 (9.1) |

*Flex > SACH ($p<0.05$)
**Flex > SACH, Carbon Copy II, Seattle ($p<0.05$)

### Joint Motion

During free walking, significant joint motion differences were noted for terminal stance ankle dorsiflexion on the prosthetic side (**Figure 1**). The Flex-Foot and the Quantum achieved significantly greater terminal stance dorsiflexion than the Seattle, Carbon Copy II, and the SACH (22 and 23° vs. 16, 17, and 14° respectively; $p<0.01$) (**Table 3**). No other significant motion differences were found regarding the amputated limb.

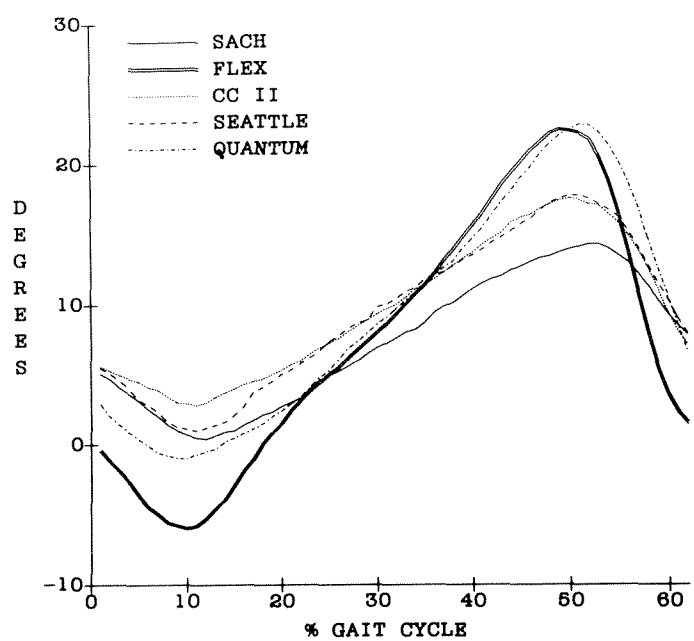


**Figure 1.**
Prosthetic ankle motion during the stance phase of free walking. Positive values indicate dorsifexion; negative values indicate plantarflexion. CC II=Carbon Copy II.

**Table 3**
Maximum terminal stance ankle dorsiflexion* amputated limb.

| Foot Type | Degrees |
|---|---|
| SACH | 14.3 (3.8) |
| Flex-Foot | 21.8 (3.6) |
| Carbon Copy II | 17.2 (2.0) |
| Seattle-Lite | 16.1 (3.2) |
| Quantum | 22.5 (2.2) |

*Flex, Quantum > Carbon Copy II, Seattle, SACH ($p<0.05$)

Sound limb knee flexion during loading response varied between feet; however, there were no statistically significant differences ($p>0.05$) as shown in **Figure 2**. **Table 4** indicates that the Quantum foot had the greatest average loading response knee flexion on the sound side (22.8°), while the Carbon Copy II had the lowest average amount of sound limb knee flexion (15.8°). No other significant motion differences were found for the sound limb.

### Force Plate Data

The initial peaks of the vertical ground reaction force of both the amputated and sound limbs showed a significant difference between feet (**Table 5**). On the amputated side, the Flex-Foot created a greater initial peak than the Carbon Copy II, Seattle Lite-Foot, and the Quantum (118.9 vs. 106.1, 106.7, and 104.9 percent body weight respectively) as shown in **Figure 3**. The vertical ground reaction forces on the sound limb exhibited a statistically significant lower initial peak of the vertical ground reaction force with the Flex-Foot compared to the Quantum (110.9 vs. 131.6 percent body weight; $p<0.05$) as shown in **Figure 4**. No other differences in the vertical ground reaction force curve were found.

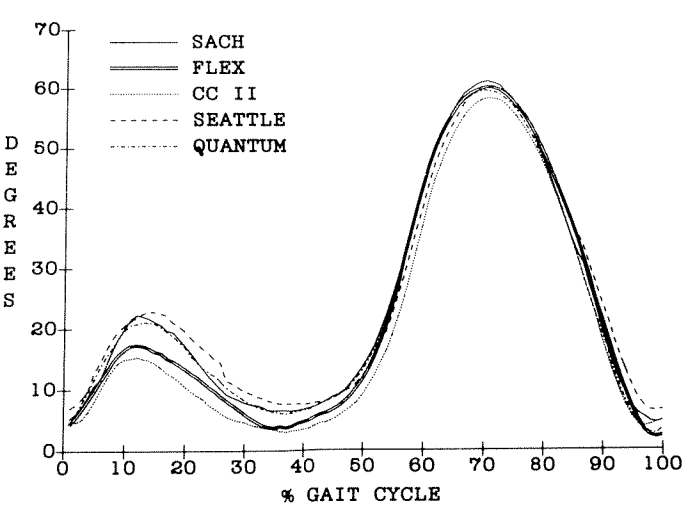


**Figure 2.**
Knee motion of the sound limb during free walking. Positive values indicate flexion. CC II=Carbon Copy II.

**Table 4**
Maximum loading response knee flexion sound limb.

| Foot Type | Degrees |
|---|---|
| SACH | 21.8 (2.6) |
| Flex-Foot | 17.7 (7.5) |
| Carbon Copy II | 15.8 (4.4) |
| Seattle-Lite | 20.9 (4.1) |
| Quantum | 22.8 (6.7) |
| Normal[12] | 15.0 |

## DISCUSSION

The results of this study indicate that the sound limb in this group of amputees was susceptible to increased vertical forces during loading (**Table 5**). This is in agreement with studies by Powers et al. (10) and Ensberg et al. (14) who found the sound limb carried more of a load than the amputated limb in persons with BK amputation. On the average, the sound limb accepted 11 percent more of body weight when averaged across all feet. Increased sound limb loading was seen for all prosthetic feet except the Flex-Foot which exhibited a relatively normal load. Compared to the normative data of Chao et al. (13), who found the

**Table 5**
Peak vertical ground reaction force at initial loading: sound limb and amputated limbs.

| | Mean (standard deviation) | |
|---|---|---|
| Foot Type | Sound limb Vertical force (%bwt) | Amputated limb Vertical force (%bwt) |
| SACH | 124.3 (11.3) | 109.7 (8.9) |
| Flex-Foot | 110.9 (25.0)* | 118.9 (9.6)** |
| Carbon Copy II | 116.3 (10.2) | 106.1 (11.1) |
| Seattle-Lite | 123.2 (14.1) | 106.7 (10.0) |
| Quantum | 131.6 (18.0) | 104.9 (4.9) |
| Normal[13] | 111.0 | 111.0 |

*Flex < Quantum ($p<0.05$)
**Flex > Carbon Copy II, Seattle, Quantum
%bwt = percentage of body weight

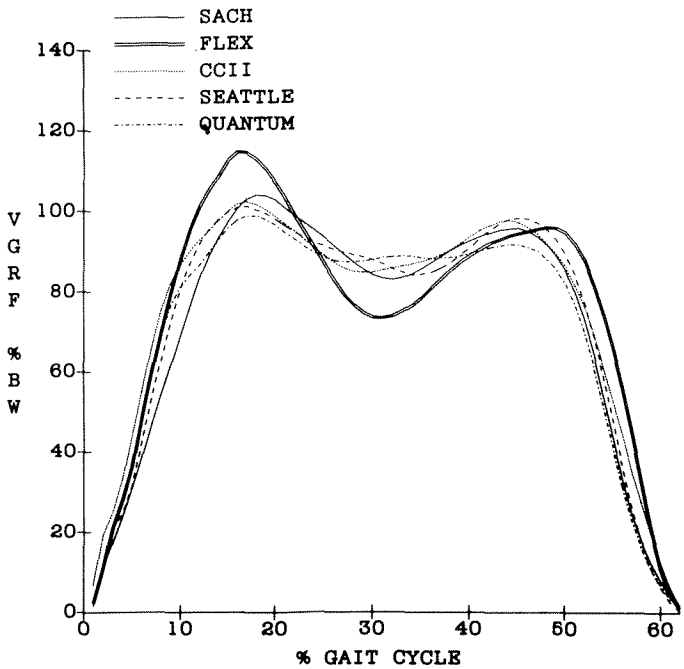


**Figure 3.**
Vertical ground reaction force (VGRF) of the amputated limb reported as a percentage of bodyweight (percent BW) during the stance phase of free walking. CC II=Carbon Copy II.

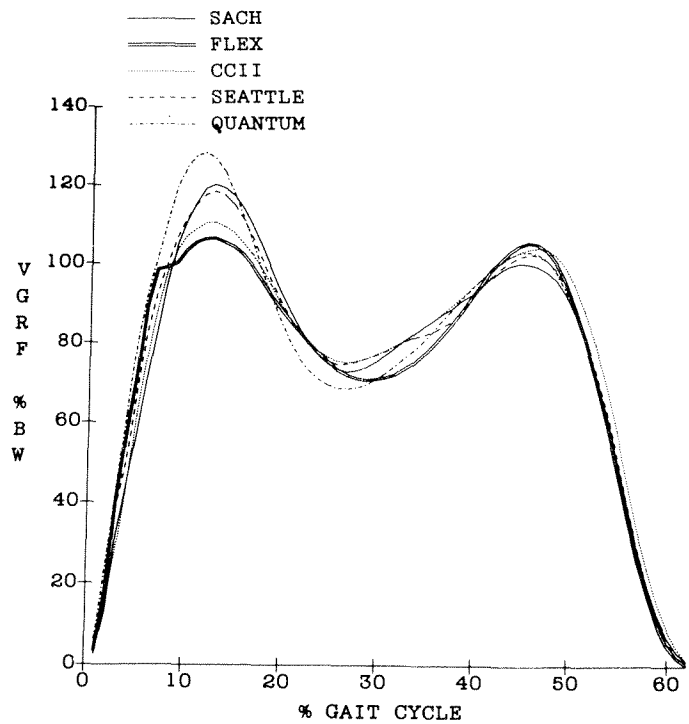


**Figure 4.**
Vertical ground reaction force (VGRF) of the sound limb reported as a percentage of bodyweight (percent BW) during the stance phase of free walking. CC II=Carbon Copy II.

initial peak of the vertical force to average 111 percent body weight in nondisabled individuals, the vertical forces on the sound limb were excessive, while the amputated limb forces were near normal **(Table 5).**

Hurley et al., (7) and Lewallan et al., (8) found that the forces across the sound limb were near normal, and hypothesized that the slower walking velocity was responsible. This explanation appears plausible as loading rate and vertical ground reaction force has been found to be linearly related to walking velocity (15). On the average, the walking velocity of our group of persons with amputation was reduced to about 80 percent of normal. Given such, it is surprising that the sound limb still experienced significant increases in vertical loading forces. A significant increase in walking velocity was evident in the Flex-Foot compared to the SACH foot; however, the sound limb loading with the Flex-Foot was significantly less than the SACH foot. This contradicts the notion that sound limb loading can be reduced by adopting a slower gait velocity, and supports the concept of prosthetic foot design influencing loading of the sound limb.

Reduced sound limb loading with the Flex-Foot was also found by Powers et al. (10) and Wagner et al. (16) who studied two populations of persons with BK amputation. Powers and colleagues (10) concluded that prosthetic foot design played a significant role in contributing to sound limb loading by virtue of the dorsiflexion range of motion. It was theorized that the increase in terminal stance dorsiflexion evident with the Flex-Foot design, compared to the four other feet tested, reduced the need to use a heel rise for tibial progression, and thus minimized the elevation of the body center of gravity. This mechanism apparently reduced the sound limb loading with the Flex-Foot. The subjects in this study (10 persons with traumatic BK amputation), ambulated at near normal speeds.

The results of the present study found a significantly greater amount of terminal stance dorsiflexion with the Quantum and Flex-Foot designs compared to the Seattle-lite, Carbon Copy II, and the SACH feet **(Table 3)**. Although the dorsiflexion motion between the Quantum and Flex-Foot designs were similar, the sound limb loading characteristics between the two feet were markedly different. Use of the Quantum foot resulted in the greatest amount of sound limb loading (131.6 percent body weight) compared to all other feet, while the Flex-Foot was the lowest (110.9 percent body

weight). This difference could not be explained by walking speed, as the velocity with Flex-Foot was greater than that of the Quantum (71.6 vs. 67.7 m/min), although not statistically significant. According to the theory put forth by Powers et al. (10), both feet should demonstrate relatively similar sound limb loading patterns as a result of similar dorsiflexion range.

One explanation for this phenomenon may be related to possible motion analysis error giving the impression of "apparent" dorsiflexion motion. The Quantum foot with its interchangeable outer shell and independent forefoot keel may promote a much more lively metatarsal break compared to the Flex-Foot (17). If the motion analysis markers at the forefoot were placed anterior to this metatarsal break, motion in the area of the metatarsal-phalangeal joints would have resulted in apparent ankle dorsiflexion, as the entire foot was modeled as a single segment. Visual inspection of the Quantum foot keel revealed that the forefoot break is much shorter than other prosthetic feet and not anatomically matched with the location of the sound limb metatarsal-phalangeal joints. Since motion markers on the amputated limb were estimated from the sound limb, it is likely that our forefoot markers were anterior to the metatarsal break.

If true dorsiflexion was occurring with the Quantum foot, then one might expect to see an increase in stride length similar to that of the Flex-Foot. The Flex-Foot is constructed as one long carbon-fiber composite keel with the assembly attached to the socket (17). This design improves the ankle rocker mechanism allowing the advancing sound limb to progress further forward before initial contact. The fact that the Flex-Foot had a greater stride length is indicative of greater tibial advancement as a result of increased dorsiflexion. The relative decrease in stride length with the Quantum foot suggests a lack of tibial progression and supports the premise that the amount of "true" ankle dorsiflexion was over estimated as a result of marker placement.

The primary shock absorbing mechanism during loading response is knee flexion. Perry (18) reports that the quadriceps function eccentrically during this phase of the gait cycle to restrain but not totally prevent knee flexion, which assists in reducing the force of floor impact. The amount of loading response knee flexion for normal speed walking (82 m/min) is reported to be 15° (18) and has been found to vary linearly with walking velocity, that is, increasing flexion with greater velocity (19). Despite a walking velocity of approximately 80 percent of normal, the average amount of knee flexion in this subject population was 20° when averaged across all feet. This excessive amount of loading response knee flexion suggests a compensatory mechanism by which the increased sound limb loading forces can be minimized. The penalty of such a compensation is an increased demand and muscular effort at the knee (18), which is consistent with the increased energy cost of ambulation associated with this population (3).

Although there were no significant differences in loading response knee flexion between feet, there was a trend toward greater flexion with the prosthetic foot components that resulted in the greater amounts of vertical forces during loading of the sound limb. The Quantum, SACH, and Seattle feet had the greatest sound limb vertical forces (131.5, 124.3, and 123.2 percent body weight, respectively) and the greatest amount of loading response knee flexion (22.9, 21.9, and 20.9°, respectively) as shown in **Tables 3** and **4**. The Flex-Foot and the Carbon Copy II feet demonstrated the lowest magnitudes for vertical forces during sound limb loading which resulted in somewhat lower knee flexion values (15.8 and 17.7°, respectively). This trend suggests that persons with dysvascular amputation may be sensitive to the impact of the sound limb, and can accommodate these increased forces through varying the degree of knee flexion. This was evident based on the varying results with the different types of prosthetic feet worn.

Although the sample size of this study was relatively small, these results suggest that a prosthetic foot design that allows for adequate mobility at the ankle, may provide a smoother transfer of body weight to the sound limb during gait. This has significant implications as the forces and muscular demands of the sound limb may be significantly increased, thus contributing to an asymmetrical gait pattern and increased energy expenditure.

## CONCLUSION

The results of this study indicate that the person with dysvascular amputation experiences greater sound limb forces than with the amputated limb despite a reduced walking velocity. The Flex-Foot, however, appears to protect the sound limb against excessive vertical forces by virtue of its flexible long keel and large arc of dorsiflexion motion. In addition, persons with dysvascular amputation attempt to modulate the

sound limb forces by increasing the amount of shock absorption through loading response knee flexion. Further research is needed to determine the effects of excessive limb loading in contributing to further vascular pathology and its relationship with premature amputation of the sound limb.

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## END NOTES

### *Suppliers*

1. Flex-Foot Incorporated, 27071 Cabot Road, #106, Laguna Hills, CA 92653.
2. The Ohio Willow Wood Company, P.O. Box 192, Mount Sterling, OH 43143.
3. Model and Instrument Development, 861 Poplar Place, Seattle, WA 98144.
4. Hosmer-Dorrance Corporation, 561 Division St, Campbell, CA 95008.
5. Kingsley Manufacturing Company, P.O. Box CSN 5010, Costa Mesa, CA 92928.
6. B & L Engineering, 8807 Pioneer Boulevard, Unit C, Santa Fe Springs, CA 90670.
7. Oxford Metrics Ltd, Unit 14, 7 West Way Botley, Oxford Ox20JB.
8. Kistler Instruments Corporation, 2475 Grand Island Boulevard, Grand Island, NY 14072.
9. BMDP Statistical Software Incorporated, 1440 Sepulveda Boulevard, Suite 316, Los Angeles, CA 90025.