CLINICAL REPORT

Efficiency of Dynamic Elastic Response Prosthetic Feet

Jacquelin Perry, MD and Stewart Shanfield, MD, Rancho Los Amigos Medical Center, Downey, CA 90242; VA Medical Center, Long Beach, CA 90822

INTRODUCTION

Following years of accepting the Solid Ankle Cushion Heel (SACH) foot as the optimum compromise between durability and functional effectiveness, as well as being of reasonable cost, several new feet with dynamic elastic response qualities have been designed. The stimulus for these new designs is the recent development of materials which offer the potential to “store and release energy” in a manner that facilitates walking and running. Numerous new prosthetic feet have become available commercially. The effectiveness of these designs is not known, though each has its strong clinical advocates (1,2,3,4). It is claimed that these feet reduce the energy required for walking, and increase mobility. Four dynamic elastic response (DER) feet representative of this design were selected for study. The objectives of this project were to compare the efficiency of four DER prosthetic foot designs (Seattle, Flex-Foot, Carbon Copy II, Sten) to that of the traditional SACH foot; define the gait mechanics induced by each foot; and determine the relative effectiveness and cost/benefit ratio of these new feet for the dysvascular and traumatic amputee populations.

BACKGROUND

The principles of quantitated gait analysis and modern prosthetics were established by the Biomechanics Laboratory at the University of California at Berkeley. Following the fundamental studies of gait (6,7,8) attention was directed to improving prosthetic design. Pertinent to this proposal was their development of the patellar-tendon-bearing below-knee (BK) prosthesis and the SACH foot (9,10,11). By its structural durability and biomechanical soundness, the SACH foot readily replaced the earlier single-axis wood foot and has outperformed other designs until the present (12).

Limitations in SACH foot performance, however, are being documented. A survey of 179 veteran amputees (69 percent with BK amputation) identified excessive foot stiffness as a frequent problem: examination of 54 BK prosthetic feet substantiated this defect in 67 percent of those surveyed. Fatigue and heaviness of the prostheses were other common complaints. The size of the modern commercial foot heel cushion was about half of that originally designed (13). A static load response study indicated all of the SACH heel cushions were too hard (14).

Today, the SACH foot design is being challenged by new materials which provide controlled mobility by their capacity to “store and release energy.” Functionally, they are being classed as DER feet.

At present, multiple designs are in regular clinical use (3,15). While they differ in material and structural design, each uniquely replaces the rigid SACH keel with a flexible segment that is proposed to replicate controlled “ankle” motion. Patients
describe a feeling of buoyancy when walking with these DER feet, and subjectively report using less energy compared to that expended when walking with the SACH foot.

Analysis of the “energy storing” prosthetic feet is just beginning. Czerniecki, et al., used kinematic and kinetic data obtained on two normal and one BK amputee to calculate energy storage and power output during running (16,17). They concluded that the Flex-Foot had the greatest (terminal stance) output power and the SACH had the least, with the Seattle foot midway between the two (16). Their kinematic calculations also indicated a high hip extensor power output in running that was reduced by the greater prosthetic ankle energy. The theoretical high hip extensor activity in terminal stance differs from the EMG evidence of normal running and walking, where hip extensor muscle action occurs only in early stance (18,19). This discrepancy between calculated requirements and actual functional performance indicates the need to combine EMG with kinematics and kinetics. The interplay between the multiple segments of the limb is both subtle and complex.

Wagner, et al., studied three subjects fitted with both a SACH foot and a Flex-Foot, and three others with only the Flex-Foot. Gait velocity and cadence were similar for both feet and less than normal, a finding consistent with the usual amputee limitation (20). The major difference in function was the greater ankle dorsiflexion (DF) in late stance by the Flex-Foot (20° vs. 11°). Terminal floor reaction forces were similar, with both foot types approaching that of the sound limb. A reduced terminal floor reaction force occurred in one subject with terminal stance knee hyperextension rather than flexion. Increased contralateral loading force was greater with both prosthetic feet. The authors concurred with others (20,21,22,23) that terminal stance force is a product of alignment rather than dynamic push-off. Their conclusion was that factors other than the terminal stance force must be considered in the investigation of energy storage and release. This is a major motivation for including dynamic electromyography (EMG), and relating the pattern of muscle action with the kinematics and kinetics of the amputee’s gait.

These initial studies are useful pilot explorations, but meaningful comparisons must also accommodate the differences among patients. Consequently, a larger group of amputees must be analyzed in a single study. In addition, both the efficiency and mechanics of each prosthetic foot need to be addressed by direct energy cost analysis.

Many studies have assessed the energy cost of different amputation levels and types of pathology. Comparisons of their findings have been inconclusive, however, because each project assessed only one population, and techniques differed (24,25,26, 27,28,29). Also, the custom of measuring the rate of oxygen use failed to consider the reduction in physiological cost through gait velocity modification. This limitation is overcome by using energy cost per meter traveled as the measurement assessed (5,30). A series of amputee studies completed at Rancho Los Amigos Medical Center, which used a common testing and analysis system, demonstrated a significant correlation between the energy cost of walking, and both the level and etiology of amputation (5,31,32).

SIGNIFICANCE

A BK amputation causes loss of plantar sensation, free ankle and foot mobility, and selective muscular control of these joints. Current prosthetic replacement with a modern patellar-tendon-bearing BK socket and a SACH foot has only partially restored optimum walking ability (20,23,31). Even the young adult traumatic amputee, while expending energy at a 25 percent greater rate than normal walking, accomplished only 87 percent of the normal velocity (32). Dysvascular amputees lack the necessary physiological vigor and strength and must slow their velocity to 47 percent of normal to maintain a normal rate of energy use (32). Amputees desiring to run must be extremely vigorous as major physical adaptations are needed to accommodate to the limitations of their prosthesis (3,15). Ramps and uneven ground are other daily experiences which present difficulty.

Below-knee has become the most common level of amputation following the advances in the diagnosis of limb viability (33). With the knee preserved, the amputee has retained a potential for greater function. Realizing this potential, however, depends on optimum prosthetic support. Hence, the focus of this study was to characterize the gait of the amputee using different prosthetic feet. Achieving
this goal will provide the clinician with objective data to assist in prescribing a prosthetic limb that will give the BK amputee optimum gait.

**METHOD**

The energy cost and gait mechanics of four prosthetic feet with DER characteristics were compared to the functional qualities of the SACH foot.

**Subjects**

Seventeen BK amputees were studied. This group consisted of 10 amputees of traumatic origin and 7 subjects with amputations secondary to dysvascular disease. All subjects had a well-healed stump, had worn a prosthesis for at least 6 months, and were able to walk without an assistive device for 20 minutes without rest. All subjects were informed of the nature of the study and the time commitment involved. Each subject signed and received a copy of the Consent to Participate in an Experimental Project form, and the Bill of Rights of Human Subjects statement. All subjects were offered the prosthetic foot of their choice following completion of their participation in the study.

**Prosthetic Management**

Each subject was fitted with an endoskeletal prosthesis which allowed the interchange of foot components. In random order, the subjects were provided with four different feet of the DER type (Carbon Copy II, Flex-Foot, Seattle, Sten) and a SACH foot. Each foot was worn by the subject for approximately one month prior to kinesiological testing, to allow for adaptation to the prosthetic foot and ensure that it was fully functional for daily activities.

All prosthetic fabrication was completed at the Long Beach VA Medical Center. Anthropomorphic measurements included weight, height, limb length, and the measurements used for prosthetic fitting.

**Instrumentation and Procedure**

Functional testing was done at the Pathokinesiology Laboratory at Rancho Los Amigos Medical Center. This testing included energy cost, dynamic EMG, motion, joint moments (ankle, knee, and hip), and stride analysis.

Footswitches taped to the soles of the subjects’ shoes were used to record the sequence of foot-floor contact. These compression closing sensors, located in the area of the heel, heads of the first and fifth metatarsal, and the great toe, respond to 3 psi. The footswitch data were used to identify the pattern of floor contact and the basic stride characteristics.

Dynamic EMG recorded the timing and relative intensity of muscle activity. Fine wire electrodes were inserted with a 25-gauge needle into the vastus lateralis, long head of biceps femoris, short head of biceps femoris, and gluteus maximus of the amputated limb being recorded. Electrode placement was confirmed by mild electrical stimulation through the inserted wires. The EMG signals were transmitted via FM-FM telemetry to the data acquisition computer which sampled the signals at 2,500 Hz. The amplitude of EMG recorded during a “maximal” manual muscle test was used to normalize the EMG recorded during gait.

Motion of the trunk, pelvis, hip, knee, and “ankle” was recorded by the Vicon motion analysis system. Reflective markers were taped to the lateral aspect of the body overlying the axis of the hip, knee, and “ankle” joints, and the pelvis and trunk utilizing designated anatomical landmarks. Positioning of the prosthetic ankle marker was estimated from the location of that joint on the intact limb.

Forceplate recordings identified the ground reaction forces during the stance phase of gait. The forceplate is obscured in the walkway, and the subject was not informed of its presence. The subjects were positioned at the beginning of the walkway so that their natural stride would place the desired foot on the forceplate. Trials were repeated until one stride had been obtained with the reference foot landing completely on the forceplate. The current system for determining the joint moments utilized an Apple Ille computer and video recording system for visual vector display. The moments occurring at each joint during gait were calculated utilizing the visual vector (resultant ground reaction force) and joint centers from the video motion system.

All measurements, other than energy cost, were performed during both free and fast velocity walking on a 10-meter walkway with the middle 6 meters designated for data collection. In addition, ascending and descending a 20-foot, 10 percent grade ramp, and 4 stairs (with a 6-inch rise) were evaluated. The middle stride on the stairs was used for analysis to exclude acceleration and deceleration. On
the ramp and stair trials, stride characteristics, EMG, and motion of the amputated limb were recorded.

Function of the subject's contralateral limb was assessed by motion, joint moment, forceplate, and stride analysis during free and fast-paced walking.

Energy cost was determined on a 60.5 meter circular outside track. The subject's expired air was collected in a modified Douglas bag for subsequent oxygen and carbon dioxide analysis. Heart rate, respiratory rate, and cadence (using a heel switch) were telemetered by a transmitter attached to the subject. All gas volumes were corrected to standard temperature, pressure, and humidity. Each test walk lasted 20 minutes with expired air collected and physiological parameters recorded at 5-minute intervals. During the first 5 minutes, the initial 3 minutes served as a warm-up to attain a steady state with data collected in the final 2 minutes. The subsequent data collection intervals began at 9, 14, and 19 minutes.

Data Processing

The EMG data were rectified and integrated over a 0.01 second interval. Baseline noise was removed utilizing data from a quiet resting run. All gait EMG data were normalized to values determined from a "maximal" muscle test and expressed as a percent of the muscle test. Multiple strides of EMG data recorded were combined into a single representative stride for each activity tested (free/fast level walking, ascending/descending stairs and ramps). The EMG was further processed to identify the on/off timing of each muscle and the relative intensity and duration of muscle activity occurring in the functional phases of the gait cycle during these activities. The timing of the phases in stance was identified from the footswitch signals. To facilitate comparisons between subjects, and to retain the specificity of stance or swing muscle activity, each of these phases was normalized to the average stance and swing percent of the gait cycle for each activity.

Motion data were collected at 0.02 second intervals and normalized to the average stance/swing phase percent for each trial. Multiple runs and strides were averaged to obtain representative joint motion for each activity.

The fore-aft, medial-lateral, and vertical ground reaction forces were collected at 0.016 second intervals and normalized to the average stance phase duration. All values were also normalized by the subject's bodyweight. This facilitated comparison among multiple subjects. The ground reaction forces were utilized to determine the center of pressure and the magnitude of the ground reaction vector used in calculating joint torques.

The velocity, stride length, cadence, single stance, and duration of single and double stance and swing were calculated from the footswitch data. The durations of heel, foot-flat, and forefoot contact were also determined from this information.

Energy cost was defined by two measures of oxygen use, rate (milliliters per minute) and net (ml per meter walked). Physiological demand was identified by the rate of oxygen use ($O_2$ ml/kg/min). Efficiency of walking was determined from the measurement of net oxygen use ($O_2$ ml/kg/m), which combines rate and gait velocity.

Data were collected on 17 subjects under 5 different foot conditions (85 testing sessions). To date, 70 of these data sets have been processed. Data processing for the traumatic group has been completed, while 60 percent of the dysvascular group data has been processed.

RESULTS

The results of the traumatic amputee group have been analyzed and summarized. These involve the loading of the sound limb during free walking, the functional demand of stair climbing in this population, and the comparison of energy cost among the different prosthetic feet. The results of each study are given below.

Below-Knee Amputee Gait with Dynamic Elastic Response Prosthetic Feet: A Pilot Study

Preliminary results of three traumatic and two dysvascular amputees were studied for any demonstrated trends in producing optimum gait. Minimal differences were noted between the five feet. The Flex-Foot resulted in significantly greater ankle dorsiflexion ($19.8 \pm 3.3^\circ$; $p < 0.005$) and ankle joint torque ($19.9 \pm 7.5$ a.u; $p < 0.005$) in terminal stance compared to the other feet. All feet resulted in similar forceplate values on the amputated side. EMG analysis revealed no differences in intensity or phasing among the five feet tested; however, all had...
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prolonged activity in stance compared to normals. Analysis of oxygen consumption revealed no significant differences.

Of the five prosthetic feet tested, only the Flex-Foot resulted in slight changes in gait dynamics. This difference, however, was not translated to an increase in velocity or energy expenditure. The results of these five subjects suggest that there are no apparent advantages of the DER feet.

Influence of Prosthetic Foot Design on Sound Limb Loading in Unilateral Below-Knee Amputees

Forceplate, motion, and stride characteristics were analyzed in the group of 10 traumatic amputees. When comparing loading of the sound limb among the various prosthetic feet tested, it was found that the Flex-Foot caused a significant reduction in vertical ground reaction force (109 percent BW), compared with the SACH foot (135 percent BW), Carbon Copy II (129 percent BW), Seattle (127.9 percent BW), and the Quantum (129.2 percent BW) (p < 0.001). Stride characteristics among the five feet were similar, with the only significant difference being a greater stride length with the Flex-Foot compared to the SACH and Quantum (1.5 m; p < 0.05). There were no significant differences in free-walking velocity between feet. Motion analysis revealed that the Flex-Foot achieved greater dorsiflexion in terminal stance compared to all other feet (23.3°; p < 0.0001). No other differences were evident with respect to the other joints of the sound or amputated limb. These results indicate that the Flex-Foot, by nature of its large arc of ankle dorsiflexion, reduced the need to use a heel rise for tibial progression. The subsequent minimization of the rise in the body center of gravity resulted in a lower vertical loading force on the sound limb, with the implication of decreased joint reaction forces on the sound limb.

Function of the Seattle Foot in Ascending and Descending Stairs

The gait characteristics of 10 BK amputees using the Seattle foot during stair ascent and descent were compared to a group of 14 nonamputee subjects. Stride characteristics revealed that the amputee group had a significantly lower rate of ambulation on the stairs than normal (1.6 vs. 1.8 stairs per second) (p < 0.05). The amputee group also had significant asymmetry between their two limbs in duration of stance with a shortened stance on the amputated limb (60 percent vs. 69 percent). The nonamputee subjects had equal stance times on both legs. Motion analysis recorded significant limitations in motion of the prosthetic ankle compared to the normal ankle during stair ambulation. During loading response, the prosthetic ankle lacked normal dorsiflexion (DF) (7° vs. 14°). In early pre-swing, the prosthetic ankle was in maximum DF while the normal ankle moved into plantarflexion (PF) (5° DF vs. 15° PF). During initial swing, the prosthetic foot remained in DF, while the normal ankle further plantarflexed to 16°. The hip and knee joint motion was similar to that displayed by the nonamputee subjects.

The limited DF range of the prosthetic foot-ankle assembly in the amputees compromised the rocker action at the ankle, which was compensated for by forward trunk-lean in stair ascent. The forward trunk-lean augmented the forward progression, but resulted in prolonged activity of the semimembranosis. The vastus lateralis had very high intensity of action during stair descent to control forward progression over the rigid ankle rocker. Future designs for prosthetic feet should consider the need for greater DF mobility, combined with stability, to allow easier stair ambulation for the person with a BK amputation.

Below-Knee Amputee Gait in Stair Ambulation: A Comparison of Stride Characteristics Using Five Different Prosthetic Feet

Stride characteristics of 10 traumatic BK amputees using five different prosthetic feet were evaluated to determine if any provide for increased performance during stair ascent and descent. Results indicate that the Flex-Foot and Carbon Copy II foot provided for a more symmetrical gait during the initial double limb support (IDLS) phase of stair ascent. The ratios of the amputated versus sound limb for the duration of IDLS were 1.03 and 1.05 for the Flex-Foot and the Carbon Copy II, respectively, compared to 1.3 for the SACH foot (p < 0.05). No other significant differences in stride characteristics were found between feet. These results indicate that none of the five feet tested were clinically more advantageous for the task of stair ambulation.
A Comparison of Energy Expenditure Between Five Different Prosthetic Feet

Seventeen male amputees (10 traumatic and 7 dysvascular) were evaluated for differences in energy expenditure while wearing five different prosthetic feet. No significant differences in heart rate, respiratory rate, cadence, respiratory quotient, and energy expenditure per distance traveled were noted between any of the prosthetic feet tested. However, there was a significant difference between the traumatic and dysvascular groups in velocity (82.3 vs. 64.0 m/min; p < 0.05); stride length (1.49 vs. 1.26 m; p < 0.05); resting heart rate (65.4 vs. 82.1 b/min; p < 0.05); and energy expenditure (13.7 vs. 17.7 ml O2/min; p < 0.005).

These results indicate that prosthetic design does not contribute to energy conservation in this population. The dysvascular amputee demonstrates increased energy expenditure as a result of the limitations of physical conditioning associated with peripheral vascular disease.

FUTURE WORK PLANNED

Upon completion of the data processing for the dysvascular group, comparisons will be made to the traumatic group across all prosthetic feet tested. Of particular interest are the loading characteristics of the sound and amputated limb of the dysvascular amputee compared to its traumatic counterpart. In addition, the stride characteristics, EMG patterns, and joint motion of the dysvascular group will be analyzed for differences across the different prosthetic feet as well as between the two groups. Energy cost of the dysvascular amputee, as well as functional demand (joint torques), will also be analyzed.

REFERENCES