Gait analysis of low-cost flexible-shank transtibial prostheses

Winson Lee
University of Wollongong, ccwlee@uow.edu.au

Ming Zhang
The Hong Kong Polytechnic University

Peggy Chan
The Hong Kong Polytechnic University

David A. Boone
The Hong Kong Polytechnic University

Publication Details
Gait analysis of low-cost flexible-shank transtibial prostheses

Abstract
The latest lower-limb prosthetic designs have been incorporated with dynamic elastic response (DER) components to enhance prosthesis flexibility, which are suggested to be beneficial to gait. Although DER prosthetic feet are preferred by most transtibial amputees and their benefits to gait are supported by some biomechanical studies, many are still utilizing the simple conventional solid ankle cushioned heel (SACH) designs because of the lower cost. The monolimb, a transtibial prosthesis with the socket and the shank molded from a single piece of thermoplastic material, perhaps is an alternative to DER feet for providing flexibility at the shank. In addition to shank flexibility, low cost and light weight are other characteristics of monolims. In spite of the potential benefits, little analysis has been done to examine the simple-structured monolimb prosthesis. The main aim of this study is to evaluate the gait and perception of unilateral transtibial amputees using a flexible elliptical-shank monolimb as compared to a thicker circular-shank monolimb and a conventional rigid-shank prosthesis. Results suggested that a properly designed monolimb may potentially offer similar functional advantages to the relatively expensive DER feet.

Keywords
low-cost, flexible-shank, analysis, prostheses, gait, transtibial

Disciplines
Engineering | Science and Technology Studies

Publication Details

This journal article is available at Research Online: http://ro.uow.edu.au/eispapers/6679
Gait Analysis of Low-Cost Flexible-Shank Transtibial Prostheses

Winson C. C. Lee, Ming Zhang, Peggy P. Y. Chan, and David A. Boone

Abstract—The latest lower-limb prosthetic designs have been incorporated with dynamic elastic response (DER) components to enhance prosthesis flexibility, which are suggested to be beneficial to gait. Although DER prosthetic feet are preferred by most transtibial amputees and their benefits to gait are supported by some biomechanical studies, many are still utilizing the simple conventional solid ankle cushioned heel (SACH) designs because of the lower cost. The monolimb, a transtibial prosthesis with the socket and the shank molded from a single piece of thermoplastic material, perhaps is an alternative to DER feet for providing flexibility at the shank. In addition to shank flexibility, low cost and light weight are other characteristics of monolimbs. In spite of the potential benefits, little analysis has been done to examine the simple-structured monolimb prosthesis. The main aim of this study is to evaluate the gait and perception of unilateral transtibial amputees using a flexible elliptical-shank monolimb as compared to a thicker circular-shank monolimb and a conventional rigid-shank prosthesis. Results suggested that a properly designed monolimb may potentially offer similar functional advantages to the relatively expensive DER feet.

Index Terms—Amputee gait, dynamic elastic response prosthetic foot, flexibility test, monolimb, shank flexibility.

I. INTRODUCTION

MONOLIMB refers to a transtibial prosthesis without a foot, and the shank molded from a single piece of thermoplastic material. Polypropylene thermoplastic is one commonly used material in monolimbs for its strength and ductility. A conventional solid ankle cushioned heel (SACH) foot is usually used with the monolimb. Due to the flexibility of thermoplastics, the shank of a monolimb can deflect during walking leading to simulated ankle joint motion. Production cost and weight of the prosthesis are lowered as a piece of thermoplastic material is replacing the highly engineered pylon as well as connectors. Other names have been assigned to the prosthesis such as total thermoplastic prosthesis [1], ultralight prosthesis [2], [3], and Endoflex [4], which connotes that the monolimb prosthesis is made of one piece of thermoplastic material which is much lighter in weight than the conventional prostheses and can provide some flexibility at the shank.

Light weight is one of the main characteristics of monolimbs compared to conventional endoskeletal or exoskeletal prostheses. Although previous research was not able to conclude an optimal weight of a prosthesis, as reviewed by Selles [5], some studies indicated that light weight provided by a monolimb is welcomed by amputees. Reed [2] reported that the majority of their fourteen transtibial amputee patients preferred monolimbs to conventional prostheses, as lighter prosthetic weight allowed them to feel more comfortable, use less energy to walk, and control the prosthesis more easily. Similarly, Wilson and Stills [3] reported that a reduction in weight in a monolimb was highly appreciated by their two active and young transtibial amputees.

Shank flexibility of a monolimb can be increased by reducing the cross-sectional area of the shank. Valenti [3] utilized a tube-like shank for the monolimb (Endoflux), aimed at increasing the shank flexibility. They reported that of the 300 patients who have used the flexible-shank monolimbs, the majority experienced greater flexibility, felt more comfortable, and walked more efficiently. They suggested that a properly designed monolimb could be an alternative method of fabricating a transtibial prosthesis offering similar functional advantages to some high-cost dynamic elastic response (DER) prosthetic feet at the same time minimizing the total weight and cost. Some other studies also concluded that a prosthesis substituted with a deformable shank can offer improved gait efficiency and comfort to patients [6], [7].

Although some potential advantages of monolimbs can be seen, objective biomechanical analysis is needed regarding to the stress distribution at the prosthesis and gait of the wearer. In recent work [8], finite element analysis and the Taguchi method were used to derive the dimensions of an elliptical shank for the monolimb which can resist structural failure in normal use while providing high flexibility at terminal stance of the gait. It was also shown in finite element analysis that a flexible-shank prosthesis tended to lower the prosthetic socket-residual limb interface stresses [9]. Yet, objective gait analysis on amputees using monolimbs has been absent. Gait assessment has to be weighed against patient perception so as to fully evaluate the performance of monolimbs.

The objectives of this study were to evaluate the gait performance and perception of unilateral transtibial amputees towards the use of the flexible elliptical-shank monolimb as compared to...
a thicker circular-shank monolimb and a conventional modular prosthesis. A mechanical test was also performed to quantify the flexibility of the three test prostheses.

II. METHODS

A. Test Prostheses

Two designs of monolimbs with different shank shapes were tested together with the subjects’ currently used (Current) modular prosthesis. As shown in Fig. 1, one monolimb had a thicker circular-shank (CS monolimb) of inner diameter of 50 mm, and the other monolimb had a slimmer elliptical shank (ES monolimb) with the anteroposterior dimension of 25 mm and the mediolateral dimension of 45 mm. The dimension of the elliptical shank was chosen according to the design optimization process using finite element analysis and the Taguchi method [8] for transtibial amputees of body mass between 60 and 80 kg. Both monolimbs had uniform cross-sectional shanks and were vacuum-formed manually from a piece of 5-mm-thick polypropylene homopolymer (Otto Bock, Duderstadt, Germany). Using socket duplication foam (Otto Bock, Duderstadt, Germany) and an alignment duplication device, the two monolimbs were fabricated with identical socket shape, alignment and prosthetic length. The Current prostheses served as baselines for the analysis. SACH feet were used for all test prostheses.

B. Flexible Test of the Prostheses

The flexibility of the three prostheses was compared by studying the overall deformations of the socket-shank structures upon load applications. The direction and point of application of the load were referenced to load testing condition I and condition II, respectively, from ISO Standard 10328 [10], relating to the early and late stance phases of gait. An extension rod and two aluminium blocks were added so that the test load could be offset, as shown in Fig. 2. The two aluminium blocks had mounting holes with ball joints attached. The ball joints were positioned such that when loadings were applied, the position and direction of the load would follow the specifications in ISO 10328. The whole setup was mounted in a material testing machine (Model 858 Mini Bionix, MTS System Corporation). Each prosthesis was loaded to 1000 N at a loading rate of 100 N/s at both conditions I and II. The displacement of the actuator and the loading applied were respectively reported real-time by a LVDT type displacement transducer (0–100 mm) and a load cell (Max.: 10 000 N) during the loading process. Flexibility of each prosthesis was quantified by $1000 \, \text{mm}$, where $I_f$ was the vertical displacement (millimeters) of the actuator from the initial position to the position when 1000 N was applied (Fig. 2).

C. Gait Analysis

Four male subjects with transtibial amputation participated in this study. Table I shows the subject characteristics. All participants, 69–80 kg in body mass, were diagnosed without any complications associated with residual limb breakdown and did not require any additional assistive walking aids required. All subjects were using patellar tendon bearing (PTB) socket-type prostheses with SACH feet. They were recruited from the Jockey Club Rehabilitation Engineering Clinic, Hong Kong. The experiment was approved by the ethics committee of The Hong Kong Polytechnic University and written consent was obtained from the subjects.

Two AMTI piezoelectric force plates, positioned midway along a 10-m walkway, were used to determine the ground reaction force in the antero-posterior and vertical components. Spatial position of the heel and the trunk during ambulation were recorded by a six camera VICON motion analysis system.
capturing the positions of the reflective markers taped to the heel and the skin at the anterior superior iliac spine (ASIS) bilaterally. Ground reaction force and position data were simultaneously sampled at 60 Hz. Subjective feedback in terms of comfort, stability, ease of walking, perceived flexibility, and prosthetic weight was collected at the end of the gait analysis.

Three sessions were arranged separately on consecutive days for each subject. Initially, a baseline gait test was performed with the Current prosthesis. The subjects were instructed to walk along the 10-m long walkway at self-selected walking velocity with ground reaction force and position data obtained simultaneously. A walking trial was deemed successful when the foot of interest landed fully on the force plate. Repeated trials were performed in order that five successful trials for each of the prosthetic and sound limb were obtained.

In the second and third sessions, each subject was given a half-day accommodation period, to get accustomed to each of the two monolimb designs. The order of the use of the two monolims was randomly assigned, and the monolims were externally covered so that the subjects were effectively blinded to being fitted with monolims of different shank geometries. Gait test was performed after the accommodation period on each of the two monolims. The data acquisition protocol was identical to that used at the baseline gait analysis. At the end of the third session, subjective feedback of the use of the three prostheses was collected and the three test prostheses were weighed using a balance scale. Each subject use of the three prostheses was collected and the three test prostheses were weighed using a balance scale. Each subject was asked to rank verbally the three prostheses in terms of flexibility and weight among the test prostheses.

Three prostheses—CS monolims, ES monolims, and the subjects’ Current prostheses—were studied. On average CS monolims and the ES monolims weighed 24% and 37%, respectively, less than the Current prostheses (Table I). The ES monolims were lighter in weight than the CS monolims because of the use of the smaller adaptors. The Current prostheses served as baselines. Particular attention was paid to any differences in walking performance between the two monolims, which had the same socket shape and alignment but differed in shank geometry.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>Age (yr)</th>
<th>Body mass (kg)</th>
<th>Years since amputation (yr)</th>
<th>Reason for amputation</th>
<th>Prosthetic shank length (mm)</th>
<th>Mass (kg) and type of currently used prosthesis</th>
<th>Mass of CS monolimb (kg)</th>
<th>Mass of ES monolimb (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>75</td>
<td>4</td>
<td>Trauma</td>
<td>245</td>
<td>1.2 / endoskeletal</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>47</td>
<td>74</td>
<td>40</td>
<td>Trauma</td>
<td>220</td>
<td>1.2 / endoskeletal</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>69</td>
<td>18</td>
<td>Congenital</td>
<td>230</td>
<td>1.4 / endoskeletal</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>56</td>
<td>80</td>
<td>17</td>
<td>Trauma</td>
<td>245</td>
<td>1.6 / exoskeletal</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

III. RESULTS

Fig. 3(a) and (b) shows the force-displacement relationship when loadings related to the early and terminal stance were applied to the three test prostheses belonging to subject #4. As expected, the ES monolimb had the highest flexibility compared to the CS monolimb and the Current prosthesis at both early stance (ES monolimb 475 N/mm; CS monolimb 873 N/mm; Current prosthesis 1480 N/mm) and terminal stance (ES monolimb 38 N/mm; CS monolimb 85 N/mm; Current prosthesis 180 N/mm). Because of the longer load lever arm during walking at terminal

A. Flexibility Test of the Prostheses
stance, the prostheses showed much higher flexibility at the terminal stance as compared to early stance.

B. Stride Characteristics and Trunk Motion

The mean walking speed ranged between 66.5 and 67.8 cm/s, without significant differences among the three prostheses (Table II). When using the ES monolimb, the mean sound side step length were, respectively, 3.2% and 1.7% longer than the CS monolimb and the conventional prosthesis, and the mean prosthetic side step length were, respectively, 3.3% and 1.9% shorter. This produced the step symmetry ratio closer to 1 for the ES monolimb. However, the differences in step length and step symmetry ratio did not reach statistical significance. Fig. 4 shows one typical vertical trunk motion during the entire gait cycle. It is noted that the ES monolimb tended to lower the position of the trunk during late stance phase of the prosthetic side, compared to the CS monolimb. This characteristic was seen in three out of four subjects. In the other subject, very small difference in the vertical trunk position during late stance phase of the prosthetic side was found.

C. Temporal Characteristics

The mean stance time of the prosthetic side and sound side varied in small ranges from 0.73 to 0.74 s and 0.77 to 0.79, respectively, without significant differences among the three prostheses (Table II). Similarly, no significant difference was found in swing time of the prosthetic side and sound side which varied from 0.73 to 0.74 s and 0.77 to 0.79, respectively (Table II).

---

**TABLE II**

<table>
<thead>
<tr>
<th>Gait parameters/ Test prostheses</th>
<th>Current prosthesis</th>
<th>CS monolimb</th>
<th>ES monolimb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity cm/sec</td>
<td>67.2 (13.1)</td>
<td>66.5 (11.6)</td>
<td>67.8 (14.0)</td>
</tr>
<tr>
<td>Step length (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prosthetic side</td>
<td>688 (107)</td>
<td>697 (118)</td>
<td>675 (132)</td>
</tr>
<tr>
<td>Sound side</td>
<td>637 (98)</td>
<td>627 (98)</td>
<td>648 (100)</td>
</tr>
<tr>
<td>Step symmetry</td>
<td>1.08 (0.04)</td>
<td>1.11 (0.05)</td>
<td>1.04 (0.08)</td>
</tr>
<tr>
<td>Stance time (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prosthetic side</td>
<td>0.73 (0.12)</td>
<td>0.74 (0.11)</td>
<td>0.73 (0.12)</td>
</tr>
<tr>
<td>Sound side</td>
<td>0.77 (0.11)</td>
<td>0.79 (0.09)</td>
<td>0.78 (0.09)</td>
</tr>
<tr>
<td>Swing time (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prosthetic side</td>
<td>0.50 (0.06)</td>
<td>0.48 (0.04)</td>
<td>0.49 (0.05)</td>
</tr>
<tr>
<td>Sound side</td>
<td>0.43 (0.05)</td>
<td>0.44 (0.05)</td>
<td>0.42 (0.05)</td>
</tr>
</tbody>
</table>

Fig. 3. Force-displacement relationships of the three prostheses when loadings related to the (a) early stance and (b) terminal stance were applied.

Fig. 4. Trunk motion during an entire gait cycle of subject #1. It can be observed that the ES monolimb tended to lower the position of the trunk during late stance phase of the prosthetic side. At that instance, the heel of the sound limb prepares to contact on the floor. Similar characteristics were seen in three out of four subjects.
Fig. 5. Position of the heel marker during an entire gait cycle of subject #1. It can be seen that the ES monolimb tended to delayed heel rise compared to CS monolimb. However, the prosthetic limbs showed obvious earlier heel rise when compared to the sound limb. Similar characteristics were seen in all subjects.

D. Ground Reaction Force

Table III shows the ground reaction force data. The ES monolimb demonstrated a significant reduction ($p < 0.0001$) in the mean magnitude of the first-peak vertical ground reaction force at the sound limb (843 N), compared to the CS monolimb (906 N) and the Current prosthesis (923 N). Delayed heel rise of the prosthetic foot attached to the flexible ES monolimb (Fig. 5), and reduced prosthetic side vaulting (Fig. 4) might explain the lowering of the associated sound limb impact in the following step. The ES monolimb also induced a significant reduction ($p < 0.05$) in the second peak of the vertical force at the prosthetic limb (696 N), compared to the CS monolimb (707 N) which might be explained by the flexible design of the shank. No statistical differences were found in other force data.

E. Subjective Feedback

Table IV tabulated the ranking of the three prostheses reported by the subjects. All subjects perceived that the ES monolimb was the most flexible among the three prostheses. When further asked at what particular instance they perceived the extra flexibility during the use of ES monolims, they all reported that the perceived flexibility was at the late stance phase of the gait. Three out of four subjects reported that the two monolims were lighter in weight than their own prostheses. The lighter prosthetic weight was welcomed by the subjects as they perceived that they consumed less energy when swinging the monolims during the gait. Two subjects perceived that the ES monolimb was lighter than the CS monolimb and the other two subjects perceived that the two monolims had the same weight. Three subjects reported that they perceived greater comfort when using the Current prostheses and the other one perceived the ES monolimb gave him the best comfort. Comparing the ES monolimb to the CS monolimb, all subjects perceived that the ES monolimb gave them better comfort, and three subjects reported that the ES monolimb provided them with greater stability and ease of walking.

IV. DISCUSSION

This study focused on some gait parameters including self-selected walking speed, step length, ground reaction force, trunk motion, stance, and swing time. These parameters were chosen because they are accepted as important variables and are known to demonstrate differences between people with and without unilateral transtibial amputations [13]–[15]. In addition, these parameters are most often used in previous studies comparing DER prosthetic feet to conventional feet, although other parameters such as muscle activity, energy expenditure, and joint angles can also be of interest.

Normal gait is characterized by high degree of symmetry between both legs in terms of temporal, kinetic, and kinematic parameters [16], which allow an energy efficient mode of gait [13]. Transtibial amputee patients who received prosthetic treatment, however, usually demonstrate asymmetries between the sound limb and the prosthetic limb. Specifically, the prosthetic limb has a shorter stance phase time, longer step length and swing time, lower range of knee flexion, and vertical peak forces than the sound limb [13]–[20]. The disturbances of the symmetry in the temporary, kinetic, and kinematic parameters cause amputees to walk with higher energy cost and at lower speeds than nonamputees [21]–[23].

Many studies have looked into the effect of the provision of flexibility and compressibility at the shank and keel on different gait parameters of the gait. Flex feet, Seattle feet, and Tele-Torison pylons were most often compared to relatively low-cost SACH feet, as reviewed by Hafner 2002 [24]. It has been suggested that many amputees subjectively prefer DER feet and shock-absorption pylons to conventional SACH feet on normal and fast walking [25]–[28]. In addition, a few biomechanical gait analyses have demonstrated the improvements in performance of using DER feet. Many amputees, however, still utilize the simple conventional SACH designs because of their lower cost.
Little attention has been paid to monolimbs. This study focused on the simple-structured monolimb attached to a SACH foot, replacing some highly engineered prosthetic components. Light weight and low cost are apparently the advantages of monolims. Using finite element analysis and statistical-based Taguchi method, our previous study has suggested an elliptical shank design of monolimbs which offers appropriate flexibility at terminal stance of the gait and resistance to structural failure [8]. Here, we compared the flexibility among rigid-shank conventional prostheses, ES and CS monolimbs, and, more importantly, analyzed the walking performance of using the three prostheses. Gait analyses were performed on different days. Although no known data in an amputee population on day-to-day variability of gait parameters has been published, high repeatability was shown in nonamputees in previous studies on temporal, kinetic, or kinematic parameters between test days [29].

This study showed that the flexible ES monolimb might have similar effects to high end DER prosthetic feet in a few aspects. It is well documented that people with unilateral transtibial amputations amble at lower speed and with a shorter step length. When switching from a SACH to DER type of foot, the majority of previous studies indicated that the walking speed and the step length at the sound side as compared with persons without amputation are common [13], [14]. It has been reported that prosthetic limbs are common associated sound limb impact in the following step. The reduction in the sound limb initial loading. Delayed heel rise of the prosthetic foot attached to the flexible ES monolimb, and reduc prosthetic side vaulting might explain the lowering of the associated sound limb impact in the following step. The reduc of load transfer to the sound side may serve to reduce the chance of degenerative arthritis changes which commonly affect the sound side knee joint of unilateral amputees [42], [43] and may protect the sound limb from ulceration. This study, however, did not show a trend of increase in the prosthetic side anteroposterior force.

Concerning other peak ground reaction forces in vertical and anteroposterior components, previous studies had failed to show a strong trend of increase or decrease. This study showed, in addition to the sound side initial vertical loading, the ES monolimb significantly reduced the second peak vertical force at the prosthetic limb, when compared to the CS monolimb. The difference was small (1.6%). The small reduction in vertical force at terminal stance may be a sign of increased flexibility of the shank which simulates dorsiflexion to some extent.

Asymmetry in stance and swing time between the sound and prosthetic limbs are common findings in persons with transtibial amputations [13], [14]. It has been reported that flexible DER feet produced longer midstance support time bringing more symmetric midstance time between both sides [35]–[37], [44]. A similar finding was found in this study as the more flexible ES monolimb tended to delay heel-rise. When looking into the entire stance time of a gait cycle, however, this study showed no significant differences among the three prostheses.

In addition to increased flexibility, light weight is another characteristic of monolims. This study showed that three out of four subjects could perceive that the monolimbs were lighter in weight than the Current prostheses. Lighter prosthetic weight was welcomed by the subjects as they perceived that they consumed less energy to swing the monolimb during the gait. The gait analysis data showed, however, no significant difference in swing time among the three test prostheses. This is consistent with most previous studies which did not find a statistical difference in swing phase kinematics after altering the prosthetic mass and the center of mass location [5]. It could be interesting to look into the EMG intensity of muscles around the thigh and the energy cost during ambulation with the use of a light-weight monolimb to observe if the perceived lower energy cost is justified by biomechanical data.

<table>
<thead>
<tr>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comfort</strong></td>
<td>Current</td>
<td>CS</td>
<td>ES</td>
</tr>
<tr>
<td>Lightness</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Stability</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Flexibility</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Ease of walking</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE IV**

SUBJECTIVE FEEDBACKS OF THE SUBJECTS. RANK 1 INDICATES THE BEST COMFORT, LIGHTEST, THE MOST STABLE AND FLEXIBLE, AND THE EASIEST TO WALK AMONG THE THREE PROSTHESES.
Short accommodation period of the use of monolims given to the subjects is one limitation of this study. The short accommodation time may explain why three out of four subjects perceived better comfort with their own prostheses than the two monolims. Comparing the two monolims, however, all subjects reported that the ES monolimb provided them with greater comfort than the CS monolimb. This is supported by our previous study using FE modeling which showed that increased flexibility of the shank tended to reduce stresses applied from the prosthetic socket onto the residual limb [9]. Field test on the use of monolims is needed so that the long term effect of shank flexibility can be observed. In future studies, fatigue failure test will be performed to estimate the interval of structural inspection of monolims. Once we have a good grasp on the fatigue life of the flexible-shank monolims, field tests will also be conducted.

V. CONCLUSION

The performance of an ES monolimb was compared to a thicker CS monolimb and the subjects’ current rigid-shank prosthesis. The more flexible ES monolims significantly reduced sound limb vertical ground reaction force at early stance phase and the prosthetic limb vertical force at terminal stance. Subjective feedback showed that although most subjects reported that they perceived greater comfort when using the current prostheses, most welcomed the lighter prosthetic weight given by the two monolims and could perceive a greater flexibility with the ES monolimb. Comparing the ES monolimb to the CS monolimb, all subjects perceived that the ES monolimb gave them better comfort. Field test on the use of monolims is needed so that the long term effect of shank flexibility can be observed.

REFERENCES


Winson C. C. Lee was born in Hong Kong in 1979. He received the B.Sc. degree in prosthetics and orthotics and the Ph.D. degree in biomedical engineering at the Hong Kong Polytechnic University, Kowloon, in 2001 and 2006, respectively. He is now a Postdoctoral Research Fellow at Queensland University of Technology, Brisbane, Australia, performing analysis and mechanical design of transfemoral osseointegrated fixation system. His fields of expertise are analysis and design optimization of lower limb prostheses using gait analysis, structural testing, and computational FE modeling. He has published over 20 refereed publications in the past three years. Dr. Lee received Sir Edward Youde Memoral Fellowship award in 2003–2005 in Hong Kong.

Ming Zhang was born in China in 1961. He received the B.Sc. degree in automatic control engineering and the M.Sc. degree in mechanical engineering from Beijing Institute of Technology (BIT), Beijing, China, in 1982, and 1985, respectively, and the Ph.D. degree in medical engineering from University of London, London, U.K., in 1995. He is currently an Associate Professor at The Hong Kong Polytechnic University, Kowloon. His main research interests include computational modeling and simulation, prosthetic and orthotic bioengineering, biomedical engineering design, foot biomechanics and footwear design, tissue biomechanics, bone biomechanics, and osteoporosis prevention.

Peggy P. Y. Chan photograph and biography not available at the time of publication.

David A. Boone photograph and biography not available at the time of publication.