Comparative roll-over analysis of prosthetic feet

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Abstract
A prosthetic foot is a key element of a prosthetic leg, literally forming the basis for a stable and efficient amputee gait. We determined the roll-over characteristics of a broad range of prosthetic feet and examined the effect of a variety of shoes on these characteristics. The body weight of a person acting on a prosthetic foot during roll-over was emulated by means of an inverted pendulum-like apparatus. Parameters measured were the effective radius of curvature, the forward travel of the center of pressure, and the instantaneous radius of curvature of the prosthetic feet. Finally, we discuss how these parameters relate to amputee gait.

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1. Introduction

Given the design of a prosthetic foot, how does it match the function of a biological foot? In human plantigrade gait the foot rolls over the ground during each step, analogous to a wheel (Hansen et al., 2004a), while the stance leg acts like an inverted pendulum (e.g., Winter, 1995a,b). The center of mass (CoM) located roughly at the level of the pelvis, travels in a series of arcs (Fig. 1A). The overall motion can be described by a rocker-based inverted pendulum model, which, in contrast with a simple inverted pendulum with a peg, allows the center of pressure (CoP) to travel forward along the curved foot (Fig. 1A–D). It has been shown that able-bodied people have curvatures of about 30% of the leg length during walking (McGeer, 1990; Hansen et al., 2004a). The energy cost of walking is lower on long, smoothly curved feet than on flat or pointy feet. It has been reported that metabolic costs are optimal when walking on a foot with a curvature of 30% of the leg length (Adamczyk et al., 2006). Moreover, foot curvature has been demonstrated to be surprisingly invariant to walking speed, loads carried, and shoe heel height (Hansen et al., 2004a; Hansen and Childress, 2005, 2004). On the other hand, considerable differences were found between gait initiation, steady-state walking, and gait termination (Miff et al., 2008). Here, the orientation of the curvature changed from ‘flexed’ to ‘neutral’ to ‘extended’ (Fig. 1C) through active muscle control.

The major challenge when designing prosthetic feet is to substitute the actions of the biological counterpart as efficiently as possible by means of a passive dynamic device. In this endeavor the design of prosthetic feet has become increasingly sophisticated in recent years. From this development arises an immediate need for a standard test method not only quantifying the mechanical properties of prosthetic feet, but further allowing a seamless translation of mechanical test data to performance data of gait experiments in individual patients.

A wide range of mechanical properties of prosthetic feet have been studied, such as stiffness (Van Jaarsveld et al., 1990; Lehmann et al., 1993), natural frequency (Lehmann et al., 1993), energy recovery and hysteresis (Van Jaarsveld et al., 1990; Postema et al., 1997; Geil et al., 2000), viscoelasticity (Geil, 2002), and material fatigue (Toh et al., 1993). While these studies have addressed important properties of prosthetic feet, the resulting qualitative characteristics have often lacked a seamless translation into amputee gait characteristics due to separate measurement techniques. Furthermore, the nature of loading applied during testing is very different to that in walking. During testing the loading was increased at a constant ground angle, while during actual gait the ground angle changes during roll-over. In a similar method, introduced by Hansen et al. (2000), the complex actions of the ankle–foot system are captured in an overall motion. Through quasi-static loading with a custom-made jig the authors estimated the roll-over shape, i.e. the effective
The purpose of this study is to determine the roll-over characteristics of a range of prosthetic feet and to discuss their biomechanical implications for prosthetic gait. Further, we will quantify the effect of different types of shoes on these characteristics. We expect the differences between the prosthetic foot models to be stronger than the effects imposed by the various shoes.

2. Methods

We designed an experiment in which we investigated the roll-over characteristics of a number of prosthetic feet in combination with different shoes by means of an inverted pendulum-like apparatus. Roll-over shapes of these foot–shoe combinations were simulated for a hypothetical subject with a body mass of 70 kg and a body height of 1.80 m.

2.1. Apparatus

The inverted pendulum-like apparatus consisted of a shaft, with a prosthetic foot attached to the lower end and a mass (m) of 70 kg mounted to the upper end of the shaft. The pendulum length (l), the distance between the foot sole and the CoM of the added weight, was 0.98 m, a typical leg length for a person of 1.80 m body height. A custom-made rig provided lateral guidance during testing with a minimum of friction; further it restricted the anterior–posterior range to predefined limits.

Seven prosthetic feet of three different manufacturers were included in this study (Table 1): Endolite (Espri, Navigator), Ossur (Flexfoot, Vari-Flex), and Otto Bock (1C40, 1D10, 1D35). All feet were right sided and sized 270 mm. Each prosthetic foot was tested under 4 different conditions: (1) without shoe, (2) with a men’s leather shoe, (3) with a running shoe, and (4) with a hiking boot.

The prosthetic feet were mounted in neutral alignment, i.e. the feet were flat on the ground when the shaft was vertical under zero-load. The alignment was adjusted for shoe heel height to obtain a vertical standing position of the shaft under zero-load.

The ground reaction forces (GRF) and the position of the center of pressure (CoP) data were measured with an AMTI (a) force plate, sampled at 1000 Hz. Two reflective markers were placed on the shaft. The markers were tracked by an eight-camera VICON motion analysis system (b) at a sampling frequency of 100 Hz. The data was then further processed with Matlab (c). This delivers, amongst others, shank angle (α) and ankle moment data.

2.2. Experimental procedure

The experimenter applies a horizontal force to the top weight necessary for an angular velocity of ±10 deg/s, making the foot roll over from heel to toe and back. The measurement range was −15° to 20° with respect to the absolute vertical, corresponding to heel-contact and toe-off. The testing procedure was repeated three times for each foot–shoe combinations. (A video of the experimental procedure is available as Supplementary Material.)

2.3. Data analysis

2.3.1. Effective radius of curvature (ρ)

During part of the stance phase a biological ankle–foot system acts like a smoothly curved solid object. The CoP progresses forward from heel to toe, similar to that of a rolling wheel with a particular radius. Hansen et al. (2004a) proposed a method that allows estimating the effective ‘ankle–foot roll-over shape’ of an ankle–foot system from CoP data. The strength of this method is its universal applicability, ranging from a simple rolling wheel, to deformable objects and complex multi-joint systems. By transforming successive CoP location data from a laboratory-based coordinate system into a shank-based coordinate system the effective curvature geometry can be determined. The resulting ankle–foot roll-over shape is similar to a circle and reflects the overall motion of the system. The radius...
of curvature is determined by fitting the best-fit circular arc to the transformed data (Hansen et al., 2004a).

2.3.2. Center of curvature ($x_0$)

The horizontal position of the center of curvature ($x_0$) with respect to the shank determines the orientation of the foot curvature (Fig. 1B and C). For feet with an extended orientation the center of curvature is anterior to the shank, while for feet with a flexed orientation it is posterior.

2.3.3. Forward travel ($s$)

As the foot is rolled over, the CoP travels along the curvature of the foot (Fig. 1D). A fast forward travel ($s$) as a function of shank angle ($x$) corresponds to a very flat/large radius of curvature, while a highly curved/small radius of curvature produces only little forward travel as a function of shank angle. A large radius of curvature is to be considered as more stable than a small radius of curvature. Interestingly, feet with a small radius of curvature appeared almost invariant to the effect of applying shoes. Along with the effective radius of curvature ($\rho$), the roll-over characteristics of a foot are determined by the horizontal position of the center of curvature (Fig. 4B). The center of curvature ($x_0$) varied widely among foot models. It shifted closer towards the shaft as response to the different shoes. As a result the roll-over shapes created by the foot–shoe combinations have a rather ‘neutral’ orientation. Fig. 5A illustrates the effect of shoes on the forward travel ($s$) of the Esprit foot. The characteristic S-shaped forward travel is

\[ s = 2\rho + x_0. \] (1)

2.3.4. Instantaneous radius of curvature ($s'$)

The instantaneous radius of curvature ($s'$) is determined as the first derivative of the forward travel ($s$) on the ground with respect to the shank angle ($x$)

\[ s' = \frac{ds}{dx}. \] (2)

It is related to the position-dependent stability of the foot, which increases with the instantaneous radius of curvature ($s'$). In contrast to the effective radius of curvature ($\rho$), the instantaneous radius of curvature ($s'$) refers only to the CoP displacement over the floor.

2.4. Comparative single case study

In addition to the mechanical testing of the different foot–shoe combinations, we performed a single case study to get an estimate for the agreement between roll-over characteristics measured in an actual amputee and those obtained through mechanical testing.

Fig. 2. The inverted pendulum-like apparatus. The apparatus consisted of a prosthetic foot, a shaft, and a 70-kg mass. The CoM of the weight was mounted at a height of 0.98 m. Two reflective markers were placed on the shaft to determine the shank angle. The GRF and the position of the CoP were measured with a force plate. Roll-over characteristics were determined over a range of $-15^\circ$ to $20^\circ$. A custom-made rig provided lateral guidance during roll-over.

Exemplary roll-over shapes superimposed on contour drawings of prosthetic feet are shown in Fig. 3A. The depicted roll-over shapes of the Esprit foot (left) and the Vari-Flex foot (right) appear to be geometrically distinct. While the roll-over shape of the Esprit foot is characterized by a rather flat middle section, the roll-over shape of the Vari-Flex foot is more circular. Further differences become evident when studying the formation of roll-over shapes with respect to the angular displacement. For the Esprit foot the CoP at zero-degree shank angle (circle) is located more proximal to the ankle than that of the Vari-Flex foot. Further, the clustering of stars (five-degree increments) at the tails of the left roll-over shape indicates that during roll-over the CoP remains at the heel, and afterwards quickly travels forward. In the other example, by contrast, the stars are more evenly distributed, indicating a rather constant curvature. These differences become even more prominent when examining the forward travel (Fig. 3B). The forward travel of the Esprit foot is characterized by an S-shaped progression, with little forward travel in the two plateau phases. The more forward travel there is, i.e., the steeper the slope, the larger is the radius of curvature. The forward travel changes during roll-over, it increases in the middle section, thereby making the foot more stable at this shank angle. The almost linear forward travel of the Vari-Flex foot suggests a nearly constant radius of curvature (Fig. 3C). Here, the instantaneous radius of curvature ($s'$), i.e. the slope of the forward travel, deviates little from the effective radius of curvature ($\rho$, stippled line). The S-shaped progression of forward travel in the Esprit foot is reflected in the three-phased structure of the instantaneous radius of curvature.

The effective radius of curvature ($\rho$, Fig. 4A) was found to differ widely between the tested foot models. Shoes cause a reduction in radius of curvature. Interestingly, feet with a small radius of curvature appeared almost invariant to the effect of applying shoes. Along with the effective radius of curvature ($\rho$), the roll-over characteristics of a foot are determined by the horizontal position of the center of curvature (Fig. 4B). The center of curvature ($x_0$) varied widely among foot models. It shifted closer towards the shaft as response to the different shoes. As a result the roll-over shapes created by the foot–shoe combinations have a rather ‘neutral’ orientation.
straightened by means of different shoes. The hiking boot appeared to modulate the forward travel the strongest. The instantaneous radius of curvature \( s' \) shows these differences between foot models by a reduction in range (Fig. 5B).

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Material &amp; Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endolite</td>
<td>Esprit</td>
<td>• Carbon fiber&lt;br&gt;• Mobility Grades 1–4</td>
</tr>
<tr>
<td></td>
<td>Navigator</td>
<td>• Snubber, ankle ball&lt;br&gt;• PTFE poly(tetrafluoroethylene)-coated keel&lt;br&gt;• Mobility Grades 2 and 3</td>
</tr>
<tr>
<td>Össur</td>
<td>Talux</td>
<td>• Carbon fiber&lt;br&gt;• Tarsal core&lt;br&gt;• Mobility Grades 2 and 3</td>
</tr>
<tr>
<td>Vari-Flex</td>
<td></td>
<td>• Carbon fiber&lt;br&gt;• Mobility Grades 1–4</td>
</tr>
<tr>
<td>Otto Bock</td>
<td>1C40/C-Walk</td>
<td>• Carbon fiber&lt;br&gt;• Mobility Grades 3 and 4</td>
</tr>
<tr>
<td></td>
<td>1D10/Dynamic foot</td>
<td>• Contoured core and foam&lt;br&gt;• Mobility Grades 1 and 2</td>
</tr>
<tr>
<td></td>
<td>1D35/Dynamic motion</td>
<td>• Plastic spring and foam&lt;br&gt;• Mobility Grades 2 and 3</td>
</tr>
<tr>
<td>Nike</td>
<td>Air</td>
<td>• Running shoe</td>
</tr>
<tr>
<td>Vertice</td>
<td></td>
<td>• Leather shoe</td>
</tr>
<tr>
<td>Scarpa</td>
<td>ZG40</td>
<td>• Hiking boot</td>
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The general effects of shoe models on the forward travel \( s \) are given in Fig. 6A. Differences between foot models were prominent (Fig. 6B); while some feet are characterized by a distinct S-shape, others have a rather linear forward travel.
Fig. 3. Roll-over characteristics of prosthetic feet. (A) Exemplary roll-over shapes (solid line) of the no-shoe condition of the Esprit foot (left) and the Vari-Flex foot (right). The circles mark the instantaneous position of the CoP in a shank-based coordinate system at zero-degree shank angle; stars denote the position of the CoP in five-degree increments. (B) The forward travel ($s$) of the CoP during roll-over. (C) The instantaneous radius of curvature ($s'$) is determined as the derivative of the forward travel ($s$). The stippled line indicates the effective radius of curvature ($r$). The larger the radius of curvature, the more stable is the foot.
In amputee gait the prosthetic knee is in full extension during roll-over, making the inverted pendulum apparatus a relevant model of the shank angle of the amputee. The ground reaction forces acting on the prosthetic foot during mechanical testing versus amputee gait are shown in Fig. 7A. The vertical ground reaction force ($F_y$) of amputee gait is characterized by a two-peak shape, corresponding to heel-strike and toe-off. The measurement range of mechanical testing ($r_{15}$ to 20$^\circ$) covers the angular area corresponding to those two peaks. However, the vertical forces produced during mechanical testing are more even and lack the heel-strike/toe-off peaks. Nonetheless, contrasting the forward travel ($s$) obtained by mechanical testing with that of a transtibial amputee revealed strong similarities (Fig. 7B). The gait measurements revealed an effective radius of curvature ($r$) of 352 mm, compared to 322 mm found in mechanical testing.

4. Discussion

Mechanical testing of a broad range of prosthetic feet revealed that the typical radius of curvature varied around 312 mm (Fig. 4A). This effective radius of curvature agrees closely with that found in able-bodied people (Hansen et al., 2004a). In an experiment on the effect of different rocker-foot curvatures on the metabolic costs of walking of able-bodied subjects, a curvature of about 0.3$^\circ$ (leg length) was shown to be energetically
advantageous (Adamczyk et al., 2006). The shoes induced a small reduction in radius of curvature, which made the feet more similar to each other. This reduction in curvature will probably be related to an interaction between shoe stiffness and the unloaded shape of the sole of these shoes. Hansen et al. (2000) reported that shoes did not have as significant an effect on the curvature of a roll-over shape, but offset the roll-over shape by the sole thickness. However, Hansen et al. (2000) used just a single shoe model in their experiment, a soft-soled Nike ACG hiking shoe. The modulating effects of different shoe models on the forward travel, as presented here, indicate that different shoes indeed lead to change in curvature and not just an offset of roll-over shape.

The horizontal position of the center of curvature, which reflects the orientation of the foot curvature, differs widely between feet. Shoes generally reduced the extended orientation of the foot curvature, which is due to heel height of the shoes. The resulting, almost neutral orientation agrees with values found in able-bodied people during steady-state walking (Miff et al., 2008). It is to be noted that the position of the center of curvature of a prosthetic foot can be influenced through the alignment of the prosthesis. Mounting a prosthetic foot in a more dorsally flexed orientation under zero-load should be beneficial for gait initiation, while a more extended orientation serves gait termination (Hansen et al., 2004a, 2000; Miff et al., 2008). For this reason, each prosthetic foot is to be aligned according to its inherent properties and the needs of the patient. This sensitivity of prosthetic foot properties to alignment may also explain why numerous studies failed to identify consistent differences in amputee gait, despite the mechanical differences between the tested prosthetic feet (e.g. Zmitrewicz et al., 2006; Postema et al., 1997; Powers et al., 1994).

However, modeling the roll-over shape as a circle with a uniform radius of curvature and fixed center neglects that feet have no constant curvature. We showed that the forward travel

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**Fig. 6.** Forward travel (s). (A) The effects of shoe on the forward travel of the CoP; data presented are the overall means for all foot models. (B) The forward travel of different foot models measured without shoe.

**Fig. 7.** Comparative illustration of GRFs and forward travel. (A) The vertical ($F_y$) and the forward ($F_x$) component of the GRFs of the amputee (prosthetic side) and during mechanical testing. (B) The forward travel (s) of the CoP during roll-over.
does not progress linearly as it would be the case in feet with a constant curvature. In fact, the forward travel follows an S-shaped curve, in which three sections can be discriminated: a steeper middle section (−5° to 10°), and flattened begin and end sections. The increase in forward travel in the middle section implies a flat/large instantaneous radius of curvature. This suggests a greater stability in stance, which can be assumed to be beneficial for standing stability. Besides, feet with a large travel give in a reduced initial peak of vertical ground reaction forces for the contralateral limb (Hansen et al., 2006; Adamczyk et al., 2006). This may eventually be explained by an increased gain in velocity of the CoM during roll-over and an enlarged directional change of the CoM for feet with a small travel. We propose forward travel as another important measure of prosthetic foot characteristics, due to its implications for gait and stability. We found that forward travel was strongly distinct between prosthetic feet. Shoes imposed slight effects on the forward travel—they made it more constant. This is directly related to the fact that shoes have also curvatures when not loaded.

We found that the available prosthetic feet have widely different biomechanical properties, including strongly distinct roll-over shapes. Shoes modulate these roll-over shapes slightly, but most likely functionally significantly. Since predicting the effect of shoes on prosthetic feet is not straightforward, measurements are indispensable. Here, our study offers a simple method to determine roll-over properties of user-defined foot–shoe combinations. The required equipment is that of a standard gait lab, comprising a force plate and a motion tracking system. In this study the inverted pendulum, which simulated the prosthetic leg, was moved in a strictly sagittal plane with the prosthetic foot pointing straight forward. In clinical practice it is sometimes necessary to mount the prosthetic foot in a deviating orientation. The effects of different outlines of a prosthesis on the roll-over characteristics can be simulated exactly in the same way.

While this method allows emulating the body weight of a person that acts on a prosthetic foot during roll-over, it cannot accurately reproduce the complex multi-joint dynamics that occur during amputee gait. Despite the differences in vertical ground reaction forces, the forward travel curves for amputee gait and mechanical testing were remarkably parallel. The offset between both curves can be explained by differences in prosthesis alignment. With respect to the good agreement of measured roll-over characteristics, the proposed method represents a valuable means to objectively compare foot–shoe combinations. Mechanical testing has advantages compared to measurements in amputees; most importantly, it is not affected by step-to-step variability in amputees. Furthermore, the patient might adjust his gait pattern to the roll-over characteristics of a foot–shoe combination, which would blur the actual differences in roll-over.

In the future it would be interesting to systematically manipulate single properties of prosthetic feet and test their effect on amputee gait. This would give us valuable information on the dynamics of amputee gait and prosthetic design.

 Suppliers

(a) Advanced Mechanical Technology Inc., 176 Waltham Street, Watertown, MA 02472-4800, USA
(b) Vicon Motion System, 14 Minus Business Park, West Way, Oxford OX20JB, UK
(c) The MathWorks Inc., Crystal Glen Office Centre, 39555 Orchard Hill Place, Suite 280, Novi, MI 48375, USA
(d) SPSS Inc., 233 S. Wacker Drive, 11th floor, Chicago, IL 60606-6307, USA

Conflict of interest

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Reprint of the images in Table 1 with kind permission of Otto Bock HealthCare GmbH and Chas A Batchford & Sons Ltd. is acknowledged.

Appendix A. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2009.04.009.

References