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Staying in dynamic balance on a prosthetic limb: A leg to stand on?

Carolin Curtze[a,b,*], At L. Hof[a,c], Klaas Postema[a], Bert Otten[c]

[a] Department of Rehabilitation Medicine, University Medical Center Groningen, Groningen, The Netherlands
[b] Department of Neurology, Oregon Health & Science University, Portland, OR, USA
[c] Center for Human Movement Sciences, University of Groningen, Groningen, The Netherlands

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ABSTRACT

With the loss of a lower limb, amputees lack the active muscle empowered control of the ankle that is important for balance control. We examined single-leg stance on prosthesis vs. sound limb balancing on narrow ridges in transtibial amputees. When balancing on the prosthetic limb, the lateral displacement of the center of pressure was reduced and was compensated by an increase in counter-rotation. We show that single-leg stance on a prosthetic limb can be compared to balancing on a narrow ridge. Standing on a prosthetic limb involves the same balance mechanisms as balancing on narrow ridges of 40-mm to 20-mm width. Yet, the ability to balance on a narrow ridge with the sound limb was only a weak predictor for an amputee's ability to stand on the prosthetic limb. Balancing in single-leg stance on a prosthetic limb is not a common activity. The ability to compensate with the sound limb may therefore be functionally more important than the ability to stay in dynamic balance on the prosthetic limb.

1. Introduction

Single-leg stance is a challenging task and instability in this task is oftentimes considered an indicator for vulnerability [1,2]. To maintain balance when standing on one leg humans use two mechanisms of balance control: (1) moving the center of pressure (CoP) under the stance foot (ankle strategy) and (2) counter-rotation movements around the center of mass [3].

Lower limb amputees lack the active ankle control in their prosthetic limb; both around the talocrural joint, which enables the anterior–posterior ankle strategy, and around the subtalar joint, which enables the lateral ankle strategy in normal feet. From research into perturbed balance in lower limb amputees, we know that the passive properties of the prosthesis contribute to balance control [3, 4]. More specifically, when being perturbed in anterior–posterior direction while standing with both feet on the ground in parallel stance, the CoP can (to some extent) travel along the curvature of the prosthetic foot, thereby contributing to balance control in anterior-posterior direction. Perturbations in lateral direction are counteracted through the load-unload strategy (i.e. modulation of the hip moments) [4].

We propose that when standing in single-leg stance on a prosthetic limb the lateral ankle strategy is limited, similar to standing on a narrow ridge [5-7]. Due to the passive properties of the foot, the CoP under the prosthetic foot can only move laterally when the leg tilts. We hypothesize that amputees will compensate for the lack of active ankle control (lateral ankle strategy) by using the counter-rotation mechanism.

In this paper, we study the balance control mechanisms of lower limb amputees standing on their prosthetic limb in single-leg stance. The analysis method we apply allows dissociating the contribution of CoP displacement (due mainly to the passive stability of the prosthesis) from the counter-rotational mechanism (due to the active balance control of the patient). Finally, this study evaluates balance on narrow ridges with the sound limb as a predictor of balance on the prosthetic limb. We also hypothesize that high balance scores on the Narrow Ridge Balance Test [5] will be correlated with good balance on the prosthetic limb.

2. Methods

2.1. Participants

A group of 18 male unilateral transtibial amputees and 15 male able-bodied controls were included in the study. The amputees had a mean age of 57.1 ± 9.2 years, height of $1.84 \pm .05$ m and weight 88.3 ± 12.9 kg. The most frequent reason of amputation was trauma (12), followed by vascular disease (4), osteomyelitis (1), and limb deficiency (1). Six of the 18 amputees had undergone a transtibial amputation of their right limb, and 12 of their left limb. The time since amputation was between 2 and 44 years (median 6 years). All amputees were experienced and able walkers (K-level $\geq$ 2). In the experiment the amputees used their habitual prostheses which were equipped with one of the following prosthetic feet: Otto Bock

* Corresponding author at: Department of Neurology, Oregon Health & Science University, Portland, OR, USA. Tel.: +1 503 418 2602.
E-mail address: curtze@ohsu.edu (C. Curtze).

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Nomenclature

CoM	center of mass
CoP	center of pressure
$\boldsymbol{F}_G$	ground reaction force
l	effective pendulum length (trochanteric height times 1.34)
r.m.s.	root-mean square
x_{CoP}	lateral position of CoP (mm)
x_{CoM}	lateral position of CoM (mm)
x_h	horizontal distance of CoM to the line of action of the ground reaction force (mm); measure for the 'counter-rotation' mechanism, proportional to arm and leg motion
x, y, z	x-axis medio-lateral, y-axis anterior-posterior, z-axis vertical

1C40 (9), Otto Bock 1D10 (3), Otto Bock 1D35 (2), Otto Bock 1A30 (2), and Endolite Multiflex (1). They were fitted with the following socket and suspension systems: suction suspension (8), elevated vacuum (3), shuttle locking pin (4), KBM (1), PTB (1), and thigh corset (1). The controls had a mean age of 55.3 ± 10.2 years, height of 1.87 ± .05 m and weight of 86.4 ± 9.9 kg.

2.2. Procedure

The participants performed three trials of single-leg stance on the force plate. Both limbs were tested in alternating order, starting with the sound/preferred limb. Subsequently, they performed the Narrow Ridge Balance Test (NRBT) [5]. Participants were asked to balance on one foot, first on the floor and subsequently on six ridges of gradually decreasing width (width 80, 60, 40, 20, 10 and 4 mm, height 25 mm, length 400 mm), placed in dorsoventral direction. The balance tests were performed shod. Participants were free to use arm and leg movements for balance. The test follows an "up-and-down" principle. If the participant maintains balance for 20 seconds the ridge width is decreased, else the ridge width is increased. The test is completed after five trials of less than 20 s each or more than 20 s on the narrowest ridge. One full point is given for each condition that is maintained for 20 s, .25 point for each 5 s stance increment. The scores therefore range theoretically from 0 (unable to maintain single-leg stance on the floor) to 8 (able to stand for more than 20 s on the narrowest ridge). Amputees performed the NRBT with their sound limb only, controls with each limb in alternating order.

The ground reaction forces and moments were recorded by means of a force plate (AMTI; Watertown, Massachusetts) sampling at a rate of 100 Hz. Reflective markers on the toe of each foot were tracked by an eight-camera motion analysis system (Vicon Motion System, Oxford, UK) at a sampling frequency of 100 Hz.

2.3. Outcome parameters

The contribution of the first mechanism was measured as the root-mean square of the lateral displacement of the CoP under the stance limb (r.m.s. x_{CoP}). This mechanism is predominantly active when standing on a wide base of support. The second mechanism, the counter-rotation strategy, comes into play when standing on a narrow base of support. The contribution of this mechanism is described by the r.m.s. distance between the CoM and the line of action of the ground reaction force ($\boldsymbol{F}_{\mathrm{G}}$; Fig. 1; [6]):

$$x_h = (x_{CoP} - x_{CoM}) + l\frac{F_{Gx}}{F_{Gz}}$$

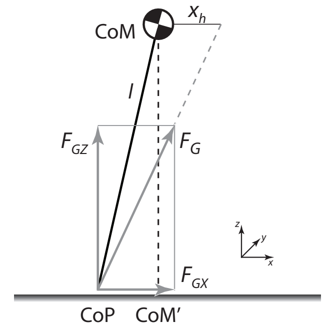

Fig. 1. Inverted pendulum model.

The CoM position x_{CoM} was determined by the 'combi' method [8] from both x_{CoP} and F_{Gx}. To avoid filtering transients the signal section to be evaluated was padded fore and aft by the same signal with reversed time. Finally the r.m.s. value of only the original middle section was used. The effective pendulum length (l) was estimated as trochanteric height times 1.34 [9]. Only data on medio-lateral balance will be given. The vertical acceleration and position of the toe marker of the free leg was used to parse out the beginning and end of single-leg balance.

The Narrow Ridge Balance Test is rated based on the time in balance in relation to the width of the base of support [5]. Only the best of all trials were scored (i.e. the trial on the narrowest ridge with the longest time in balance) per limb. The Narrow Ridge Balance Test has a possible range of 0 – 8 points. A stopwatch was used to time single-leg stance.

2.4. Statistical analysis

The mean r.m.s. of x_{CoP} and x_h was calculated for multiple trials for the same participants. Paired t-tests, as well as independent t-tests were used for comparison. Kruskal–Wallis one-way analysis of variance was used to determine whether there were differences between the two groups in the NRBT score. For controls the best score achieved on either leg was used for comparison. Spearman correlation analyses were used to assess the relationship between the NRBT and the amputees' ability to balance on the prosthetic limb. The level of significance was set to $p \leq .05$.

3. Results

Time series of x_{CoP}, x_{CoM} and x_h of different single-leg stance conditions of an amputee participant are given in Fig. 2. There was a noticeable increase in magnitude of x_h in the more challenging tasks (i.e. standing on the prosthetic limb - Fig. 2B) and balancing on ridges of decreasing width (Fig. 2C & D). This increase in x_h indicates that the counter-rotation mechanism dominates. This can also be observed in the increased arm, free leg, and trunk movements (a video is available as supplementary material).

During single-leg stance on the floor, the r.m.s. x_{CoP} under the prosthetic limb was less than that of the sound limb ($t(17) = -6.677$, $p < .001$) and the controls ($t(31) = -6.410$, $p < .001$; Fig. 3). No differences in r.m.s. x_{CoP} were found between standing on the sound limb in amputees and the controls ($t(31) = -.456$, $p = .651$).

Most amputees maintained balanced on the prosthetic limb for about 2 s only (Fig. 4). Yet, two amputee participants excelled at consistently maintaining single-leg stance on the prosthetic limb for 10 s and longer. There was a large variance in r.m.s. x_h during single-leg stance on the floor (Fig. 4). This variance decreased as a function of time in balance. Variance of r.m.s. x_h was greatest