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The dead spot phenomenon in prosthetic gait: Quantified with an analysis of center of pressure progression and its velocity in the sagittal plane☆

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ABSTRACT

Background: The "dead spot" phenomenon in prosthetics is a disruption in forward progression observed in the rearfoot of passive prosthetic foot-ankle systems which results in a compensatory and inefficient gait pattern by amputees. A metric to quantify the dead spot as a kinetic event has not yet been introduced. The present study implements a three-part metric to evaluate the dead spot in terms of time, magnitude, and total area using center of pressure velocity and a novel threshold value calculation.
Methods: The metrics are implemented for proof of efficacy using a convenient sample of four amputees (2 transtibial, 2 transfemoral) who walked in a 3D motion capture system with integrated force plates over five foot conditions.
Findings: "Continuous-lever" feet designs showed the most favorable metric results between subjects ($p < 0.05$) and in an *ad hoc* analysis compared to an ideal foot condition within subjects ($p > 0.05$). Ten of 18 (55.6%) foot conditions found to be similar to the ideal were continuous-lever feet. Lack of significant similarity between the feet and ideal conditions (1 of 18, 5.6%) were found in transfemoral subjects.
Interpretation: The metric calculations were able to show statistical difference among foot conditions between subjects. One foot (continuous-lever, glass composite) had no detectable dead spot in the transtibial subjects. The lack of significant findings in transfemoral subjects indicates a different coefficient in threshold calculations may be more appropriate for these subjects *versus* transtibial subjects. Further research with larger sample is needed to determine clinically significant findings among feet and between transtibial and transfemoral subjects.
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1. Introduction

The "dead spot" phenomenon (DSP) is a disruption in forward progression observed in the rearfoot of passive prosthetic foot-ankle systems during the stance phase of gait. Amputees describe this phenomenon as a "flat spot" or "stall" in the foot and as a feeling of having to "climb over the prosthetic foot." (De Asha et al., 2013, 2014) The occurrence of the DSP is clinically significant as it requires the amputee to implement a compensatory gait strategy to maintain a smooth prosthetic roll-over which reduces energy efficiency (Adamczyk et al., 2006; Adamczyk and Kuo, 2013; DeLisa et al., 2010; Kuo and Donelean, 2010; Perry and Burnfield, 2010; Ruina et al., 2005; Winter, 2009). This increased ambulatory energy requirement can reduce walking speed, stability, and activity (Kannenberg et al., 2014). Some prosthetic manufacturers claim the DSP is absent or minimized with use of their feet, however, the DSP has not yet been clearly identified kinetically making it difficult to make such a determination.

Progression of the prosthetic foot during the stance phase of gait can be quantified using center of pressure (CoP) (Han et al., 1999). CoP is defined as a point representing the mean of all ground reaction force

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(GRF) acting on the foot at any given time during stance (Berki et al., 2015). The importance of CoP to gait stability has been well-documented as it influences the progression of the whole-body center of mass (CoM) (De Asha et al., 2013, 2014; Schmid et al., 2005). CoP patterns have been reported for prosthetic gait with a "stall" or "dwell" of CoP progression commonly occurring in the hindfoot, and a less frequent stall commonly occurring in the forefoot (De Asha et al., 2013, 2014; Schmid et al., 2005). One report identified corresponding points of acceleration change in prosthetic feet.(Schmid et al., 2005) and another described a "braking effect" in amputee gait (De Asha et al., 2013). This braking effect is described as a biomechanical adaptation of the prosthetic foot involving acceleration of the CoM and, as such, may differ between individuals. The DSP is being differentiated here as it is a local mechanical behavior specific to the prosthetic foot.

Several metrics have been created to describe prosthetic foot behavior. Roll-over shape is a transformation of CoP in relation to the shank or leg to provide a representation of prosthetic foot or total prosthesis behavior (Hansen et al., 2000, 2004). The resulting roll-over radius is a best-fit curve, which enables gross description of CoP progression, but may lack precision in quantifying short-duration perturbations according to De Asha et al. (2013). Thus, roll-over shape may not be able to identify if a DSP occurs in CoP progression within a prosthetic foot, nor does it attempt to separate DSP from the remaining foot behavior. Inverse dynamic calculations have also been used to describe foot behavior and gait by quantifying ankle action (Shultz et al., 2010; Stief et al., 2008). Inverse dynamic calculations are based on assumptions of rigid segments and defined joint axes which are not present in most feet designed to mimic the polycentric action of the anatomical ankle-foot complex (De Asha et al., 2013). Therefore, inverse dynamic methods will likely have measurement error thus reducing accuracy in prosthetic application. Moreover, the ability for traditional inverse dynamic methods to be able to quantify DSP is questionable. Any proposed method to quantify DSP must be applicable across all prosthetic foot designs. Further, such a method must include the ability to discern small kinetic events as the DSP may be an accumulation of short-duration events rather than a gross event.

The purpose of this study was to quantify the dead spot phenomenon of prosthetic gait in various passive prosthetic foot-ankle system designs using a convenient sample of lower extremity amputee subjects. It was hypothesized that a thorough analysis of center of pressure progression, using its velocity in the sagittal plane, would differentiate DSP behavior in prosthetic foot-ankle systems with various design and material characteristics from one another. It was also hypothesized that these metric values could distinguish between various systems compared to a hypothetical ideal condition devoid of any dead spot occurrence.

2. Methods

2.1. Metric development

CoP data is used to determine foot progression in stance phase and is recorded by systems utilizing force plates, plantar pressure sensors, and gait mats, providing potential for several modes of implementation of the proposed metric. A CoP sagittal plane velocity (CoP_{vs}) can be calculated from the CoP position data by dividing the difference in position between consecutive data points by the elapsed time between them. This graph (Fig. 1) yields troughs which correspond to the plateaus in the CoP position graph. The first trough indicates the DSP. An ideal CoP_{vs} mean can be taken by dividing the foot length by stance time for each step being evaluated. This value would represent a CoP progression devoid of any disruption and, therefore, the most energy efficient outcome (Adamczyk et al., 2006; Adamczyk and Kuo, 2013; Ruina et al., 2005). From this mean, a threshold is calculated to isolate DSP data using a constant coefficient. Analyses performed during the initial development of the metric showed a coefficient of 0.6, or 60% of the mean CoP_{vs}, to yield the most significant results between conditions. Only CoP_{vs} data within 10–50% of stance phase is compared against the DSP threshold. Data before 10% of stance is excluded, as it is the initial loading action of the heel lever and is confounded by double support (Perry, 1992). Data after 50% of stance is also excluded, as it is behavior specific to the toe lever of the prosthetic foot (Schmid et al., 2005).

CoP_{vs} data which falls below, or at a slower rate than the DSP threshold value during the target timeframe is identified as dead spot-qualifying data. The proposed metric utilizes three values (Fig. 2) to quantify the DSP: 1) total dead spot time; the sum of DSP-qualifying data time reported as a percent of stance, 2) dead spot magnitude; the minimum DSP-qualifying CoP_{vs} value, and 3) total dead spot area; the sum of the areas of each DSP-qualifying data point. For each area, which is essentially the area under the CoP_{vs} curve determined using the threshold as a baseline, the height is the difference between that DSP-qualifying CoP_{vs} value and the DSP threshold. The width is the regular time elapsed between each CoP_{vs} data point. The location of occurrence of the dead spot magnitude is also reported as a percent of stance phase as it may prove to be a factor in perception of the DSP. The aforementioned variables are recorded per step on the prosthetic foot and averaged across a number of trials. Each of these variables independently describe an aspect of DSP occurrence and are vital to understanding DSP as it relates to prosthetic foot behavior and design.

2.2. Subjects

Subjects were recruited from local prosthetic clinics. Inclusion criteria includes:

- ≥18 years of age
- ≥2 years prosthetic experience
- Currently use a prosthesis regularly
- Function at ≥K3 functional level
- Non-vascular etiology
- Stable health and residual limb status
- Communicate effectively in English.

Subjects were excluded if any of these criteria were not met.

2.3. Data collection

The study protocol was approved by the Institutional Review Board of Eastern Michigan University (Ypsilanti, Michigan, USA). All subjects gave informed consent prior to testing. Data was collected using an 8-camera Vicon Motion Capture system (Oxford, United Kingdom) and an 8.5 m elevated platform with two embedded AMTI force plates (Watertown, Massachusetts, USA). After collection of anthropometric data, subjects were fit 37 reflective markers placed on anatomical landmarks in accordance with the plug-in gait model (Vicon) (Plug-In Gait Details, 2015). Subjects completed a static calibration pose and performed dynamic walking trials at their preferred self-selected gait velocity (SSGV) until ten complete prosthetic foot strikes on either force plate were recorded for each foot condition. Trajectory and kinematic data was recorded at 120 Hz and kinetic data was recorded at 960 Hz. Desired variables were extracted from using MATLAB R2013a (MATHWORKS, Natick, Massachusetts, USA). CoP data were low-pass filtered using a fourth-order Butterworth filter with a 15 Hz cutoff frequency before statistical analysis.

This study utilized a randomized, double-blinded, repeated-measures design (Raschke et al., 2015). Subjects were tested on five foot conditions. Selected feet were all designed for high-activity users, but varied in material and design characteristics (Table 1). The feet were adjusted to the height of the subject's usual foot, aligned to manufacturer specifications, covered in a white sock, and zip-tied at the proximal attachment by a study prosthetist. The feet were presented in random