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Lower-limb amputee ankle and hip kinetic response to an imposed error in mediolateral foot placement

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ABSTRACT

Maintaining balance while walking is challenging for lower limb amputees. The effect of prosthetic foot stiffness on recovery kinetics from an error in foot placement may inform prescription practice and lead to new interventions designed to improve balance. Ten unilateral transtibial amputees were fit with two prosthetic feet with different stiffness properties in random order. After a 3-week acclimation period, they returned to the lab for testing before switching feet. Twelve non-amputees also participated in a single data collection. While walking on an instrumented treadmill, we imposed a repeatable, unexpected medial or lateral disturbance in foot placement by releasing a burst of air at the ankle just before heel strike. Three-dimensional motion capture, ground reaction force and center of pressure (COP) data were collected for two steps prior, the disturbed step and three steps after the disturbance. During undisturbed walking, coronal ankle impulse was lower by 42% for amputees wearing a stiff compared to a compliant foot ($p=0.017$); however, across steps, both prosthetic recovery patterns were similar compared to the sound limb and non-amputees. Peak coronal hip moment was 15–20% lower for both foot types during undisturbed walking ($p<0.001$), with less change in response to the medial disturbance ($p<0.001$) compared to the sound limb and non-amputees. Amputee prosthetic COP excursion was unaffected by the disturbance (2.4% change) compared to the sound limb (59% change; $p<0.001$) and non-amputees (55% change; $p<0.001$). These findings imply that a prosthetic foot–ankle system able to contribute to ankle kinetics may improve walking balance among amputees.

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1. Introduction

Mediolateral (ML) balance is a critical component of ambulation and relies on precise foot placement (Bauby and Kuo, 2000; MacKinnon and Winter, 1993; Townsend, 1985). To maintain ML stability, the location of the center of pressure (COP) must be within an accuracy of just a few millimeters, with large corrections from subsequent steps and fine adjustments from altered ankle and hip strategies (Hof et al., 2007; MacKinnon and Winter, 1993; Maki and McIlroy, 1997; Winter et al., 1996). Hof's study demonstrated that a coronal plane ankle response corrected for natural errors in foot placement for healthy participants and the sound limb of above-knee amputees during unperturbed walking; however, this strategy was absent for the amputee's prosthetic limb. The reduced capacity to shift the prosthetic limb COP (Hof et al., 2007; Viton et al., 2000) may limit early balance recovery (Maki and McIlroy, 1997), contribute to increased ML foot placement variability (Hof et al., 2007; Klute et al., 2007; Su and Dingwell, 2007) and increase the stepping response to foot placement errors (Segal and Klute, 2014).

Walking with a wider base of support (Curtze et al., 2011; Hof et al., 2007; Su et al., 2007) may be one strategy amputees use to compensate for limited prosthetic limb function; however, they remain 20% more likely to fall compared to age-matched norms (Miller et al., 2001). Lateral instability, which has been shown to be more pronounced in mobility-impaired populations (Holliday et al., 1990; Robinovitch et al., 2013) and a strong predictor of fall and injury risk (Cummings and Nevitt, 1994; Maki et al., 2000), likely contributes to the amputee's elevated fall-risk. Reduced prosthetic limb loading correlated with residual limb muscle weakness (Lloyd et al., 2010; Nadollek et al., 2002), decreased hip abductor moments (Molina-Rueda et al., 2014; Underwood et al., 2004) and the reduced ability to shift the COP (Hof et al., 2007; Viton et al., 2000) likely contribute to balance loss, since muscular activity of the hip abductors, gluteus medius and plantarflexor inverters were

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associated with medial acceleration of the COM (Pandy et al., 2010) and in response to lateral balance disturbances (Hof and Duysens, 2013). Furthermore, strong hip abductor muscles were correlated with improved gait parameters and standing balance (Nadollek et al., 2002).

Prosthetic foot design may influence balance recovery. For example, prosthetic foot stiffness was positively correlated with standing balance control and further study of the effect of prosthetic prescription on walking was encouraged (Nederhand et al., 2012). Winter et al. (1996) emphasized differences between standing and walking balance through differences in COP control mechanisms during quasi-tandem stance (feet separated by 45° simulating double support) versus side-by-side balancing. They suggested quasi-tandem stance was more challenging because it required collaboration between an ankle and hip strategy. Therefore, the goal of this manuscript was to study the ankle and hip joint contributions through measures of coronal moment, impulse and COP to examine the kinetic differences in recovery response. This work compliments Segal and Klute (2014), which demonstrated that amputees wearing either a stiff or compliant prosthetic foot had an exaggerated and more variable stepping response without exaggerated trunk lean. By studying the kinetic strategies, we intend to discover how specific joints contribute to recovery from a foot placement error and the influence of prosthetic prescription.

2. Methods

2.1. Participants and prosthetic components

Fourteen non-amputees and eleven unilateral transtibial amputees gave informed consent to participate in this IRB-approved study. The amputee participants wore a prosthesis for at least six hours per day for a minimum of one year, could ambulate without upper-limb aides, had no history of injurious falls within the previous six months and were considered by an experienced prosthetist to be community ambulators (K3 activity level or higher; (HCFA, 2001)). All participants were free from neurological deficits and underlying musculoskeletal disorders that may have impacted gait by self-report. The individual prosthetic prescriptions and amputee etiologies have been previously reported (Segal and Klute, 2014). All amputee participants were fit and aligned by an experienced prosthetist to two prosthetic feet with different stiffness characteristics in random order. The Seattle Lightfoot2 (model#: SFL165, Trulife, Poulsbo, WA) and the Highlander (model# FS3000, Freedom Innovation Inc, Irvine CA) were categorized as the stiff and compliant foot, respectively. After fitting, amputee subjects were given three weeks to acclimate, tested, and then crossed-over to the other study foot (Fig. 1).

2.2. Perturbation device and experimental protocol

The complete details of the perturbation device design and experimental procedures have been presented previously (Segal and Klute, 2014). Briefly, the pneumatic system's flexible hose and small elbow joint were attached to the medial or lateral ankle and to a ballast tank of compressed air, controlled by a solenoid valve and transistor. A foot switch taped to the bottom of the shoe measured the timing of two consecutive strides, which identified the delay required for a burst of air to release ~135 ms prior to the third consecutive step. This system

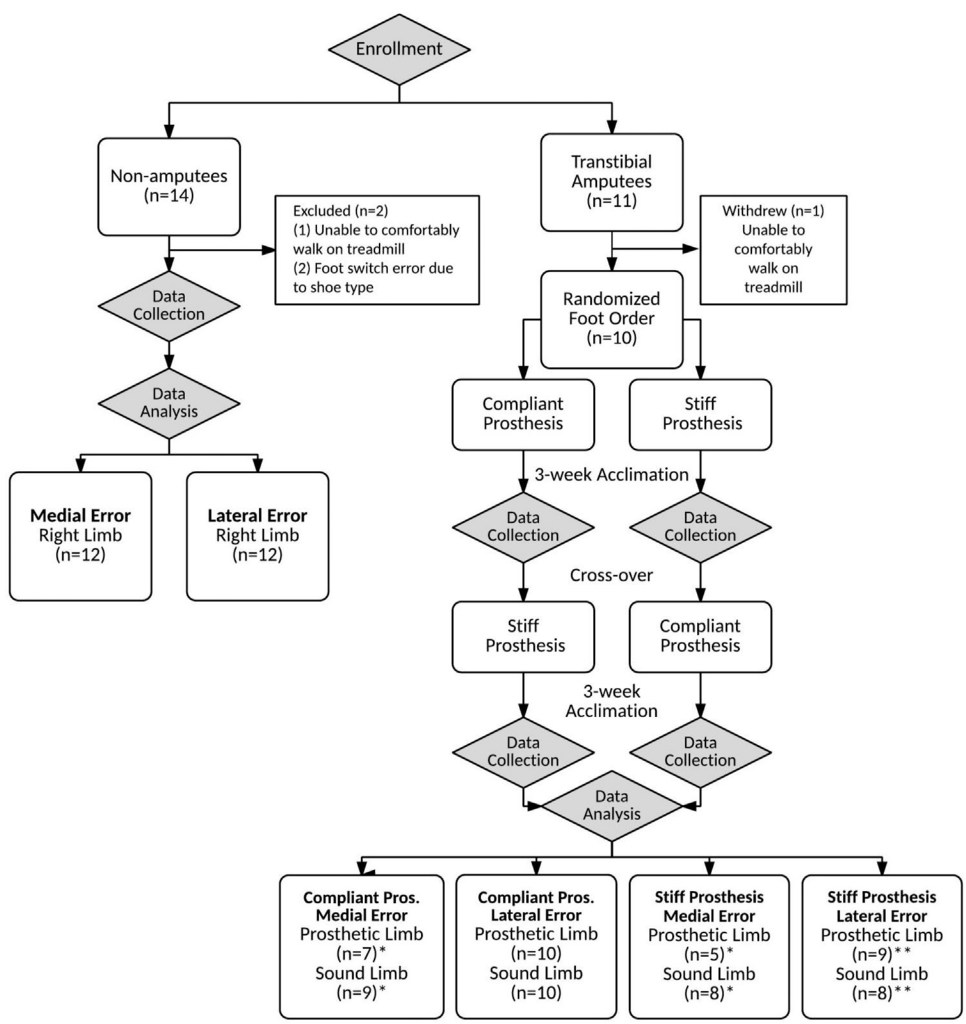

Fig. 1. Study design and subject inclusion flow diagram. Transtibial amputee participants completed a 3-week acclimation period with each prosthetic foot in random order and then returned to the lab for data collection. An asterisk (*) indicates data were excluded from the analysis due to a double foot strike on one treadmill belt. A double asterisk (**) indicates that data were excluded due to instrumentation error.