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Amputee locomotion: Spring-like leg behavior and stiffness regulation using running-specific prostheses

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ABSTRACT

Carbon fiber running-specific prostheses (RSPs) have allowed individuals with lower extremity amputation (ILEA) to participate in running. It has been established that as running speed increases, leg stiffness (K_{leg}) remains constant while vertical stiffness (K_{vert}) increases in able-bodied runners. The K_{vert} further depends on a combination of the torsional stiffnesses of the joints (joint stiffness; K_{joint}) and the touchdown joint angles. Thus, an increased understanding of spring-like leg function and stiffness regulation in ILEA runners using RSPs is expected to aid in prosthetic design and rehabilitation strategies. The aim of this study was to investigate stiffness regulation to various overground running speeds in ILEA wearing RSPs. Eight ILEA performed overground running at a range of running speeds. K_{leg}, K_{vert} and K_{joint} were calculated from kinetic and kinematic data in both the intact and prosthetic limbs. K_{leg} and K_{vert} in both the limbs remained constant when running speed increased, while intact limbs in ILEA running with RSPs have a higher K_{leg} and K_{vert} than residual limbs. There were no significant differences in K_{ankle}, K_{knee} and touchdown knee angle between the legs at all running speeds. Hip joints in both the legs did not demonstrate spring-like function; however, distinct impact peaks were observed only in the intact leg hip extension moment at the early stance phase, indicating that differences in K_{vert} between limbs in ILEA are due to attenuating shock with the hip joint. Therefore, these results suggest that ILEA using RSPs has a different stiffness regulation between the intact and prosthetic limbs during running.

1. Introduction

Recent carbon fiber running-specific prostheses (RSPs) have helped individuals with lower extremity amputation (ILEA) run by providing spring-like properties in their amputated leg. To describe the spring-like leg function during running, the whole body is often modeled with a "spring–mass model" which consists of a body mass supported by a spring (Fig. 1; Blickhan, 1989; McMahon and Cheng, 1990). In this model, stiffness of the leg spring (leg stiffness; K_{leg}) is defined as the ratio of maximal vertical ground reaction force (F_{peak}) to maximum leg compression (ΔL) during the stance phase. Previous studies have demonstrated that able-bodied humans adjust the spring-like behavior for different running speeds by increasing the angle swept (θ) by the stance limb while keeping K_{leg} nearly constant (He et al., 1991; Farley et al., 1993; McMahon and Cheng, 1990; Morin et al., 2005, 2006), indicating that the constant-stiffness leg spring may be a basic and invariant characteristic of running. However, it is still unknown whether ILEA using RSPs shows similar responses between the amputated limb and the intact limb. A better understanding of spring-like leg behavior and stiffness regulation using RSPs will lead to identify potential risk factors of amputee running and optimize prosthesis designs to mitigate these risk factors and improve prosthesis and individual performance through rehabilitation strategies.

It has also been shown that vertical stiffness (K_{vert}; ratio of F_{peak} to maximum vertical displacement of the center of mass at the middle of the stance phase) is a crucial parameter to determine the spring-like function in human running at a wide range of running speeds. Several studies have shown that vertical stiffness increases with an increase in running speed (Cavagna et al., 2005, 2012; He et al., 1991; Kuitunen et al., 2002; McGowan et al., 2012; Morin et al., 2005, 2006). In a multijointed system, K_{vert} further depends on a combination of the torsional stiffnesses of the joints (joint stiffness; K_{joint}, Kuitunen et al., 2002; Butler et al., 2003; Farley et al., 1998; Farley and Morgenroth,

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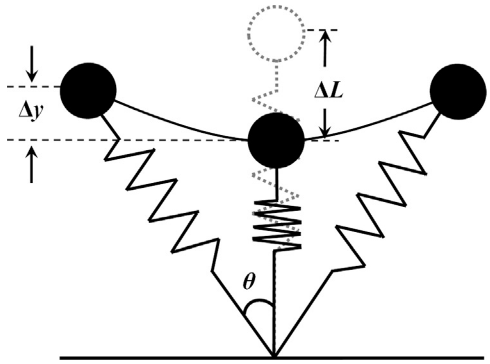

Fig. 1. Spring–mass model for running. The leg spring is compressed during the first half of the stance phase and rebounds during the second half. Maximal vertical displacement of the center of mass and leg spring compression during ground contact is represented by Δy and ΔL, respectively. Half of the angle swept by the leg spring during the ground contact is denoted by θ.

1999; Hobara et al., 2010). Past findings demonstrated that the changes in K_{vert} during running primarily depend on K_{knee} (Kuitunen et al., 2002; Arampatzis et al., 1999; Günther and Blickhan, 2002; Stefanyshyn and Nigg, 1998). Furthermore, K_{vert} is also influenced by the changes in touchdown joint angle because this angle changes the distance of the moment arm of the ground reaction force (GRF) at each joint (Farley et al., 1998; Hobara et al., 2010; Moritz and Farley, 2004).

Despite several studies examining K_{vert} during ILEA running (McGowan et al., 2012; Wilson et al., 2009), little is known about stiffness regulation at joint levels. Understanding spring-like leg behavior and stiffness regulation in ILEA using RSPs is important for evaluating their running ability and developing RSP designs and effective rehabilitation strategies. The aim of this study was to investigate stiffness regulation to various overground running speeds in ILEA wearing RSPs.

According to the previous studies, RSPs generated lower vertical GRFs than intact limbs (Brüggemann et al., 2009; Grabowski et al., 2010; Weyand et al., 2009). Hence, in the present study we hypothesized that (1) leg stiffness would remain constant with an increase in running speed, but the leg stiffness in the intact limb would be greater than the residual limb, (2) vertical and joint stiffness in both the limbs would increase with an increase in running speed, (3) vertical stiffness in the intact limb would be greater than the residual limb and (4) the difference in vertical stiffness would be associated with differences in knee stiffness.

2. Methods

2.1. Participants

Eight male subjects with unilateral transtibial amputation volunteered to participate in the experiment (Table 1). Each ILEA used his own RSP. The study was approved by the local ethics committee of the University of Maryland, College Park Institutional Review Board and prior to testing, written informed consent was obtained.

2.2. Task and procedure

Participants were instructed to run overground on a 100 m long track at 2.5, 3.0 and 3.5 m/s (Fig. 2). Each subject continuously ran around the track and data were recorded whenever the subjects passed through the capture volume. Five successful trials for each leg at each of the three running speeds were taken and averaged for further analysis. A successful trial was defined as the subject running within ± 0.2 m/s of the prescribed speed within the track section containing the force platforms and stepping within the boundaries of the force platforms during the trial. The order for prescribed running speeds was randomized. To facilitate control of the desired running speed, predetermined speeds were governed using concurrent biofeedback. Using four sets of laser sensors around the track, the average speed over the track section was instantaneously calculated when the subjects ran past the sensors, and verbal cues were provided if subjects were outside of the target speed range. Subjects rested for as long as needed between speed conditions to reduce the effects of fatigue.

2.3. Data collection and analysis

Prior to the experiment, retroreflective markers were placed bilaterally over the anterior and posterior iliac spines, heel, 3rd metatarsal head, 5th metatarsal head, and tip of the toe on the shoe. Marker clusters were placed bilaterally on the lateral thigh and shank segments. A static trial was collected prior to dynamic trials that included markers placed on the lateral and medial femoral condyles and the lateral and medial malleoli. On the amputated leg, the shank cluster was placed laterally on the socket and a marker was placed at the distal tip of the socket to define the long axis of the residual shank segment. According to a previous study (Buckley, 2000), the RSP “ankle” joint center was defined as the most acute point on the RSP curvature. Joint angular displacements were determined from the marker data using Visual3D (C-Motion, Germantown, MD) software.

Ten six-degree-of-freedom piezoelectric force platforms (60 cm × 50 cm each and the total measurement area of 600 cm × 50 cm; 9260AA6, Kistler, Amherst, NY) embedded in the track in series collected GRFs at 1000 Hz. The GRFs were filtered using a fourth order, zero lag low pass Butterworth filter with a cut-off frequency of 30 Hz. Furthermore, we captured 3D positional data of the markers using a 10-camera motion capture system (Vicon, Centennial, CO) at 200 Hz. Raw marker data were filtered using a 4th order, zero lag low pass Butterworth filter with a cut-off frequency of 6 Hz.

From vertical GRF (vGRF) data, we determined step frequency (f), stance time (t_c) and maximal vGRF (F_{peak}) in both the intact and prosthetic limbs (INT and PST, respectively). In the present study, we calculated K_{leg} utilizing the spring–mass model (Blickhan, 1989; Fig. 1). During running, the peaks of vGRF and leg compression coincide in the middle of the ground contact phase. At this point, K_{leg} (N/m) can be calculated as the ratio of F_{peak} to peak leg compression in the spring (ΔL) when the leg spring is maximally compressed:

$$K_{leg} = F_{peak}/\Delta L \tag{1}$$

ΔL was calculated from the maximum vertical displacement of the center of mass (COM; Δy), the initial length of the leg spring (L_0), and half of the angle swept by the leg spring while it was in contact with the ground (θ):

$$\Delta L = \Delta y + L_0(1-\cos\theta) \tag{2}$$

with

$$\theta = \sin^{-1}(ut_c/2L_0) \tag{3}$$

where u is the speed of the body (m/s) and t_c is the ground contact time at each step (He et al., 1991; Farley and Gonzalez, 1996; McMahon and Cheng, 1990). Based on the static standing trial, we calculated leg length in INT as the sum of lengths of the hip–knee–ankle joint centers to the ground. For the PST, we defined leg length as the sum of lengths of the hip–knee joint centers to the distal socket to the ground.

Following the previous studies (Blickhan, 1989; Kuitunen et al., 2002; Morin et al., 2005; Farley and Gonzalez, 1996), K_{vert} was also calculated utilizing the spring–mass model. Assuming F_{peak} and Δy coincide in the middle of the ground contact phase, the K_{vert} (N/m) can be calculated as follows:

$$K_{vert} = F_{peak}/\Delta y \tag{4}$$

where Δy is the maximum vertical displacement of the COM during ground contact, which is obtained by integrating the vertical acceleration twice with respect to time (Cavagna, 1975). If F_{peak} and maximal COM displacement did not coincide in the middle of the ground contact phase, we calculated the K_{vert} as the ratio of F_{peak} and COM displacement between the ground contact and the instant of F_{peak} (Hobara et al., 2008, 2009, 2010, 2012).

K_{joint} was calculated with the torsional spring model (Kuitunen et al., 2002; Farley et al., 1998; Farley and Morgenroth, 1999). The K_{joint} (N m/deg) was calculated as a change in the joint moment (ΔM_{joint}) divided by the change in joint angular displacement ($\Delta\theta_{joint}$) in the middle of the ground contact phase:

$$K_{joint} = \Delta M_{joint}/\Delta\theta_{joint}. \tag{5}$$

In the present study, the joint moments were determined by utilizing rigid linked segment model, anthropomorphic data (Dempster, 1955), and inverse dynamics analysis (Winter, 1990). Since body mass influences the stiffness (Farley et al., 1993), K_{leg}, K_{vert} and K_{joint} were divided by the subject's body weight (BW).

2.4. Statistical methods

A two-way repeated measures ANOVA with two factors, running speed (three levels) and limbs (two levels), was performed to compare INT and PST at three running speeds. Bonferroni post hoc multiple comparison was performed if a significant main effect was observed. Statistical significance was set at $p < 0.05$. Statistical analysis was executed using SPSS (IBM SPSS Statistics Version 19, SPSS Inc., Chicago, IL).