CONTRIBUTION OF ACTIVE DORSIFLEXION TO TOE CLEARANCE IN TRANSTIBIAL AMPUTEES: A CASE STUDY

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INTRODUCTION

Successful negotiation of varying terrains and obstacles is critically dependent upon minimum toe clearance, the distance between the walking surface and the toe of the swing limb, at midswing (MTC). For transtibial amputees (TTA), the absence of active ankle dorsiflexion during swing initiation lowers MTC. The associated increased probability of hitting an unseen obstacle (Best et al, 2007) may contribute to the 42.9% of TTA that reported falling over a 1 month period (Gauthier-Gagnon et al, 1999).

A recently designed prosthesis, with active control of swing phase dorsiflexion, was developed to provide adaptation to variable terrains, while increasing MTC (Ragnarsdóttir 2005). However, MTC depends not only on ankle kinematics, but also those at the hip and knee (Moosabhoy et al. 2005) all of which are walking speed-dependent (Borghese et al 1996). For this reason, active dorsiflexion alone may be insufficient to improve MTC. Therefore the purpose of this study was 1) to compare MTC for TTA on level and inclined surfaces, at varying speeds, with and without actively controlled dorsiflexion and 2) to develop a model to quantify the contribution of ankle kinematics to MTC. In all cases, we expected MTC and ankle contributions to increase with actively controlled dorsiflexion.

METHODS AND PROCEDURES

One subject (male, age 40, 81.6 kg, 1.8m) who suffered a traumatic transtibial amputation 12 years prior, and uses a prosthesis with active ankle dorsiflexion control (Proprio Foot ®, Ossur, Aliso Viejo, CA) participated. The subject walked on a treadmill for 30 sec at a slow, preferred and fast speed on 2 different inclines: level and 5º uphill, with and without the control feature of the prosthetic engaged (“on” and “off” respectively). The motion of 22 passive reflective markers was recorded at 60 Hz and used to calculate MTC and hip, knee and ankle kinematics from toe off (TO) to midswing (MS).

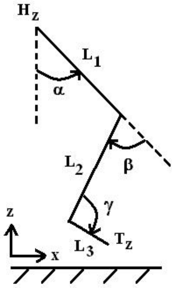

Figure 1. Three segment model of the swing limb in the sagittal plane. Positive joint angles are shown with arrow. Vertical toe and hip position (T_z and H_z respectively) and segment lengths (L_1, L_2, L_3) are noted.

A three segment model of the lower limb (Figure 1) lead to the following relationships:

$$T_z(t) = H_z(t) - L_1\cos(\alpha(t)) - L_2\cos(\beta(t) - \alpha(t)) - L_3\cos(\pi + \alpha(t) - \beta(t) - \gamma(t))$$

$$MTC = Tz(MS) - Tz(TO) = dT_z =$$

$$\int_{TO}^{MS}\left(\frac{\partial T_z}{\partial H_z}\frac{dH_z}{dt} + \frac{\partial T_z}{\partial \alpha}\frac{d\alpha}{dt} + \frac{\partial T_z}{\partial \beta}\frac{d\beta}{dt} + \frac{\partial T_z}{\partial \gamma}\frac{d\gamma}{dt}\right)dt$$

The partial derivatives (i.e. $\partial T_z/\partial\gamma$) represent the sensitivity, or rate of change of T_z with respect to each angle (Moosabhoy et al, 2005) or to hip position. Multiplying this rate of change by the observed changes (i.e. $d\alpha/dt$) and integrating over time, the "total contribution" of each joint to MTC, expressed in mm, is obtained. A positive value suggests the cumulative motion of the joint from TO to MS acts to increase MTC. Contributions for each joint are calculated on a step-to-step basis, averaged across steps (N=15 steps), and theoretically sum to MTC. Contributions can not be determined by direct comparison of single joint kinematics.

RESULTS

MTC for the "on" condition was larger than that of the "off" condition for the preferred and fast walking speeds. At slow speeds the two conditions were similar (Figure 2). For the "on" condition, MTC increased from slow to preferred speed, and the ankle contribution became positive. For the "off" condition, ankle contribution was always negative.

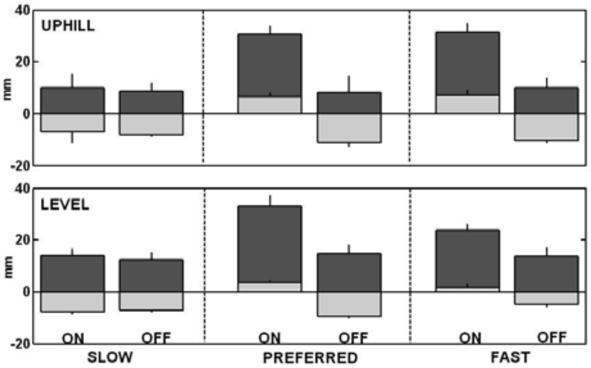

Figure 2. MTC (dark grey bar) and contribution of the ankle to MTC (light grey) for level and uphill walking, at three speeds, during on and off conditions (mean ± SD).

DISCUSSION

Active control of ankle dorsiflexion had the greatest influence on MTC at faster speeds during uphill walking. This is evidenced by the fact that MTC and ankle contributions were the largest for "on" trials at preferred and fast speeds. In addition to a positive ankle contribution, the increased MTC at higher speeds also reflects a more positive contribution from hip and knee joints. We found that ankle dorsiflexion, from TO to MS, always increased MTC ($\partial T_z/\partial\gamma<0$). A negative ankle contribution may be explained by one of two scenarios. One, the ankle does not dorsiflex ($d\gamma/dt>0$), as observed in all of the "off" trials. Two, ankle dorsiflexion begins too close to MS to counter the negative contribution due to plantarflexion in early swing. Thus, negative contributions during the "on" condition may reflect an inability of the prosthesis to properly adapt to slow speeds. Since ankle contributions were greatest during uphill walking, which requires greater dorsiflexion to clear the surface, we believe that the foot can successfully adapt to changing terrain.

Although our results constitute strategies adopted by an individual, the strength of this study lies in the variety of conditions tested and the novelty of the quantitative methods used.

SUMMARY

Active control of swing phase dorsiflexion by a prosthetic foot was directly linked to an increased MTC at preferred and fast speeds on level ground and inclines. It is unclear why ankle control at slow speeds was not associated with a positive effect on MTC.

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