The Biomechanical and Met-toe-bolic Effects of Walking on a Passive Prosthetic Foot with an Added Toe Joint

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Summary

The purpose of this study is to explore how individuals with transtibial amputation walk with vs. without a toe joint in their prosthetic foot, as well as to quantify how toe joint stiffness affects gait biomechanics and metabolic cost. We created a custom foot prosthesis that enables us to systematically vary toe joint stiffness from low to infinite (locked joint), then tested individuals walking on level ground, slopes, stairs and uneven terrain while we collected ground reaction forces, kinematics and also oxygen consumption for level ground. Here we present preliminary results from the first subject, who underwent a 4-day training and testing protocol. Data collection on additional subjects is currently underway, and we plan to present these more extensive, multi-subject biomechanics results at the conference.

Introduction

Biomimetic approaches to prosthetic foot design have primarily focused on mimicking ankle function, but the design of the foot itself has received far less attention. For instance, the biomechanical and metabolic consequences of toe joint articulation are relatively unexplored in the scientific literature. However, walking simulations suggest optimizing toe joint stiffness may improve walking economy [1]. Recently, toe joint stiffness has been shown to greatly affect center-of-mass dynamics (e.g., work done during push-off) in able-bodied subjects walking on simulator boots [2]. To date, what has not been studied is the effect of toe joint dynamics on individuals with amputation. We therefore aim to assess the biomechanical and metabolic effects of toe joint stiffness on transtibial prosthesis users (TPU) during various tasks.

Methods

We modified a commercial prosthesis (Balance J, Össur) such that we can vary the stiffness of the toe joint. In our study, subjects undergo a two-day training protocol, in which they have time to acclimate to the modified prosthesis, the different toe joint conditions and the various ambulation tasks (walking on flat level ground, uneven terrain, inclined/declined slopes, and stair ascent/descent). Subjects then return for two days of instrumented gait analysis testing, in which kinematic (Vicon), and ground reaction force (Bertec) data are collected; and also oxygen consumption (Cosmed) during level ground walking.

We are exploring three toe joint conditions: 0.27 Nm·degree^{-1} stiffness (LOW), 0.33 Nm·degree^{-1} stiffness (MODERATE), and locked-out with a metal strut (INFINITE). We compute prosthesis power using methods outlined in [3], which capture power due to rotational and translational deformation of the prosthesis. We also collect subjective user feedback. To date, one TPU (33 year old male, 119 kg, K4 mobility level) has completed the full 4-day protocol; with data collection from additional subjects ongoing. Level walking results are summarized in this Abstract, with the expectation of sharing more extensive multi-subject results at the conference.

Results and Discussion

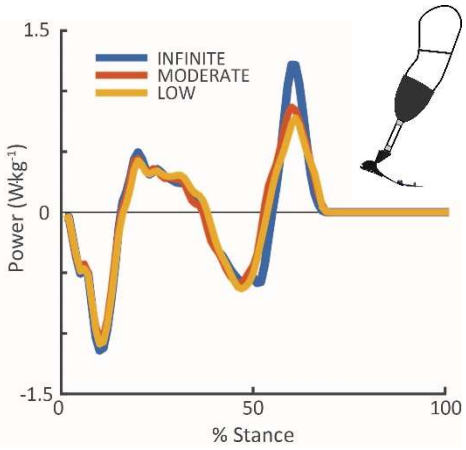

Figure 1 Prosthesis power for level walking with LOW, MODERATE and INFINITE stiffness toe joints.

During level walking, peak prosthesis push-off power was 39% (0.81 W·kg^{-1}) and 29% (0.94 W·kg^{-1}) higher with the INFINITE toe joint stiffness relative to the LOW and MODERATE stiffness conditions, respectively (N=1). This increase in peak push-off power with increasing toe stiffness aligns well with prior findings from able-bodied subjects [2]. The LOW condition yielded the lowest metabolic rate (14.1 ml O_2·kg^{-1}·min^{-1}) compared to MODERATE (14.7 ml O_2·kg^{-1}·min^{-1}) and INFINITE (14.6 ml O_2·kg^{-1}·min^{-1}); however, differences in metabolic rate between all conditions were <5%. Statistical analysis will performed pending more subjects. Interestingly, the small metabolic reduction of the LOW stiffness toe joint may have been perceived by the subject, who reported this condition as the one they felt required the least effort to walk on level ground. Over all locomotor tasks, the MODERATE stiffness toe joint was the subject's preference, despite the reduction in peak prosthesis push-off power relative to INFINITE (Fig. 1). From here, we will continue to investigate the effect of this toe-articulating prosthesis on the biomechanics and energetics of TPU across level, sloped, stairs and uneven terrain gaits.

Acknowledgments

This research was supported by NIDILRR (0IFRE0001).

References

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