Addition of a Passive Toe Joint: Considerations for Passive and Powered Ankle-Foot Prosthesis Design

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Summary

Research and design of ankle-foot prostheses has largely focused on optimizing ankle function; however, the potential benefits of modifying the foot keel remain relatively unexplored. In particular, the addition of a toe joint has the potential to positively impact the gait biomechanics of prosthetic device users, and reduce the motor demands of powered prostheses. To fill key knowledge gaps, our overarching goal is to perform a series of experiments – using powered and passive prostheses – in which we systematically vary toe joint stiffness and quantify the biomechanical effects on activities of daily living (e.g., walking, stair ascent). This abstract details prosthetic hardware development and validation testing necessary to add a variable-stiffness toe joint into powered and passive prosthetic feet in order to carry out the proposed experiments.

Introduction

The majority of existing ankle-foot prostheses do not incorporate an articulating toe (metatarsophalangeal, MTP) joint; a feature that has been shown to greatly affect gait biomechanics [1]. Based on prior experimental and simulation studies, adding a toe joint to prostheses could potentially improve the gait of users, and in the case of powered (motorized) prostheses, may also reduce the actuator and battery demands [2]. However, to date, there is very little data on how toe joint dynamics affect ambulation of lower limb prosthesis users. We seek to address this by performing a comprehensive motion analysis study in which we systematically vary toe joint stiffness; first in passive, and then in powered prostheses. However, to conduct this novel systematic study, we first need to develop and validate custom-modified prosthetic hardware. The objective of this abstract is to summarize design, fabrication and validation testing of ankle-foot prosthesis prototypes that include an adjustable stiffness, articulating toe joint.

Methods

A commercial passive ankle-foot prosthesis (Balance J, Össur) was modified to include a variable stiffness toe joint (Figure 1A). The toe joint is comprised of thin spring steel sheets secured proximally to the Balance J keel and distally to an aluminium toe plate. The stiffness of the toe joint can be systematically adjusted by varying the number (or thickness) of spring steel sheets used, and the joint can also be locked out (infinite stiffness) using an aluminium strut in place of the spring steel. The stiffnesses of the custom toe joint were characterized by holding the prosthesis stationary and measuring the force necessary to move the toe joint through a known range of motion for two through seven sheets of spring steel. The prosthesis was also tested on a subject with transtibial amputation (33-year-old male, 119 kg) who walked on an instrumented treadmill (Bertec) at 1.14 m·s^{-1} with three toe joint conditions: low (0.27 Nm·degree^{-1}), moderate (0.33 Nm·degree^{-1}), and infinite stiffness (locked joint) while kinematic and ground reaction force data were collected.

Next, we are working on adapting the foot keel of the Vanderbilt Powered Prosthesis [3] to include an articulating toe joint. Similar bench top and case study tests will be conducted to characterize the toe joint stiffness and range of motion, and confirm device function during walking. Refining the control schemes necessary to test this powered prosthesis on several activities of daily living is also in progress.

Results and Discussion

The range of available toe joint stiffnesses for the passive prostheses design are 0.17 Nm·degree^{-1} to 0.34 Nm·degree^{-1}. Results from subject testing show the low and moderate stiffness toe joint dorsiflexed during the push-off phase of walking as expected (Figure 1A). These results confirm the prototype is performing effectively during push-off with the low and moderate stiffness toe joints moving through greater ranges of motion (28.6° and 26.6° respectively) than the infinite stiffness condition (2.3°, Figure 1A).

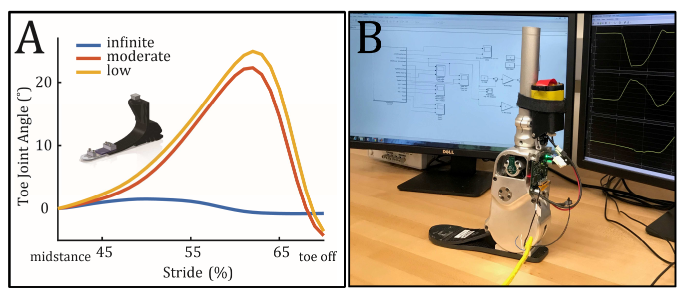

Figure 1: (A) Toe joint angle during the push-off phase of walking with passive prosthesis prototype. (B) Vanderbilt Powered Prosthesis hardware modifications and controller development are in progress.

After adding a toe joint to the powered prosthesis, participants will be fitted with the device, then control scheme parameters will be tuned individually for each user. We expect to share finalized control schemes and toe joint designs at ISB, along with preliminary biomechanics data from subjects completing activities of daily living with vs. without a toe joint.

Acknowledgments

This research was supported by NIDILRR (0IFRE0001).

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