Whole-body walking biomechanics with vs. without a toe joint: implications for prosthetic foot design

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Summary

Unilateral lower-limb amputees are at heightened risk of developing intact limb osteoarthritis, in part due to limitations of conventional prosthetic feet. Osteoarthritis onset can result from repetitive high joint loading, which amputees commonly experience during walking (Morgenroth et al., 2012). Studies suggest that elevated intact limb loading may be due to a lack of Push-off power generated by the prosthetic limb during the step-to-step transition. We posit that it may be possible to incorporate/restore toe joint dynamics in prosthetic feet, in a way that enhances overall prosthetic limb Push-off capabilities. However, the interplay between the ankle and the toe joints are not yet sufficiently understood. We sought to address this knowledge gap by developing a reconfigurable prosthetic foot that enables us to study the dynamic interplay between the ankle and toe joints during locomotion, and their effect on whole-body walking biomechanics. Preliminary experiments were performed on three able bodied male subjects wearing a reconfigurable prosthesis containing an ankle and toe joint. Inclusion of a toe joint led to an increase in peak center-of-mass Push-off power generated by the prosthetic limb. These findings suggest that it may be possible to leverage toe joint dynamics to improve amputee walking performance, by facilitating Push-off. Increased Push-off may, in turn, help to reduce repetitive, high loading of the joints, which is linked with long-term degenerative health risks.

Introduction

In order to increase prosthetic limb Push-off, and thus to reduce amputee intact limb joint loading (and long-term osteoarthritis risk), it has been proposed that prosthetic feet should be developed to generate more Push-off power. Powered prostheses have demonstrated the ability to restore biological ankle Push-off capabilities; however, they require a heavy motor and power supply, and can be expensive to design, control, and maintain. For instance, commercially-available powered prosthetic feet can cost in excess of $50,000, which limits societal accessibility and widespread adoption of the technology.

Consistent with recent modeling studies (Sun et al., 2016), we hypothesize that it may also be possible to increase prosthetic limb Push-off power without robotic actuation, by designing prosthetic feet that take advantage of anthropomorphic features found in the human foot. It has been suggested that toe joint flexion plays an important role in Push-off capabilities. However, nearly all commercially-available prosthetic feet are designed without an articulating toe joint. We developed a reconfigurable prosthesis that enables us to study the dynamic interplay between the ankle and toe joints during locomotion, and their effect on whole-body walking biomechanics. Here we present preliminary experimental findings and demonstrate proof-of-concept that the inclusion of a toe joint can indeed facilitate increased prosthetic limb Push-off capabilities during walking.

Methods

We tested how adding a toe joint into a prosthetic foot affected center-of-mass (COM) mechanics, specifically prosthetic limb Push-off power. Preliminary experiments were performed on three able bodied male subjects (mean±std, 22.7±1.5 years old, 90.2±9.8 kg, 1.82±0.02 m tall) wearing simulator boots. A reconfigurable prosthetic foot (with adjustable ankle and toe stiffness, Fig. 1) was built and attached unilaterally under the simulator boot (a boot that constrains ankle rotation).

A lift shoe was worn on the contralateral foot. Subjects underwent a 15 minute acclimation period of wearing of the prosthesis and lift shoe prior to testing. Next, the subjects walked at constant speed (1 m/s) and step frequency (85 steps/min) on a split-belt instrumented treadmill (Bertec). Each subject tested the prosthetic foot under two different conditions: with an articulating elastic toe joint vs. without (i.e., toe joint locked). Ground reaction forces were low-pass filtered at 25 Hz. We computed COM power for each limb using the individual limbs method (Donelan et al. 2002). Each subject gave informed consent to participate in this study.

Figure 1: Prosthetic foot with adjustable ankle and toe joint stiffness. We compared walking with an elastic toe joint (left) vs. without (right; rigid strut inserted across joint to prevent toe rotation).

Results

In all subjects tested we found that inclusion of a toe joint led to an increase in peak COM Push-off power generated by the prosthetic limb (Fig. 2). We also observed reduced peak intact limb COM Collision power, as compared to walking without a toe joint, in two out of the three subjects (Table 1).

Discussion

Our reconfigurable/adjustable prosthetic foot prototype (Fig. 1) provides a useful research tool, allowing us to isolate the effect of individual parameters and to gain insight into toe joint functionality during locomotion. Preliminary findings suggest that it may be possible to leverage toe joint dynamics to improve amputee walking performance, by facilitating Push-off. Increased Push-off may, in turn, help to reduce repetitive, high loading of the joints, which is linked with long-term degenerative health risks (Morgenroth et al., 2012). We acknowledge that passive feet will never fully replace capabilities of powered devices, but may nonetheless provide an affordable solution that is sufficient for community ambulators who desire to remain physically, socially and/or professionally active.

Our future studies will expand upon this pilot testing. We plan to test a larger number of able-bodied subjects, and to begin testing transtibial amputees. We will perform comprehensive, systematic testing of various parameters (e.g., ankle and toe stiffness, foot and toe lengths), which will contribute to our fundamental understanding of ankle-toe dynamics, as well as inform the design of prosthetic feet.

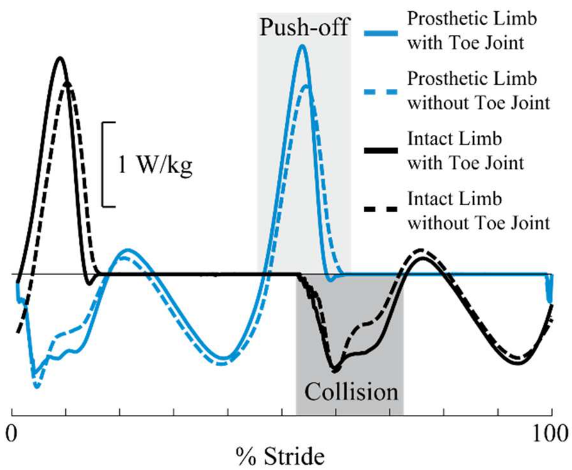

Figure 2: COM power for the prosthetic and intact limbs, for a representative subject. Inclusion of a toe joint led to increased peak Push-off power.

References

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Table 1: COM power summary measures for subjects walking with vs. without an articulating toe joint.

	With Toe Joint		**Without Toe Joint**	
Peak Power	**Prosthetic Limb Push-off (W/kg)**	**Intact Limb Collision (W/kg)**	**Prosthetic Limb Push-off (W/kg)**	**Intact Limb Collision (W/kg)**
Subject 1	2.96	-1.32	2.52	-1.03
Subject 2	2.14	-2.63	2.07	-3.08
Subject 3	2.70	-1.71	2.22	-2.05