

QUANTIFYING THE EFFECTS OF TOE AND ANKLE JOINT STIFFNESS, AND THEIR INTERPLAY, ON WALKING BIOMECHANICS USING AN ADJUSTABLE PROSTHETIC FOOT

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INTRODUCTION

The purpose of this ongoing study is to isolate the effects of the metatarsophalangeal (MTP) and ankle joint stiffness, and their interplay, on walking biomechanics. The effects of ankle stiffness (in prostheses) and quasi-stiffness (in the biological limb) have been documented in prior literature; however, the effects of MTP joint stiffness - hereafter referred to as toe joint stiffness - are less well characterized. The toe joint undergoes a dorsiflexion range-of-motion in late stance (sometimes referred to as the forefoot rocker phase) comparable to ankle range-of-motion during walking [1]. Walking models also predict that toe joint articulation may improve mechanical cost of transport [2]. However, limited experimental data exist on the effects of toe joint stiffness, or its interaction with ankle stiffness, since toe joint stiffness cannot be easily varied within the biological foot or in commercial prostheses. Here we custom-designed and tested an adjustable prosthetic foot to isolate toe joint, and ankle-toe stiffness effects. This research is expected to provide insight on the functional benefits of toe joint articulation, and may inform optimal toe joint properties to incorporate into prosthetic foot design.

METHODS

We designed and fabricated a (right and left) pair of adjustable foot prostheses with a sagittal rotational degree-of-freedom to approximate the ankle, and a single rotational degree-of-freedom to approximate the composite toe (MTP) joint axes in the biological foot. This design allows us to independently adjust ankle and toe joint stiffness, and other parameters such as toe length and shape.

Four healthy, non-amputee subjects (2 males, 2 females, 22 ± 3 yrs, 74.8 ± 5.3 kg, 1.76 ± 0.07 m) have thus far participated and provided informed consent for this gait analysis study. Subjects wore the foot prostheses bilaterally below simulator boots (which immobilize the biological ankles). Subjects walked at 1.0 m/s on a split-belt, instrumented treadmill while we recorded ground reaction forces (GRFs) and lower-limb kinematics. Each subject walked with 20 different ankle and toe joint stiffness combinations, which spanned above and below normal ranges [3]. Ankle joint stiffness was varied from 40 to 200 N·mm/deg·kg. Toe joint stiffness was varied from 0 to 10 N·mm/deg·kg, and we also tested an infinitely stiff (locked joint) condition. GRFs were used to compute center-of-mass (COM) power through the individual limbs method [4]. COM Push-off work was computed as one key outcome metric, based on prior literature (e.g., [4, 5]).

RESULTS AND DISCUSSION

Preliminary findings suggest that both toe and ankle joint stiffness affect COM Push-off dynamics, and that the effect of toe joint stiffness is more pronounced with stiffer ankles. We observed that COM Push-off work increased with toe joint stiffness. Given a constant toe joint stiffness, a medium ankle stiffness (100-160 N·mm/deg·kg) resulted in the

highest COM Push-off work. Additionally, the effects of toe joint stiffness were larger as ankle stiffness increased, as evidenced by the larger range of COM Push-off work: 4 J at the lowest ankle stiffness vs. 7 J at the highest ankle stiffness (Figure 1).

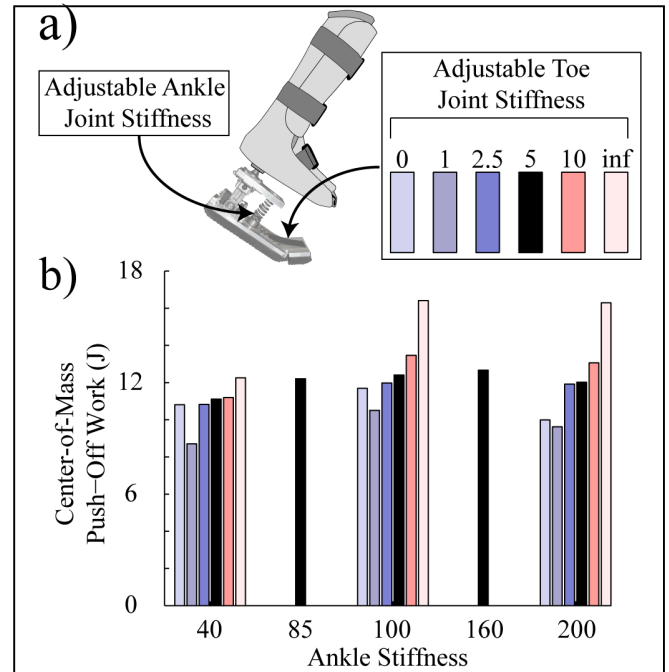


Figure 1: a) Adjustable foot prosthesis, and b) center-of-mass (COM) Push-off work during walking at 1.0 m/s for different ankle and toe joint stiffnesses ($N=4$). All stiffness values are reported in units of N·mm/deg·kg.

In this ongoing study, we also plan to examine ground reaction forces, joint kinematics and kinetics, and metabolic cost. Statistical analysis will be performed after additional subjects are collected. Other foot parameters such as toe shape, toe length, and foot length will also be varied. Results from this work will be used to inform a follow-up study on individuals with transtibial amputation.

CONCLUSIONS

Toe joint stiffness affects Push-off dynamics in gait, and the magnitude of this effect increases with ankle stiffness.

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REFERENCES

1. Bruening DA, et al. *Gait & Posture*, **35**:529-534, 2012.
2. Huang Y, et al. *IEEE/ASME ICAIM*, 625-657, 2010.
3. Zhu J, et al. *IEEE Transactions on Industrial Electronics*, **9**: 4797-4807, 2014.
4. Donelan JM, et al. *J. Biomech.*, **35**: 117-124, 2002.
5. Zelik et al., *IEEE TNSRE*, **19**: 411-419, 2011.