Effects of material of the 3D printed foot on ankle kinematics/kinetics and toe joint bending during prosthetic walking

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Introduction

Toe joint can impact a gait economy and performance while undergoing substantial flexion/extension during normal walking. To provide the benefits of a toe joint to the amputees, researchers have attempted to mimic human toe joint in their prostheses. [1] proposed a powered toe joint, and [2] applied interchangeable springs to mimic a human toe joint during prosthetic walking, which inevitably require additional parts, and thus more weight.

We previously proposed the structural pattern and material of the 3D printed prosthetic foot in [3]. However, it is not known yet how the joint kinematics/kinetics and toe joint bending are affected by the new design. Thus, in this study, we investigate how the ankle/toe joint kinematics/kinetics vary in accordance with the 3D printed prosthetic foot characteristics while walking.

Methods

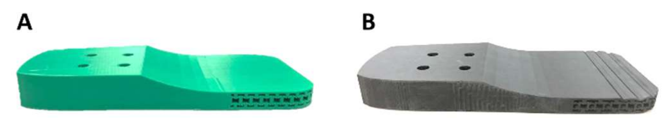

Figure 1: 3D printed prosthetic foot; (A) re-entrant structure using ABS, (B) re-entrant honeycomb with bending zone (BZ) using onyx [3]

Note that there was no stiffness difference between two proposed foot structures (Figure 1) under the small bending conditions according to the simulation result in [3]. Therefore, we focus only on the foot material in this paper.

A treadmill walking experiment was conducted using a powered transfemoral prosthesis (AMPRO II, [4]) with two different feet (ABS and onyx foot), depicted in Figure 1. A healthy subject (male, 31 yrs., 1.70 m, 70 kg) participated using an L-shape simulator and walked at his preferred speed (0.60 m/s). Joint kinematics were recorded by the optical encoders on the prosthesis. Joint kinetics were estimated based on the current from the actuators of the prosthesis. The toe bending was measured using IMUs, defined as the relative angle between the forefoot and midfoot. The control framework adopted was impedance control at the ankle and a hybrid of impedance and tracking control at the knee [4].

Results and Discussion

The onyx foot had lesser ankle dorsi-flexion than the ABS foot (Figure 2A), resulting in lesser ankle joint torque (Figure 3A). However, the difference is minimal. In Figure 2B, the greater toe flexion (2.46 °) was clearly shown when the onyx foot is used, while that of the ABS foot is smaller (0.74 °). Yet, differing from the simulation result (15 °) in [3], this flexion is still small, even in the case of onyx. This may indicate that the toe stiffness of both feet is still too stiff. Also, an insufficient loading condition due to the simulator and less body weight (compared to the simulation) can be another possible reason of a small toe flexion. Further studies should be conducted with a diverse compliant toe.

In Figure 3, the ABS foot shows a slightly larger joint torque and power than the onyx foot, even though not significant.

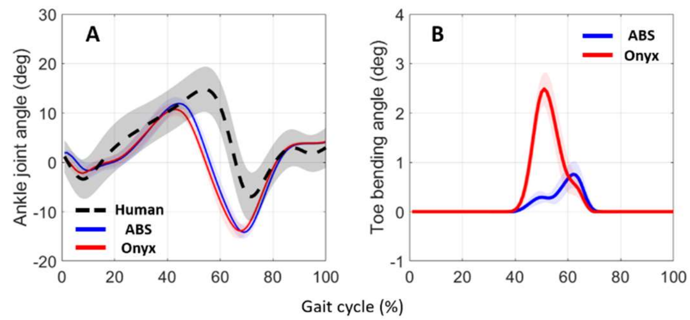

Figure 2: Kinematic comparison between ABS, onyx foot, and human data; (A) ankle joint angle (B) toe joint angle. Bold lines and shaded regions refer to the average and ± 1 s.d. of 20 consecutive steps.

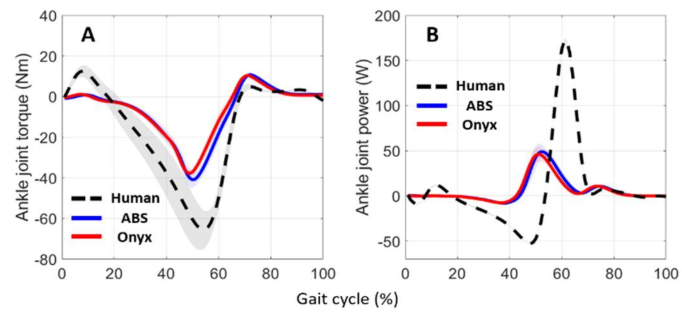

Figure 3: Kinetic comparison between ABS, onyx foot, and human data; (A) ankle joint torque (B) ankle joint power. Bold lines and shaded regions refer to the average and ± 1 s.d. of 20 consecutive steps.

Compared to the human data at a faster walking speed of 0.80 m/s [5], both feet show smaller dorsiflexion and earlier push-off, possibily due to a slight mismatch in the timing at the controller. Also, note that the ankle torque and power are smaller due to the restricted torque limit of the actuator on the prosthesis.

In this study, both feet are similar in most measures. However, since onyx foot shows more toe bending, which is more similar to human data, the onyx foot would be a preferred option.

Significance

This study shows the ankle/toe joint kinematics/kinetics using two different 3D printed feet with new structure to replicate the toe joint. Even though there was no significant difference between two proposed feet in most of the measures, still one foot showed relatively significant toe bending. This can be a good starting point for the new consideration of prosthetic foot design. Also, the proposed foot shows almost half weight (540 g) compared to the previous studies [1], [2]. Further designs for toe joint and more realistic loading conditions will be considered to maximize the biomechanical benefits of 3D printable prosthetic feet during walking.

References

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