EFFECT OF TOE STIFFNESS ON THE PUSH-OFF AND JOINT TRAJECTORIES FOR THE POWERED TRANSFEMORAL PROSTHESIS: A PILOT STUDY

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INTRODUCTION

A powered transfemoral prosthesis is an assistive device that has two actuators for ankle and knee joints to provide stable walking to the lower extremity amputees (above-knee). Transfemoral amputees commonly have gait abnormalities that can lead to long term problems, such as fatigue, arthritis and scoliosis [1]. Reducing these abnormalities could lead to a reduction in some of the long-term issues.

Human walking consists of several events: heel-strike, foot-drop, heel-off, push-off, and toe-off [2]. The entire stance phase comprised approximately 60% of the gait cycle [2]. Between heel-off and push-off, positive work is required to insert energy into the moving body and to transition from the stance phase to the swing phase [3]. To provide positive work to the user, a toe joint is essential for the foot; the toe joint lets the foot to bend naturally as the gait cycle progresses and provides appropriate push-off torque to the body [4]. However, no studies have investigated the effects of the toe stiffness in the gait characteristics of powered transfemoral prosthesis.

In this study, we investigated the effects of the toe stiffness modulation on the gait kinetics and kinematics of the powered transfemoral prosthesis. Specifically, joint trajectory profiles and the push-off force at the toe are examined while the toe stiffness was varied. It is hypothesized that providing appropriate toe stiffness will enhance the gait kinetics and kinematics of the powered transfemoral prosthesis compared with the rigid foot without a toe joint.

METHODS

We designed a foot with a toe joint as shown in Figure 1. The foot is composed of the toe joint and the foot base, connected by the hinge and flat shaped spring steel. The toe stiffness varies from 0 to 1 Nm/rad. The toe stiffness modulated by stacking multiple spring steel sheet. The decision of toe length was based on the human factor considering where the forefoot strike occurs [5].

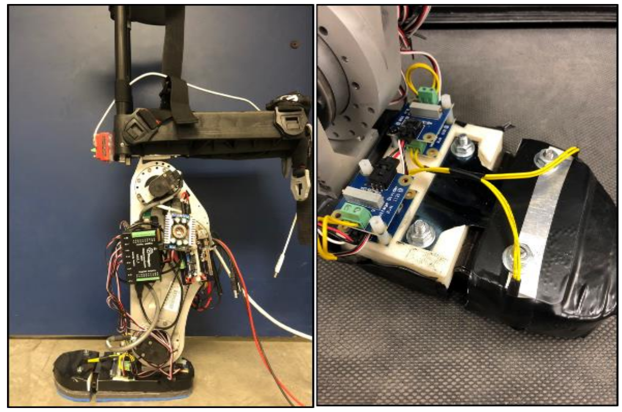

Figure 1: Human-inherent designed foot considering a toe joint with spring steel for providing required PO force.

A custom-built fully actuated powered transfemoral prosthesis (AMPRO II) was used. AMPRO II is the second generation of a powered prosthesis developed at Texas A&M University. AMPRO II utilizes feedback from the prosthetic leg and force sensors at the prosthetic foot to synthesize the control signals for the knee and ankle joints of AMPRO II. The device has a height of 470mm and weight of 4.5kg. The control framework of the prosthesis consists of two different strategies: impedance control and trajectory tracking. The impedance control was utilized during the stance phase, and the desired human joint angle trajectories were tracked by PD control during the swing phase.

The experiment was performed on one subject (age: 29 years, height: 175cm, weight: 75kg, healthy non-amputee male) who walked on a level-ground treadmill. We tested 5 different stiffnesses: no stiffness, 3 Nm/rad, 6 Nm/rad, 9 Nm/rad, and rigid foot. A treadmill speed was selected by user's preference (0.5 m/s). For each condition, the subject walked 20 gait cycles. Kinematic data (i.e., knee and ankle joint angles of the prosthesis via the embedded encoder) and kinetic data (i.e., force at the toe) were measured. The subject used an adapter to simulate an amputee gait. In order to measure toe force data, 2 force sensors (FlexiForce, Phidgets Inc. Calgary, AB, Canada) were embedded at the prosthetic foot. A qualitative analysis for both the toe force profile and joint trajectories are performed without statistical analysis for this case study.

RESULTS AND DISCUSSION

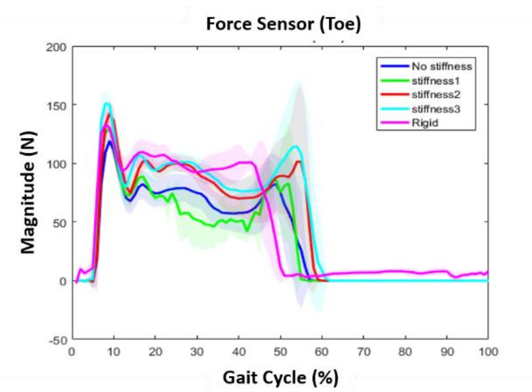

Figure 2: The bold lines are indicated the mean value of the toe force sensor data, and the shaded regions are indicated the range within one standard deviation.

Figure 2 shows the toe force profiles during the gait cycle with various toe stiffness conditions. During the foot-drop (around 10% of the gait cycle), there seems no prominent differences in the onset of first peak across the stiffness conditions. However, it is clearly observed that the onset of the second peak was delayed from 49% to 55% of the gait cycle as the stiffness increased from 3 Nm/rad to 9 Nm/rad. However, when the stiffness was infinite (i.e., rigid food), the onset timing did not follow this trend, but it happened too earlier (i.e., 43% of the gait cycle). Noting that the second peak of the vertical ground reaction force of normal human walking happens at around 50% of the gait cycle [5], toe joint contributes to the modulation of the timing of the push-off. Selecting appropriate toe joint stiffness will optimize the gait patterns of the powered transfemoral prosthesis.

Figure 3 shows the joint trajectories of both ankle and knee of the prosthesis. The dashed line is the trajectories for the normal healthy gait. Pearson correlation for the ankle trajectory was examined: r=0.90, 0.92, 0.89, 0.86, 0.88 for the five stiffness conditions. Pearson correlation for the knee trajectory was examined: r=0.97, 0.99, 0.96, 0.96, 0.96 for the five stiffness conditions. It was clearly seen that the correlation was the greatest when the stiffness was 3 Nm/rad whereas the correlation became the worse when the stiffness was too high (e.g., 9 Nm/rad or infinity).

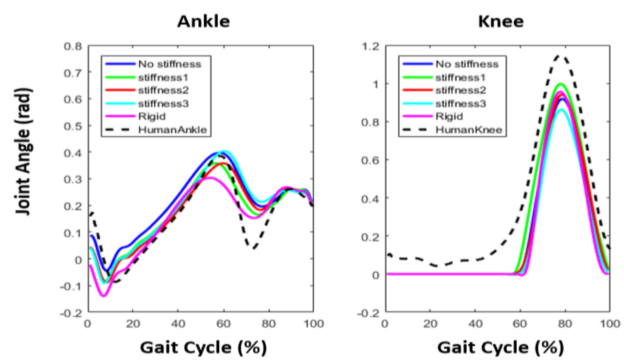

Figure 3: Ankle/Knee joint encoder data from the prosthesis compared to the human joint trajectories

CONCLUSIONS

In this pilot study, it was observed that the existence of the toe joint with appropriate stiffness enhanced both the onset timing of the push-off and the joint trajectory profiles for both ankle and knee. 3 Nm/rad was found to be optimal among 0, 3, 6, 9 and ∞ Nm/rad. We are now planning to conduct a systematic experiments with more number of subjects, motion capture system and force plates. We anticipate that optimal toe stiffness of the foot will provide optimal push-off with more normative joint trajectories for the powered transfemoral prosthesis.

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