MECHANICAL ENGINEERING
TEXAS A&M UNIVERSITY

HUman Rehabilitation (HUR) Group

http://hurgroup.net

Effect of Toe Stiffness on the Push-Off and Joint Trajectories for the Powered Transfemoral Prosthesis: A Pilot Study

Woolim Hong, Shawanee Patrick and Pilwon Hur, Ph.D.

{ulim8819,shawaneepatrick,pilwonhur} @tamu.edu

RESEARCH HIGHLIGHT

- Investigating the effects of toe stiffness modulation on the gait kinetics & kinematics of the powered prosthesis
- Examining joint trajectory profiles and the push-off force at the toe while the toe stiffness was varied

INTRODUCTION

Gait abnormality

- Transfemoral amputees commonly have gait abnormalities that can cause to long-term problems. e.g. fatigue, arthritis and scoliosis [1].

Finite human walking phases

- Human walking consists of several events: heel-strike, foot-drop, heel-off, push-off, and toe-off [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 essentia l for the foot; the toe joint lets the foot to bend naturally as the gait cycle progresses and provides appropriate pus h-off torque to the body [4].

POWERED PROSTHETIC SYSTEM

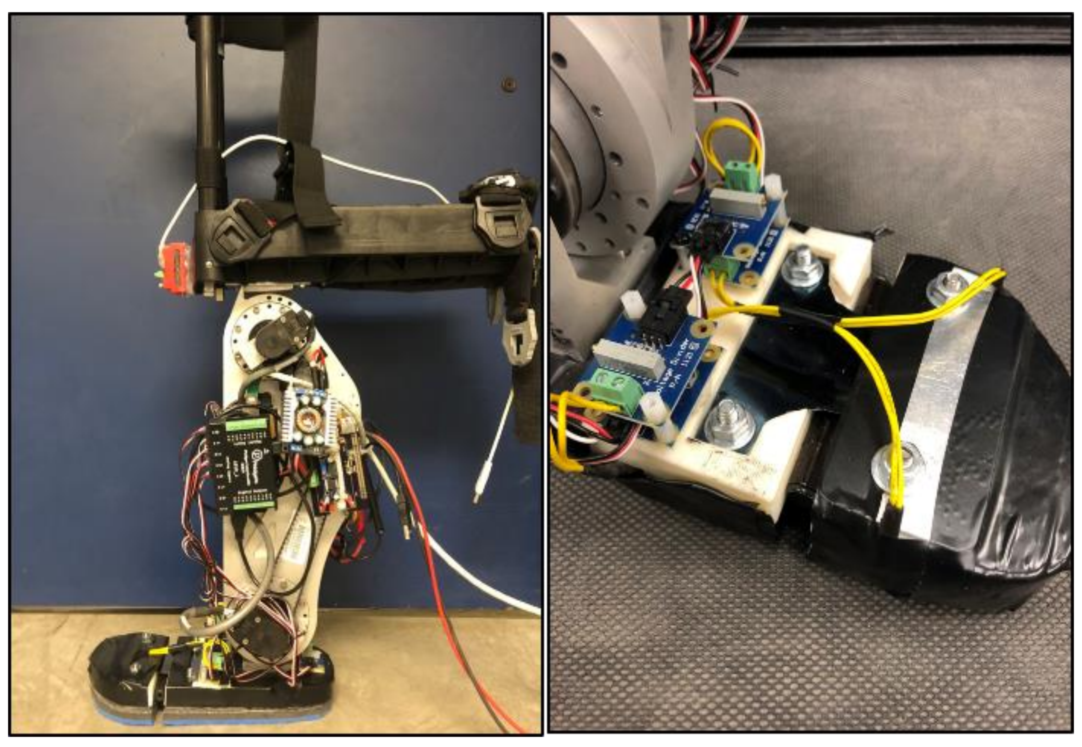

Fig. 1 The powered transfemoral prosthesis AMPRO II (left), and its human-inherent designed foot considering a toe joint with spring steel for providing required PO force (right).

Powered Transfemoral Prosthesis

- AMPRO II, the 2nd generation of custom-built A&M powered transfemoral prosthesis, has two actuations at ankle and knee.
- AMPRO II detects contact with the ground based on 5 FlexiForce sensors located on its foot.

IMU Setting

- An IMU placed on the prosthesis detects the thigh angle, which is used as the phase variable to synchronize with the user's walking progression.

Human-inherent designed foot

- Prosthetic foot consists of the toe joint and foot base.
- Two parts are connected by the hinge and flat shaped spring steel.
- The toe length is determined based on the human factor considering where the forefoot strike occurs [5].

CONTROL FRAMEWORK

Stance phase: Trajectory tracking

- Cubic Bezier polynomials generates the desired walking trajectories for the swing phase.
- The generic cubic Bezier polynomials are described as below where $t \in [0,1]$:

$$Z(t) = (1-t)^3 P_0 + 3t(1-t)^2 P_1 + 3t^2(1-t) P_2 + t^3 P_3$$

- In Fig. 2, by controlling P_1 & P_2, any different inclined walking curves can be generated.

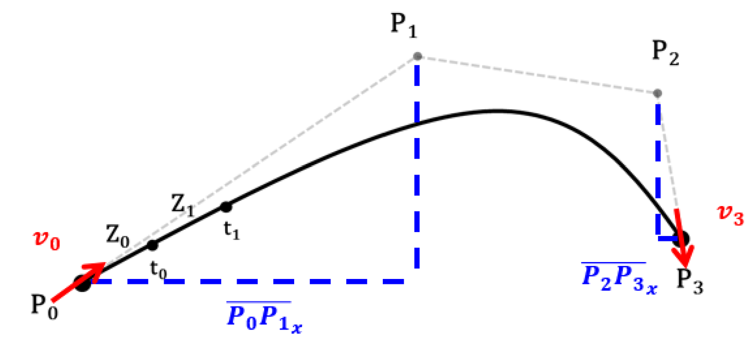

Fig. 2 The relationship between (P_1,P_2) and (P_0,P_3)

- P_0 is updated in every single gait cycle and P_3 is fixed point since all trajectories are merging at this point. $\overline{P_0P_1}_x$, $\overline{P_2P_3}_x$ are free variables to determine the control points P_1, P_2.

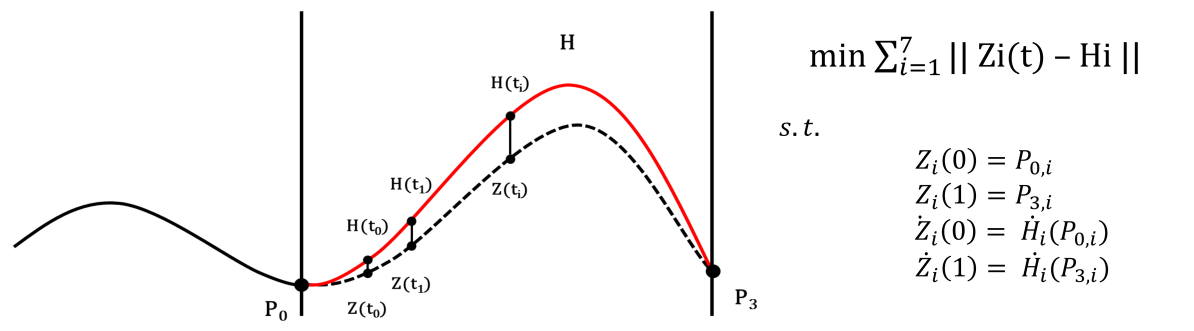

Fig. 3 H_i indicates a human walking trajectory of the i^{th} slope condition, where i = {1,2,3,4,5,6,7} ≡ {-15°,-10°,-5°,0°,5°,10°,15°} inclination. P_0, P_3 refer to the joint angle at 60%, 85% of a gait cycle, respectively.

- The optimization problem is solved to minimize the sum of error between the Bezier curves and corresponding human trajectories (Fig. 3).

Swing phase: Impedance control

- During the stance phase, impedance control is used to adopt to different terrain conditions.
- The torque at each joints can be described in series of passive impedance parameters which are the function of the phase variable.

$$\tau = k(\theta - \theta^e) + b\dot{\theta}$$

- The optimal stiffness, damping, and equilibrium were chosen from the previous studies [6-8].

EXPERIMENTAL SETUP

Experiment subject

- A healthy male (29 years, height 175cm, weight 75kg)
- Using a L-shape adapter to simulate an amputee gait

Experiment environment

- On a level-ground treadmill with 5 different stiffness (0, 3, 6, 9 Nm/rad, and rigid foot)
- User comfort speed (1.71 km/h)

Experiment data recording

- For each trial, 20 gait cycles were recorded.
- The kinematic data (i.e., knee and ankle joint angles) were captured via 2 encoders on the prosthesis.
- The kinetic data (i.e., force at the toe) was measured from 2 force sensors underneath a foot.

RESULTS

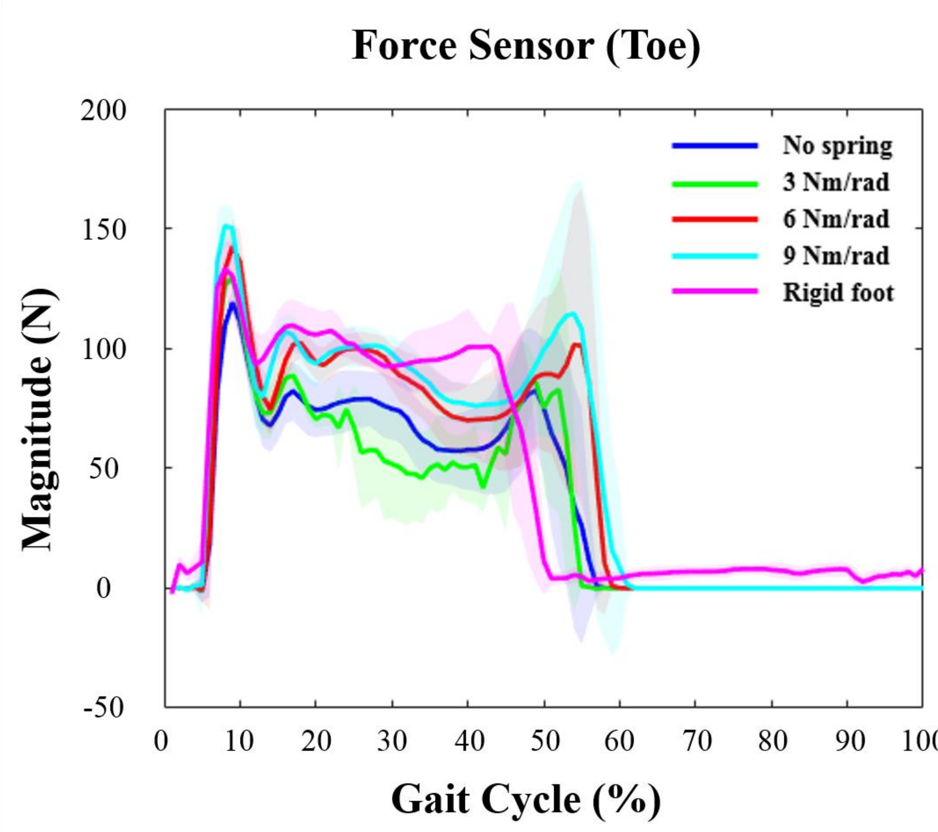

Fig. 4 The toe force profiles during the gait cycle with various toe stiffness conditions. The bold lines and shaded regions are indicated the mean value and the range within one standard deviation. (stiffness1, stiffness2, stiffness3: 3, 6, 9 Nm/rad)

- No difference in the onset of the 1st peak across the stiffness conditions, around 10% of the gait cycle (foot-drop) in Fig. 4.
- 2nd peak was delayed from 49% to 55% of the gait cycle as the stiffness increased from 3 to 9 Nm/rad.
- However, the onset timing occurred earlier (43% of the gait cycle) with the rigid foot.
- According to the 2nd peak, toe joint contributes to the modulation of the push-off timing.

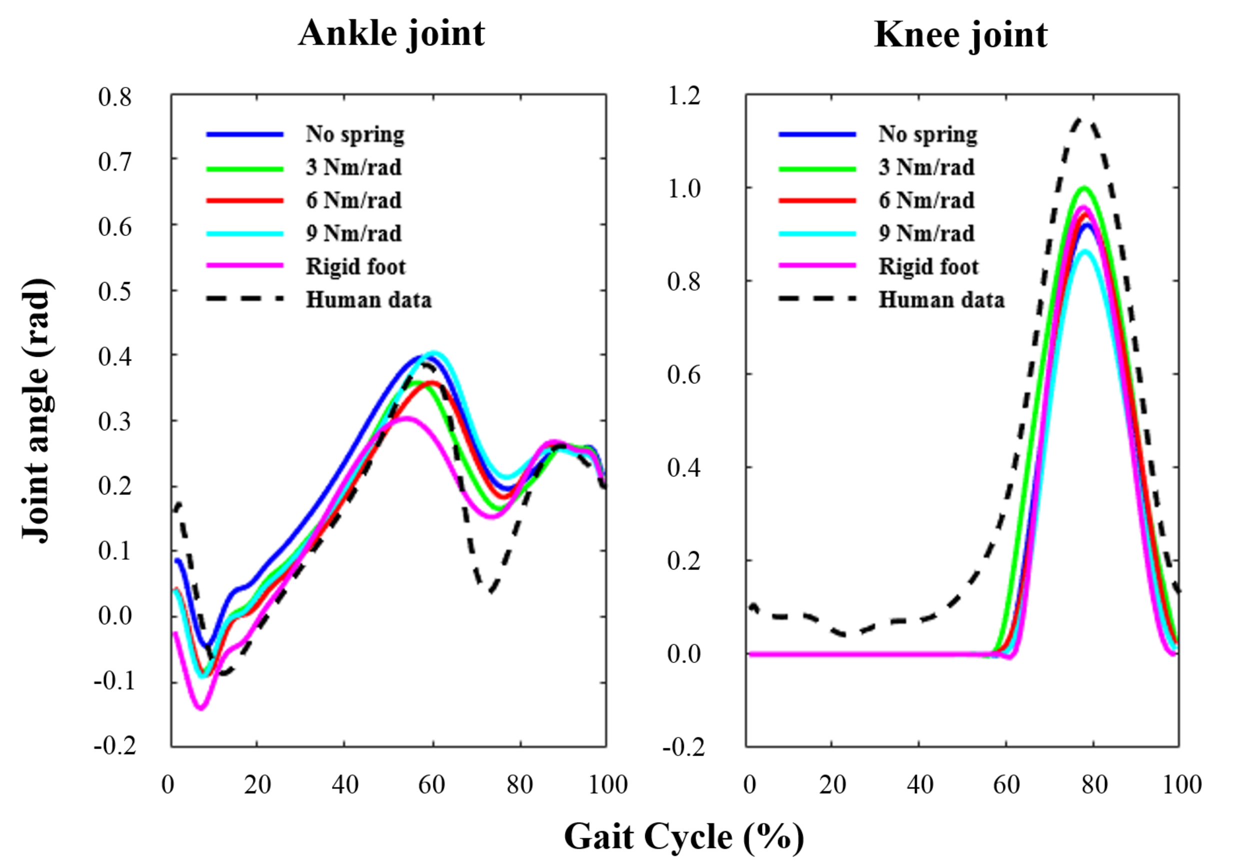

Fig. 5 The ankle (left) and knee (right) joint trajectories of the prost-hesis with various toe stiffness. The dashed line is a healthy subject gait.

- Pearson correlation (ankle): r=0.90, 0.92, 0.89, 0.86, 0.88 for the five stiffness conditions.
- Pearson correlation (knee): r=0.97, 0.99, 0.96, 0.96, 0.96 for the five stiffness conditions.
- Correlation result was the greatest when the stiffness was 3 Nm/rad whereas the correlation became the worse when the stiffness was too high (9 Nm/rad or rigid foot).

CONCLUSIONS

It was observed that …

- Toe joint with appropriate stiffness enhanced both the onset timing of the push-off and joint trajectory profiles for each joint.
- 3 Nm/rad was found to be optimal among 5 different stiffness.

FUTURE WORKS

- Conduct systematic experiments with more subjects, motion capture system, and force plates.
- Anticipate the optimal toe stiffness will provide optimal push-off with more normative joint trajectories for the powered transfemoral prosthesis

References

[1] Gailey, et al., *J.Rehabil. Res. Dev.*, 2008.
[2] Neuman, *Kinesiology of the Musculoskeletal System: Foundations for Rehabilitation*, 2010.
[3] Usherwood, et al. *Journal of The Royal Society Interface*, 2012.
[4] Honert, et al., *American Society of Biomechanics 2017*, 2017.
[5] Winter, *The Biomechanics and Motor Control of Human Gait*, 1987.
[6] H. Lee, et al., *Transactional Engineering in Health and Medicine*, 2016.
[7] E. J. Rouse, et al., *Neural Systems and Rehabilitation Engineering*, 2014.
[8] F. Sup, et al., *Neural Systems and Rehabilitation Engineering*, 2011.