Variable Stiffness Foot provides Users with Adjustment of Knee and Ankle Mechanics

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Summary

The Variable Stiffness Foot prosthesis can modulate its forefoot stiffness through the deflection of a compliant cantilever-beam keel and adjustable support fulcrum. Participants tested the effects of this modulation on leg mechanics in walking using three different VSF stiffnesses. As the VSF stiffness increased, participants exhibited less dorsiflexion and more plantarflexor moment, more knee extension, more knee flexor moment, and less power flow through the ankle. These modulations could be controlled to aid users in walking across various terrain or different speeds.

Introduction

The Variable Stiffness Foot (VSF) is an energy storage and return (ESR) prosthesis that can passively store and return energy through the deflection of a compliant cantilever-beam forefoot keel [1]. It is a semi-active prosthesis [1] that allows real-time control of stiffness that can be dependent on the type of activity (standing, flat ground walking, ramp and stairs walking). The VSF prototype's effective stiffness is modulated by a support fulcrum moved by a motor and belt.

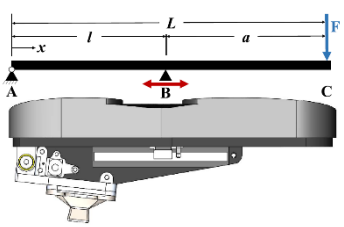


Figure 1: side drawing of the VSF highlighting the cantilever mechanics [1].

Previous studies in prosthetics found that increased range of motion for stairs and ramps is associated with improved gait [2]; a stiffer ankle (increased moment for small change of angle) is helpful for standing stability [3]; and a compliant forefoot returns more energy to the rest of the body [4]. We hypothesized that increasing forefoot stiffness would lead to decreasing ankle dorsiflexion angle, increasing peak ankle moment, and decreasing uniform deformable body power (related to decreasing energy returns in push-off), along with increasing knee extension angle and knee flexor moment.

Methods

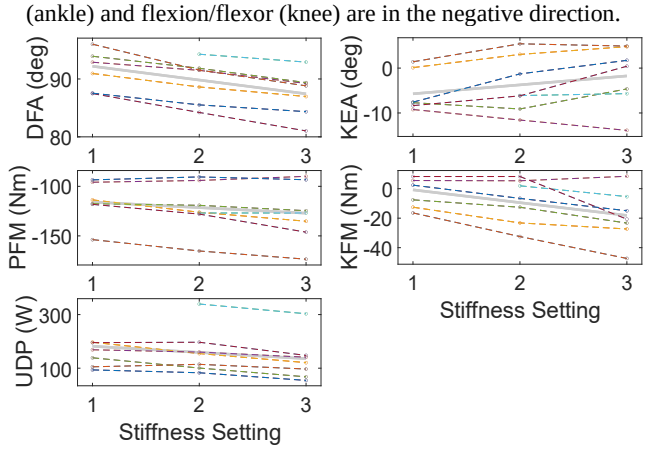
Seven persons with trans-tibial amputation walked across two force plates (one foot on each plate) in a motion capture lab. The participants walked with three different VSF stiffness settings (compliant-1, medium-2, and stiff-3; each scaled to each person's body mass) for 3 trials at 1.1±0.1m/s.

Motion and force data were processed to estimate joint angles and moments using standard inverse dynamics, and power flow through the ankle from the prosthesis using a deformable body model (Unified Deformable power, UDP) [5]. Peak values of ankle dorsiflexion angle (DFA), plantarflexor moment (PFM), midstance knee extension angle (KEA) and knee flexor moment (KFM), and UDP were computed for each stride on the prosthetic side and averaged across the three trials for each stiffness setting. Mixed linear effects models were used to estimate the sensitivity of these metrics to stiffness settings, their significance (p-value), and the coefficients of determination (r^2) of their regressions.

Results and Discussion

Stiffer VSF settings led to reduced DFA (r^2= 0.97 p<0.0001), increased KEA (r^2=0.88, p=0.0001), more negative PFM (r^2=0.95, p <0.0001), more negative KFM (r^2=0.88, p=0.0001), and reduced UDP (r^2=0.97, p<0.0001) during toe off, which correlates with reduced push off energy. Interestingly, more extended knee angle was associated with more negative knee flexor and ankle plantarflexor moments.

Figure 2: mixed linear effect trends for ankle and knee angles, moments, and UD power. The grey bar represents the mixed linear effects fit of all subjects for the given metric. Plantarflexion/flexor (ankle) and flexion/flexor (knee) are in the negative direction.



Conclusions

The VSF enables modulation of mechanical outcomes through controlled stiffness. Automated, real-time stiffness control could enable adaptation to terrain conditions such as sandy, muddy, wet or icy ground as well as stairs and ramps, or to alter biomechanical loads such as undesirable knee moments.

Acknowledgments

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