Sensitivity of Mechanical Outcomes to Various Stiffnesses of Variable Stiffness Foot (VSF)

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Introduction

The Variable Stiffness Foot (VSF) is an energy storage and return (ESR) prosthesis that can passively store and return energy to its users through the deflection of a compliant leaf spring keel in the forefoot [1]. It is a semi-active prosthesis, meaning it does not deliver power (from a motor) during stance phase, but it does adjust the stiffness during swing phase. This adjustment allows the user to have a variety of stiffnesses that can be dependent of the type of activity (standing, flat ground walking, ramp and stairs walking).

The VSF (Figure 1) prototype has a rigid ankle and a compliant forefoot keel whose effective stiffness is modulated by a support fulcrum moved by a motor and belt system. A microcontroller controls the movement to modulate the stiffness during swing phase due to user control or foot trajectory reconstructed by an inertial sensor [1].

Previous studies in prosthetics found that increased range of motion for stairs and ramps are associated with improved gait [3]; stiffer ankles (increased moments for small change of angle) are helpful for standing stability [4]; and a compliant forefoot returns more energy to the rest of the body [2].

This study tested these biomechanical effects of the VSF across level walking under three different stiffness settings. We hypothesized that the decreasing forefoot stiffness would lead toincreasing ankle plantarflexion, decreasing peak ankle moment, and increasing energy returns in push-off .

Figure 1: side view of the VSF [1]

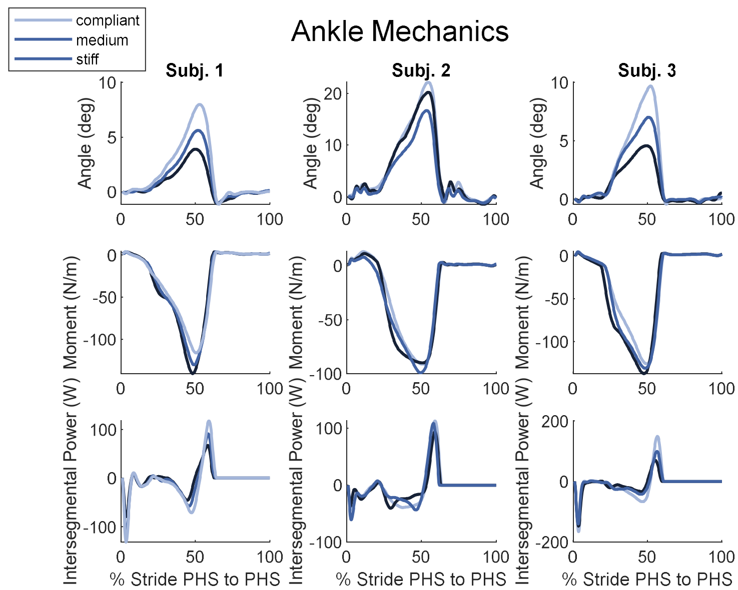

Figure 2: Results showing the angle, moment, and intersegmentatal power related to the ankle joint for each walking stride on the prosthetic side of the participants. Plantarflexion is in the negative direction. PHS: Prosthetic Heel Strike.

Methods

Seven persons with trans-tibial amputation were included in this experiment, of whom three are analyzed to date. The participants walked across two force plates (one foot on each plate) in a motion capture lab with twelve cameras. The participants walked with three different VSF stiffness settings (compliant, medium and stiff, scaled to each person's body mass) for 3 trials at 1.1±0.1m/s, with speed tracked using motion capture.

Motion and force data were processed in Visual3D and MATLAB for kinematic and kinetic calculations. We estimated ankle angle and moment according to standard inverse dynamics, and intersegmental power using a deformable body model. Peak values were computed for each stride on the prosthetic side and averaged across the three trials for each stiffness setting.

Results and Discussion

Each subject had similar trends for the angle, moment, and intersegmental power results and there was support for the three hypotheses. The ankle angles (Figure 2) had the largest plantarflexion excursions for the compliant stiffness setting. The ankle plantarflexion moments were smallest for the compliant settings The intersegmental ankle power output tended to be largest close to toe-off (around 60% of stride) for the compliant settings.

Significance

Many prosthetic users are limited to using passive feet that have fixed keel stiffness. This limited variability may be optimal for one function, but will not be suited for many different functions like standing, walking on stairs and ramps, and on uneven surfaces. This VSF can give its users the ability to change the foot stiffness that may increase comfort, adaptability, and help users get closer to functional walking. Future analysis will evalue the ideal stiffness settings for different activities. Semi-active prostheses could also be potentially used in clinics to assess stiffness preferences so prosthetists can better recommend new passive feet.

Acknowledgments

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References

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