Biomimetic Active Prosthetic Knee with Antagonistic Actuation

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SUMMARY

In contrast to traditional purely dissipative prosthetic knees, we propose a biomimetic variable-impedance knee prosthesis with two series-elastic actuators arranged in parallel in an agonist-antagonist architecture. With a quasi-passive control strategy the prosthesis is capable of mimicking human knee mechanics during level-ground walking. This strategy reduces the overall electrical power requirements, allowing for an energetically-economical powered knee system. The objective of this adaptive powered prosthetic device is to improve gait and metabolic energy consumption of above-knee amputees on variant terrain conditions.

INTRODUCTION

Developing a commercially viable powered prosthesis that is human-like in its weight, size and strength while still being efficient and noise-free, is a challenging design problem. Current approaches to the design of powered prostheses have focused mainly on the use of single motor-transmission systems directly coupled to the knee joint [1,2, www.Ossur.com]. Such direct-drive designs, however, require high electrical power consumption to fully emulate the mechanical behavior of the human knee joint. One reason for this lack of energetic economy perhaps is that such designs do not adequately leverage the passive dynamics of the leg, and elastic energy storage and return of tendon-like elastic structures, in a manner comparable to highly economical walking machine designs [3-5].

We present the design and implementation of an energetically-economical, variable-impedance knee prosthesis that comprises two series-elastic actuators arranged in parallel in an agonist-antagonist arrangement. To motivate the knee's design, we advance a variable-impedance prosthetic knee model, comprising two series-elastic clutch mechanisms and a variable-damper.

METHODS

With human gait data used to constrain the model's joint to move biologically, we vary model parameters using an optimization scheme that minimizes the sum over time of the squared difference between the model's knee joint torque and biological knee values. We then use these optimized values to specify the mechanical and control design of the agonist-antagonist prosthesis. We hypothesize that a variable-impedance control design can produce human-like knee mechanics during steady-state level-ground walking. As a preliminary evaluation of this hypothesis, we compare the prosthetic knee torque output when a unilateral transfemoral amputee walks at a self-selected gait speed, to that of a weight and height-matched non-amputee.

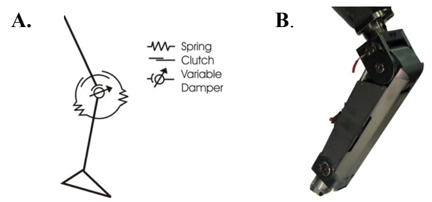

Figure 1: A) Variable-impedance prosthetic knee model. This model comprises two mono-articular series-elastic clutches and a variable-damping element. B) Image of the knee prosthesis.

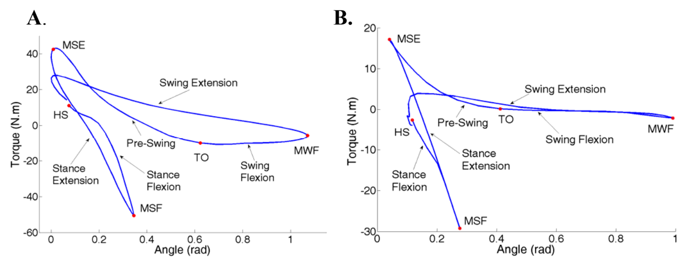

Figure 2: Average knee torque vs. angular position for level ground walking showing five phases of gait A) For a healthy male subject (81.9kg) walking at self selected speed (1.3m/s). B) For an above knee amputee (85 kg) wearing the active prosthesis (speed 0.8 m/s). Total of 10 trials. Key gait events separating the five phases are: HS-heel strike, MSF -maximum stance flexion, MSE -maximum stance extension, TO-toe off, and MWF-maximum swing flexion.

RESULTS AND DISCUSSION

Using a variable-impedance control design, we demonstrate qualitative agreement between prosthesis and intact knee mechanics for level ground walking. The antagonistic design of the knee with the variable impedance control implementation allowed for a low electrical power requirement (average 8 Watts electrical) during steady-state walking trials at a self-selected gait speed (0.81 m/sec).

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