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BIOMIMETIC PROSTHETIC KNEE USING ANTAGONISTIC MUSCLE-LIKE ACTIVATION

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ABSTRACT

The majority of commercial prosthetic knees are passive in nature and therefore cannot replicate the positive mechanical work exhibited by the natural human knee in early and late stance. In contrast to traditional purely dissipative prosthetic knees, we propose a biomimetic active agonist-antagonist structure designed to reproduce both positive and negative work phases of the natural joint while using series elasticity to minimize net energy consumption. We present the design and implementation of the active knee prosthesis prototype.

INTRODUCTION

Modern transfemoral prostheses can be classified in three major groups: passive, dynamically damped, and powered, each of which exhibits fundamental deficiencies. Passive and dynamically damped knees are by their nature capable only of negative mechanical power and therefore cannot replicate the generative phases of the natural knee [1]. As a result, the adequate locomotion of above-knee amputees is impaired; leading to asymmetric gait and elevated metabolic energy consumption relative to healthy subjects [2-4].

Powered prostheses can significantly improve these problems; nevertheless they still face challenges in weight, energy efficiency, and range of motion. Current approaches to the design of powered knee prostheses have focused mainly on the use of single actuator-transmission systems directly coupled to the knee joint [5, 6]. Ossur's "Power-Knee" is an example of such commercially available device.

Such direct drive systems, however, utilize power inefficiently as they cannot leverage the natural dynamics of the system. In this paper we present the design of a biomimetic active knee prosthesis which mimics knee biomechanics in level ground walking and uses series elasticity to minimize net energy consumption.

PROSTHESIS DESIGN

A. Prosthetic Knee Design Criteria

The ideal knee prosthetic is capable of replicating the full range of motion of the human knee as well as the ranges of torque and stiffness which are observed in normal human walking. Just as importantly, the device should not exceed the size or weight of the amputated limb and should exhibit similar dynamics to the natural limb.

B. Agonist Antagonist Architecture

To overcome the inadequacies of existing prosthetics, we propose an agonist-antagonist active knee prosthesis (AAAKP) with a mono-articular architecture inspired by the muscle anatomy of the natural human knee joint. In particular, this architecture (see Figure 1) allows for independent engagement of flexion and extension series springs so that joint position and stiffness are independently controllable. This allows the controller to utilize the passive dynamics of the system and store absorbed energy in the springs for later use, thereby increasing efficiency in power requirements.

The actuation of the AAAKP is comprised of a pair of series elastic actuators (SEA) [10,11], each of which consists of a torque source and a series spring, connected via a transmission. Two opposing SEAs are used to emulate the elasticity and damping characteristics of antagonistic muscle actuation.

In level-ground walking, this design permits the use of a quasi-passive control scheme. Active elements are used primarily to independently control the engagement of each tendon-like spring, thereby regulating the transformation of potential energy into kinetic energy. Since the ideal behavior of the knee on level ground is net dissipative, such a quasi-passive approach can in theory be extremely efficient.

We hypothesize that this device can produce an adequate positive power output at the knee joint, thereby reducing the net work produced at the hip and, consequently, the metabolic cost of level ground walking.

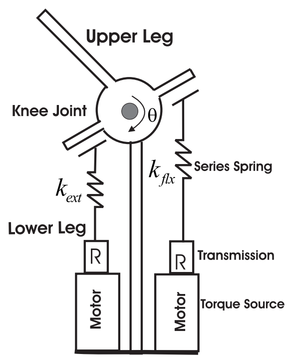

Figure 1: Simplified mechanical architecture of the agonist-antagonist active knee prosthesis

C. Main Design Components

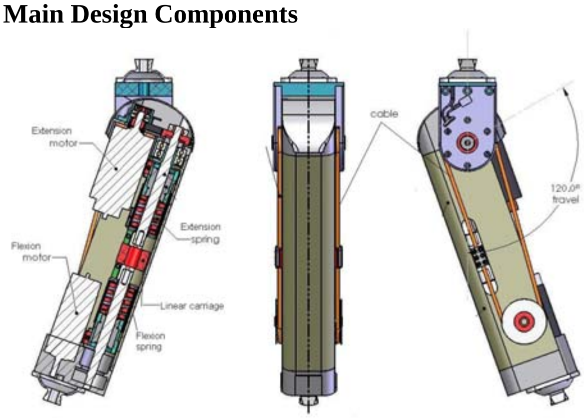

Figure 2:. Mechanical Design of the AAAKP.

1. Torque Sources and Transmission

As shown in Figure 2, the knee joint is driven by a set of parallel cables connected to a linear carriage which is free to move along the length of the device. This carriage can be engaged on either side by the extension and flexion springs, each of which is positioned by a ballscrew driven by an electric motor. Both series elastic actuators feature transmissions comprised of a belt drive and ballscrew. Brushed DC motors are used in this prototype.

2. Sensors and Electronics

Feedback to the controller is provided by the sensors listed in Table 1. In particular, locations and compression of both springs are monitored, as is the knee angle itself. An inertial measurement unit (IMU) is also used to detect motion of the limb and determine gait phase.

Measurement	Sensor
Ankle angle	Digital encoder
Motor displacement	Digital encoder
Heel strike	Hall effect
Spring compression	Hall effect
Limb acceleration	Inertial measurement unit

Table 1: Sensors utilized by the AAAKP controller

For the purposes of this prototype, all electronics are implemented in a single board which runs along the lateral side of the knee. Motors are driven by H-bridge controllers with speed governed by 20KHz pulse width modulation (PWM) and powered by a six cell Lithium polymer battery. Analog sensors are read through a 10-bit analog to digital converter (ADC). The system is controlled by an AVR microcontroller and may be monitored by either USB or Bluetooth.

Because all processing is done on-board and power can be supplied by a relatively small battery, the prototype is completely self-contained and does not require tethering.

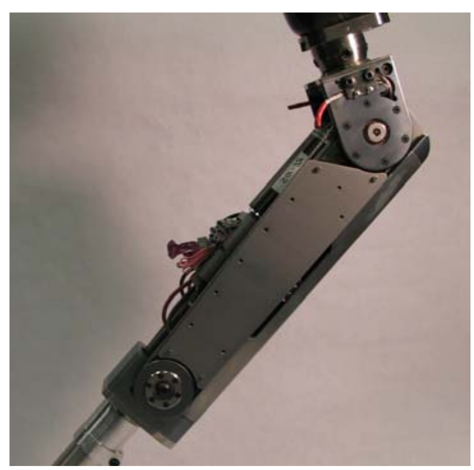

Figure 3: Active Agonist-Antagonist Knee Prosthesis.

CONCLUDING REMARKS

A biomimetic knee prosthesis comprised of a monoarticular agonist-antagonist structure with series elasticity is presented. A prototype has been designed, optimized, and built. It is hypothesized that this prosthesis will reproduce normal human knee kinematics at a relatively low energetic cost. By closely tracking the natural knee behavior, the AAAKP is expected to reduce the metabolic cost of level ground walking for transfemoral amputees This type of architecture allows for prosthetics which are lightweight, efficient, and extremely versatile. Moreover, the powered nature of the device is expected to facilitate more energetically complex tasks, such as stair and ramp traversal.

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