Biomimetic Design and Control of a Powered Transfemoral Prosthesis for the Improvement of Amputee Locomotion

by

Ernesto Carlos Martinez-Villalpando

Thesis proposal submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

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Author: ….……………………….………………………………………………………...

Program in Media Arts and Sciences

Thesis Supervisor: .....…………..…………………………………………………………..

Hugh Herr, Ph.D.
Associate Professor of Media Arts and Sciences
and Health Sciences and Technology

Thesis Reader: …....…………..…………………………………………………………..

Russell Tedrake, Ph.D.
Assistant Professor
Department of Electrical Engineering and Computer Science

Thesis Reader: …....…………..…………………………………………………………..

Daniel Frey, Ph.D.
Associate Professor
Department of Mechanical Engineering

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Abstract

The loss of a limb is extremely debilitating. Unfortunately, today's assistive technologies are still far from providing fully functional artificial limb replacements. Although lower extremity prostheses are currently better able to give assistance than their upper-extremity counterparts, very basic and important locomotion problems still remain for lower-limb amputees. Instability, gait asymmetry, decreased walking speeds and high metabolic energy costs are just some of the challenges motivating the development of a new kind of prosthetic device. Another problem is that amputees still consider modern prosthetic devices as separate mechanisms and not as intimate extensions of their own bodies. These challenges point to the need for highly versatile, fully integrated lower-extremity powered prostheses that can mimic the biological behavior of human lower limbs.

In this thesis I present the design and implementation of a novel biomimetic active knee prosthesis capable of interfacing with a state of the art robotic ankle-foot prosthesis. The integration of the two devices results in a full lower-limb powered prosthetic system for transfemoral amputees. Furthermore, I explore the use of a control architecture based on a neuromuscular model in order to enhance functionality and adaptation to an amputee's walking speed and variation of terrain surfaces. Such novel device architecture attempts to resemble the body's own musculoskeletal design using actuator technologies that have muscle-like behaviors and control methodologies that exploit the principles of human locomotion. The proposed biomimetic transfemoral prosthesis is evaluated on three unilateral above-knee amputees in order to assess its clinical impact, particularly focusing on improving the amputee's gait symmetry, walking speed and metabolic requirements. With this work I aim to advance the field of biomechatronics, contributing to the development of integral assistive technologies that adapt to the needs of the physically challenged.

Thesis Supervisor: Hugh Herr, Ph.D.
Title: Associate Professor of Media Arts and Sciences,
and Health Sciences and Technology

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1 Executive Summary

Today, commercially available technologies for lower limb amputees are still far from providing fully functional replacements of biological legs. Even with the most advanced prosthetic systems available on the market, above knee amputees still exhibit clinical problems associated with the lack of adequate mobility such as gait asymmetry, instability, decreased walking speeds and higher energy requirements. In order to solve these problems, the field of biomechatronics has initiated the development of robotic limbs that can emulate healthy leg behavior. This task poses many challenges for researchers as they investigate novel electromechanical designs and control strategies that can adequately integrate and adapt to the patients' needs.

In this thesis, I propose a novel modular robotic prosthesis that improves transfemoral amputee locomotion. This modular system consists of a motorized (actively-powered) knee prosthesis and motorized ankle-foot prosthesis. My thesis work focuses on the design and implementation of an active knee prosthesis, an essential element of the active artificial limb. Furthermore, I propose a control strategy based on a neuromuscular model that coordinates the behavior of the full robotic leg. The biomimetic approach to the design and implementation of the prosthetic leg and its control seeks to improve amputee's gait symmetry, walking speed and energy demands while adapting to his or her mobility requirements.

The key design architecture and mechanical components of the active knee were established from biomechanical descriptions of the human knee during level ground walking. The knee design is capable of interfacing with the latest powered ankle-foot prosthesis under development by iWalk, LLC, which has recently emerged as a leading prosthetics company. This ankle-foot prosthesis evolved from various prototypes designed by the Biomechatronics Group of the MIT Media Laboratory. The resulting knee and ankle biomimetic leg is capable of replicating human-like joint mechanics. Two aspects of the modular leg contribute to its efficiency and economy in terms of energy consumption. First, it leverages the natural motion dynamics of the leg; second, it uses tendon-like elastic structures to store and release energy, thereby minimizing the power demands on the leg's motors.

In order to evaluate the performance and clinical impact of the proposed active leg prosthesis, a series of experiments will be conducted with three above-knee, unilateral amputees. This work has been approved by MIT's Committee on the Use of Humans as Experimental Subjects (COUHES). The experiments are divided into three sessions. An initial assessment session will qualitatively determine the degree to which the active prosthesis can improve amputee gait. Secondly, a biomechanics assessment will evaluate joint mechanics while the amputee walks at slow, moderate and fast speeds. Finally, an energetic assessment session will evaluate if the active transfemoral prosthesis reduces the metabolic cost of walking on the amputee.

My dissertation aspires to improve our understanding of the principles of human locomotion and their application in the development of advanced bionic limbs. Both objectives are aimed to improve the lives of the people with physical disabilities.

2 Introduction

In the United States, there are approximately 1.7 million people living with lower limb loss (NLLIC, 2008). According to the National Center for Health Statistics, the number of lower transfemoral amputees in the U.S. exceeds 300,000 (NCHS, 1999). It is estimated that 30,000 new lower limb amputations are conducted in the U.S. every year (Feinglass et al, 1999). In order to restore amputees' lost leg function, some sort of prosthetic technology is used. However, there is no prosthetic leg that is completely able to restore intact leg performance.

A significant limitation of commercially available technology in lower limb prostheses is their inability to provide net positive power output at the joints. This limitation translates into the inability of the prosthesis to restore normal leg functionality and, consequently, in the amputee suffering from clinical problems associated with the lack of mobility and locomotion fatigue. Furthermore, recent development of active powered prostheses has given rise to the pursuit of control strategies that can adequately guide a biological behavior while allowing a more integrated and intuitive human-machine interface

The biomechanics of normal walking provide a basis for the design and development of new actuated artificial limbs. These prosthetic systems ideally need to fulfill a diverse set of requirements in order to mimic the biological behavior of normal and healthy limbs. In general, the important features to consider for these prosthetic devices include the capacity to vary their stiffness and damping characteristics as well as to provide non-conservative motive power. In addition, these systems must be adaptive, such that they can change their functional behavior given particular environment disturbances and individual amputee's gait.
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In this thesis, I present the design and implementation of a modular biomimetic leg prosthesis for transfemoral amputees that is capable of mimicking the behavior of the intact human lower limb. The biomimetic approach to the design and control of the prosthesis seeks to improve amputees' gait symmetry, walking speed and metabolic requirements while enhancing the prosthesis gait adaptation. With this thesis I aim to advance the field of biomechatronics and human-machine integration, contributing to the development of assistive technologies that benefit from the development of biologically inspired models.

3 Proposed Approach & Methodology

I propose the implementation of a powered biomimetic transfemoral prosthesis in order to improve amputees' locomotion. This artificial limb is comprised of two powered prosthetic joint modules, an active knee prosthesis and an active ankle-foot prosthesis, . The emphasis of this thesis is given to the novel design and implementation of the active knee prosthesis, as it is one of the main contributions of the proposed work. In the following sections I introduce the two prosthetic joint modules as well as the proposed control architecture for the coordinated integration of the two systems. I then proceed to describe my methods of assessing the performance of the powered artificial leg and its clinical impact on lower limb amputees. Lastly, I describe the preliminary work that has already been conducted and discuss the main contributions of this thesis work to the field of biomechatronics.

3.1 Active Knee Prosthesis

The active knee prosthesis I propose incorporates an agonist-antagonist arrangement of two unidirectional series-elastic actuators (SEAs) positioned in parallel. This design is motivated by a variable-impedance prosthetic knee model, comprising two series-elastic clutch mechanisms and a variable-damper. This model uses intact human gait data to obtain its parameters so that it constrains knee joint behavior to biological biomechanics. The selected model parameters then specify the mechanical design components and a low-level control strategy.

Because of its design architecture, the knee can be controlled to behave as antagonistic series-elastic clutch elements during the stance phase of the gait cycle, and as a variable-damper during the swing phase, resulting in an energetically-economical knee prosthesis for level-ground walking. The knee design is fully motorized with series-elastic force sensing. Thus, knee joint torque can be directly controlled for more energetically expensive tasks, such as stair and ramp ascent gaits, as well as standing from a seated posture. Hence, the knee architecture is designed to accommodate non-conservative, high mechanical power movements, while still providing for a highly economical level-ground walking mode.

The extension actuator, proximal to the knee joint, is a series elastic actuator (Pratt & Williamson, 1995) driven by a brushless motor. This motor is connected to its series elastic elements via a transmission. The series elastic elements are two identical pre-compressed passive mechanical springs whose stiffness matches that of the model's extension actuator. Both springs fit within an SEA cage. This linear spring cage can be displaced linearly by means of the extension transmission. The transmission is comprised of a belt drive system coupled to a ball screw mechanism that displaces the cage. The SEA cage is directly coupled to the knee joint, converting the linear motion of the cage to a rotary motion of the knee joint through its attachment to the drive cable system.

The flexion actuator consists of a brushless dc motor that drives a single passive mechanical spring via a transmission. The flexion transmission, similar to the extension side, has a belt drive system that is connected to a lead screw that displaces the linear flexion spring cage. This actuator is not coupled directly to the rotary motion of the knee joint; however, it can flex the knee if it back-drives the extension SEA cage.

Both actuators can be used independently to control the knee angle at which the series springs are engaged. Both cages, SEA and flexion spring, are guided by two steel rails in each wall. Each cage contains a set of rollers that ride on each rail as the actuator drives their motion. All actuation mechanisms are fully supported by an aluminum structure that resembles the lower limb anatomical envelope. The design of the prosthesis facilitates its maintenance because of its detachable side and front covers, allowing easy access to the driving actuators and mechanisms.

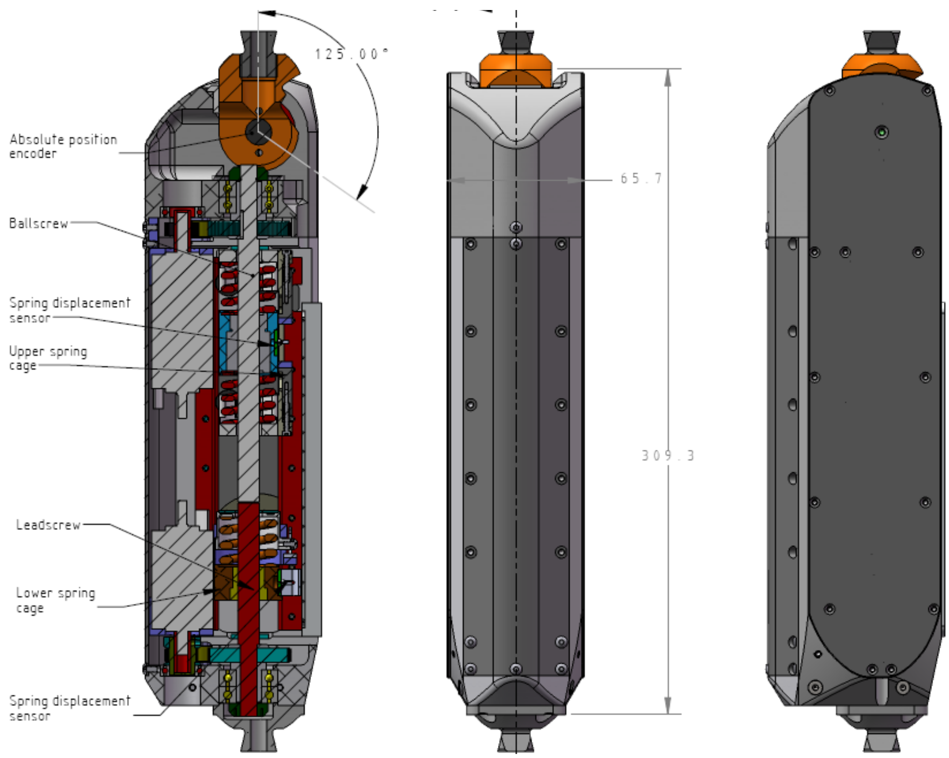

Figure 1. Mechanical design of the antagonistic active knee prosthesis

3.2 Active Ankle-Foot Prosthesis

The active ankle-foot prosthesis used in this thesis is the latest prototype under development by iWalk, LLC. This prosthesis has evolved from the diverse prototypes developed at the Biomechatronics Group of the MIT Media Laboratory (Au et al, 2006, 2007, 2008, 2009). This device is self-contained and resembles the weight and size of an average adult intact biological ankle-foot complex.

The ankle joint design couples a lower foot structure to an upper leg shank structure capable of attaching to the distal end of the active knee prosthesis. The foot is a passive low profile commercial "Flex-Foot" prosthesis that helps minimize ground contact shock. This prototype has a unidirectional leaf spring (the *parallel spring*) that acts across the ankle joint and engages when the ankle and foot are perpendicular to each other. This spring acts in parallel to a powered drive train and provides a passive function similar to that of the biological achilles tendon. The powered drive train is a motorized link across the ankle joint and it consists of a brushless motor, a belt drive transmission and a linear ball screw. At the foot, there is a Kevlar-composite leaf spring that acts as a *series spring* connecting the foot to the ball nut. The drive train and the series spring together comprise a series-elastic actuator (SEA).

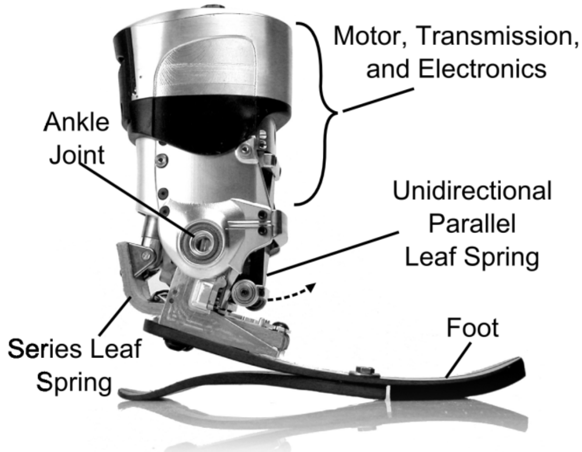

Figure 2. Powered Active Ankle-Foot Prosthesis

3.3 Modular Biomimetic Transfemoral Prosthesis

The biomimetic robotic lower-limb prosthesis for above knee amputees includes the self-contained (non-tethered) powered knee and powered ankle-foot devices described above. Each joint of the leg can be used as an independent prosthesis component with its own inherent control strategy, or can be integrated to form a single powered leg system with a coordinated control (described in the following section). The following image depicts the modular system with first version prototypes of the active knee and ankle-foot prosthetic systems.

Figure 3. Modular lower limb powered prosthesis with early versions of active knee and ankle-foot prosthetic systems.

3. 4 Control Architecture

The purpose of the control architecture is to command the appropriate torques at the knee and ankle joints of the transfemoral prosthesis. This thesis evaluates the use of a controller based on a neuromuscular model with a reflex scheme. Similar models have been previously proposed in legged locomotion simulation studies (Geyer & Herr, 2010; Geyer & Seyfarth, 2003). The proposed neuromuscular model-based prosthetic controller will provide the torque commands to the powered artificial limb (knee and ankle-foot joints) worn by the amputee. These torques should be adequate to the amputee's gait cycle as determined by the feedback information from sensors embedded in each of the prosthetic modules of the robotic leg device. The goal of the proposed approach is to provide a control with the inherent ability to adapt to an amputee's walking speed as well as to variations of the terrain conditions.

The neuromuscular model represents a group of muscle-tendon units that span the leg joints. In addition, it considers the reflexive muscle response due to some combination of afferent signals from corresponding muscle spindles and Golgi tendon organs. The sensory information of joint states (position and velocity) from the artificial lower limb leg (hip, knee and ankle) are used as inputs to the model. The model uses these joint states to determine the internal state for each of its virtual muscles, and establishes what the individual virtual muscle force and stiffness should be given particular levels of muscle activation determined from a spinal reflex scheme. The predicted forces and stiffnesses from all the modeled muscles are then used to compute joint torques and stiffnesses using muscle moment arm values from the literature. The model estimates are then sent to the controller as desired net torque and stiffness values for the biomimetic robotic leg joints. The controller then tracks the desired torque and stiffness values at each artificial joint.

A top level state machine control is included as part of the control architecture. This top level control is implemented as a finite state machine that is synchronized to the amputee's gait cycle. This state machine is continuously observing the sensory information from the biomimetic robotic leg and determines the transitions between different gait phases, which in turn inform the rest of the neuromuscular model described earlier. The proposed model-based control scheme is shown schematically in the following figure.

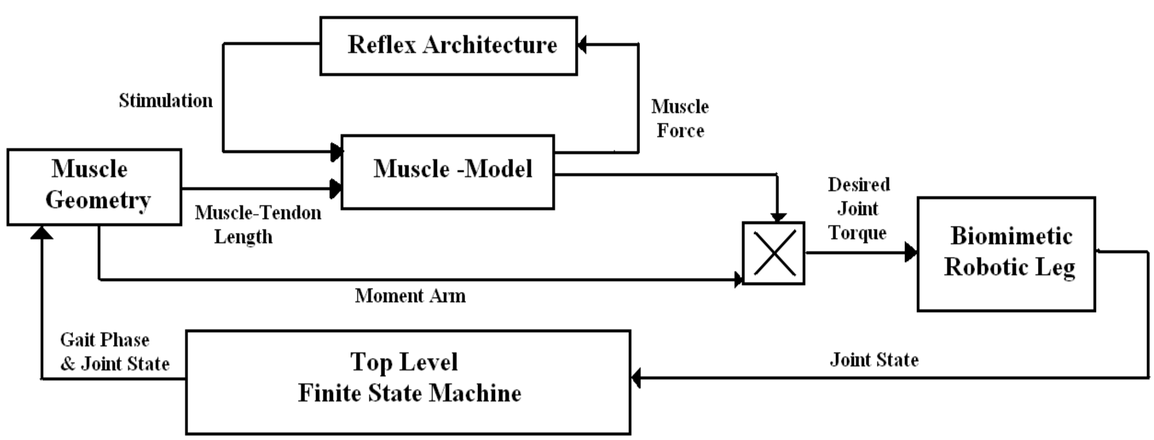

Figure 4. Block diagram of the general neuromuscular model architecture

When the active transfemoral prosthesis is worn by an amputee, angular sensors at the ankle and knee measure joint state for these joints. For the hip joint, the absolute orientation of the user's thigh would be determined using both the angular joint sensor at the prosthetic knee and an IMU positioned between the prosthetic knee and the ankle joints. To estimate hip position and velocity, the control architecture would work under the assumption that the upper body (torso) maintains a relative vertical position during gait.

3.5 Performance Evaluation

The series of experiments to assess the clinical impact and performance of the prosthetic device were approved by MIT's Committee on the Use of Humans as Experimental Subjects (COUHES). The assessment objective is to evaluate the efficacy of the active transfemoral prosthesis that is designed to improve gait symmetry and speed, and to lower metabolic energy demands during walking.

For the experiments, three healthy participants with above-knee amputations will be recruited. The study participants are volunteers and are permitted to withdraw from the study at any time and for any reason. Before taking part in the study, the participants read and sign a statement acknowledging informed consent.

Participants will meet the following eligibility criteria. They will be experienced at prosthesis ambulation, with a capacity of ambulation at least at a K3 level (i.e. having the ability or potential for ambulation with variable cadence). Additionally, amputee participants will be generally healthy and will have no other musculoskeletal problems or any known cardiovascular, pulmonary or neurological disorders.

For each amputee participant, a complete study will include three separate experimental sessions conducted in three different locations. These locations are: The Biomechatronics Group, MIT Media Laboratory; the Holodeck room in CSAIL at MIT; and the Indoor Track at MIT's Johnson Athletic Center. The time between experimental sessions will be approximately one to two weeks, and the duration of each session will be two to three hours.

3.5.1 Initial assessment

In the first session, each amputee participant will be scheduled to visit the Biomechatronics Group in The MIT Media Laboratory. The main purpose of this session is to qualitatively assess the degree to which the active prosthesis can improve amputee gait. Morphological data (for example, height, weight, limb length and circumference) of the participant will be recorded using the biomechanical data collection form. These data will be used during analysis of data gathered during the gait research sessions.

Each participant will be asked to walk along a 30-foot level walkway in the Biomechatronics Group. During the session, each participant will be asked to walk at slow, normal and fast paces for each of two walking conditions. For each condition and speed, approximately 10-15 trials will be performed. Parallel bars will be utilized to prevent any injury to the subject if he were to lose balance and fall. A safety harness attached to the ceiling will also be utilized if the subject makes that request. In addition, a member of the laboratory staff will accompany the study participant to catch him in the event of a fall, if necessary. The participant may ask to rest or to terminate their participation in the study at any time.

Each participant will be walking on the platform 60-90 times for the entire first session, which should take approximately 2 hours. When using the active prosthesis with the walking program, our researchers will tune the parameters of the walking program to the participant's own gait pattern. The parameters used to tune the walking program will be recorded for use in Sessions 2 and 3.

3.5.2 Biomechanics assessment

In the second session, amputee study participants will be scheduled to visit the Holodeck room in CSAIL at MIT (Rm 33-339), which is equipped with a motion capture system to measure human movement. The main purpose of this session is to collect joint kinematics, torque and power on amputees walking at slow, moderate and fast speeds. These active knee prosthetic data will then be compared to conventional prosthetic behaviors measured at the same three speeds.

Each participant will be asked to walk along a 30-foot level walkway in the Holodeck room in CSAIL at MIT. Before conducting experiments, one of the investigators will place reflective markers on the participant's skin with tape at specific points over joints of their body.

These special markers are then seen by the cameras in the room (See Data Collection Instruments). During the session, each participant will be asked to walk at slow, normal and fast paces for each of two walking conditions. For each condition and speed, approximately 10-15 trials will be performed. Motion data is collected from cameras in the room and from the force plates that are placed in the walkway. As the device has been setup in the first session, two members of the laboratory staff will walk on each side of the participant throughout the experiment. The second session should take between 2 and 3 hours.

3.5.3 Energetic assessment

In the third session, each transfemoral amputee participant will be scheduled to visit the Indoor Track of the Johnson Athletic Center at MIT, which is located at the 2nd floor of the Athletic Center. The main purpose of this session is to test if the active transfemoral prosthesis does, in fact, reduce the metabolic cost of amputee walking.

During the session, each participant will be asked to wear a Cosmed Oxygen Consumption (VO2) mask that will measure the metabolic rate. Two members of the laboratory staff will walk on each side of the participant throughout the experiment. The procedure for the experiment will be as follows:

The participant will be asked to wear the VO2 system and first walk for 8 minutes on the track with an assigned commercially, available above knee prosthesis (Otto Bock C-Leg or Ossur Rheo) to establish a control metabolic rate. After resting for 8 minutes, he/she will wear the active prosthesis and get acclimated to the device by walking for 5 minutes. He/she will then walk on the track for 8 minutes as we measure his/her metabolic rate with the device. The participant will then rest for another 8 minutes. This protocol will be repeated two additional times, and the entire experiment will take approximately 3 hours. Throughout the study, each participant will be videotaped and photographed to document the effect of the prosthesis on walking.

3.6 Progress to date

To this date two full prototypes of the active knee prosthesis have been developed. I implemented and evaluated the first active knee prototype in an initial gait study. following the methodology described in the *Performance Assessment* section. The first version of the knee prosthesis is comprised two series-elastic actuators positioned in parallel in an agonist-antagonist arrangement. The design of the knee was motivated by advancing a variable-impedance prosthetic knee model, comprising two series-elastic clutch mechanisms and a variable-damper. Because of its architecture, the knee can be controlled to behave as agonist-antagonist, series-elastic clutch elements during the stance phase, and as a variable-damper during the swing phase resulting in an energetically-economical knee prosthesis for level-ground walking.

In the initial gait study I demonstrated that a variable-impedance control implemented with a finite state machine can produce human-like knee mechanics during steady-state level-ground walking. In particular, prosthetic knee biomechanics were measured when worn by a unilateral transfemoral amputee walking at a self-selected gait speed and were compared to that of a weight and height-matched non-amputee. Results showed a qualitative agreement between prosthesis and human knee mechanics.

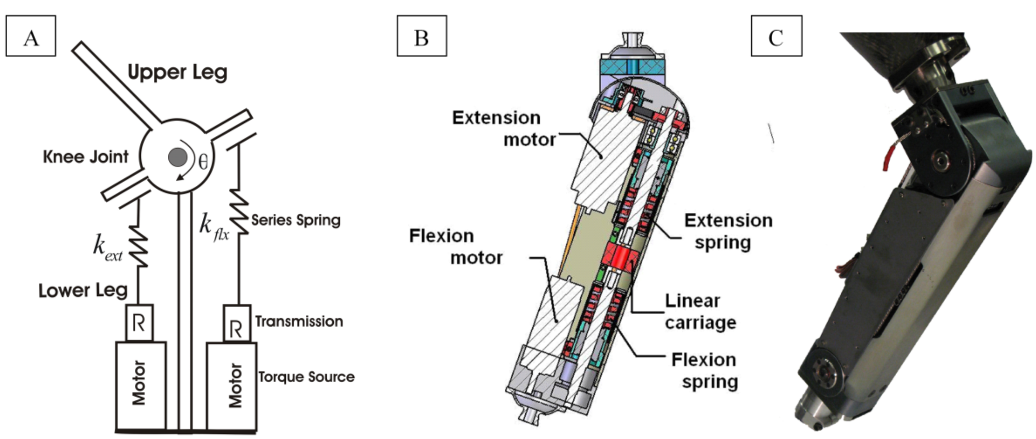

Figure 5. Prosthesis Design. In A), a simplified mechanical schematic of the agonist-antagonist knee is shown. In B) and C), a mechanical design and image of the active knee prosthesis first version are shown, respectively.

In this investigation, I showed biomechanical improvements in the patient's gait while using the active knee prosthesis such as: evident early-stance knee flexion and two positive power output bursts at mid-stance and late stance that are qualitatively comparable to intact knee behavior. In addition to the novel mechanical architecture, the variable-impedance control implemented in the knee allowed for adaptation to the different phases of gait and walking speed while maintaining a minimal electrical energy cost. This work suggested that the use of a novel active knee can offer an improved metabolic economy of gait compared to variable-damping and mechanically passive prostheses, in addition to a decrease in positive work generation at the hip during terminal stance and pre-swing.

The description and results of all preliminary work has been described in previously published publications (Martinez-Villalpando and Herr. 2009 ; Martinez-Villalpando et al, 2008).

3.7 Main Contributions

At the culmination of the dissertation work, I expect to have made the following contributions:

- Two active knee prostheses prototypes capable of reproducing knee biomechanics during level ground walking and integrating with an advanced ankle-foot prosthesis.

- A modular biomimetic trasnfemoral prosthesis for above knee amputees comprised of one of the powered knee prosthesis mentioned above and a powered ankle-foot prosthetic device. This prosthesis seeks to improve amputee’s locomotion, particularly gait symmetry, walking speed and energetic demands.

- A neuromuscular model based controller that coordinates the behavior of the robotic joints of the biomimetic prosthesis as well enhances the device’s adaptation to the patient’s walking speed and to variations in the walking terrain.

- A generalized control architecture framework for lower-limb prostheses that aims to further advance man-machine integration in the context of assistive technologies.

- A comprehensive gait study data set of three above knee amputees walking on level ground with their commercial prosthesis and with the biomimetic lower-limb prosthesis presented in this thesis. Data will include kinematics, kinetics and metabolic requirement metrics.

4 Resources and Anticipated Timeline

The work presented in this thesis is supported by:

- U.S. Veterans Administration under Grant VA241-P-0026.
- U.S. Department of Defense Award Number W81XWH-09-2-0143

The clinical experiments were approved by MIT's Committee on the Use of Humans as Experimental Subjects (COUHES) Application No. 0804002682

The clinical trial has also been registered in the National Clinical Trials Registration ID: NCT00771589 (in clinicaltrials.gov).

For this thesis, three healthy above knee amputees will be recruited. The recruitment is supported by the National Orthotics and Prosthetics Company in Boston. This study requires that amputees are fitted and supervised during the whole study by a certified prosthetist and orthotist.

The facilities used in this thesis include the Biomechatronics Group's research lab space at the MIT Media Lab, MIT's room 33-339 (a.k.a. Holodeck) and MIT's indoor track of the Johnson Athletic Center.

This work requires the assistance of a trained electronics technician capable of developing and troubleshooting the custom electronics system required for the complete prosthetic device.

The specialized equipment for the gait study is COSMED's K4B^2 pulmonary gas exchange study (metabolic requirement experiments).

For the completion of this thesis, a general anticipated timeline is as follows:

May – July 2010	• Finalize knee prosthesis integration • Evaluate performance of top-level control strategy • Gait and metabolic study on single above knee amputee
August- October 2010	• Ankle-foot prosthesis integration • Finalize neuromuscular control development and implementation on biomimetic leg prosthesis
November 2010- January 2011	• Amputee gait study (3 participants)
February 2010	• Data Analysis and Verification
March 2010	• Thesis Draft
April 2010	• Dissertation Defense

5 Background

In the United States there are more than 1.7 people living with limb loss (NLLIC, 2008). The total number of persons with an amputation and using a prosthesis is expected to reach 2.4 million by the year 2020 (Ziegler-Graham, 2008). In the U.S. alone above knee amputees exceed 300,000 (NCHS, 1999). Every year more than 30,000 transfemoral amputations are conducted in the U.S. (Feinglass et al, 1999).As a consequence of lower limb loss, patients present several clinical problems, all associated with lack of mobility and higher energetic demands. Even though currently available prosthetic technology provides certain advantages to amputees, it is still limited as it is incapable of fully restoring intact leg functionality.

For lower limb amputees one of the major problems associated with reduced mobility is pain and walking fatigue (Postema et al, 1997). Although, the pain felt at the residual limb corresponds to the behavior of the entire prosthetic system (i.e. from the liner and socket interface to the pylon and the rest of prosthetic components) it is particularly associated to the coupling between the residual limb and the prosthetic leg. The imperfect coupling allows relative motion between the socket and the femur stump caused by the compression of the soft tissue. This motion is uncomfortable for the amputee and causes a lack of confidence to apply large forces to the prosthetic leg. In addition, the relatively short moment arm between the hip joint and the socket reduces the force that the hip muscles can apply to the artificial limb (Whittle, 1991). Recent advances in socket technology have reduced pain in patients by focusing on cushioning, a primary contributor to comfort. Such technologies cover a large gamma of products, from gel liners and vacuum-assisted sockets to modern interfaces that rely on residual limb laser scanning and computer aided manufacturing. Two particular technologies that have proved to be successful in pain reduction have been shock absorbing pylons and dynamic elastic response (DER) prosthetic feet (Perry et al, 1992). The damping and compliance features they provide have made them popular in most of the commercially available prosthetic systems. Albeit their success in preference among amputees, abnormal gait patterns and associated with walking fatigue are still prevalent.

Walking fatigue is synonym of higher metabolic expenditure and is a common affliction of lower limb amputees. Walking fatigue in lower limb amputees is considerably higher than their matched able body counterparts at comparable speeds. Measures of metabolic expenditures during walking are commonly obtained by analyzing oxygen level consumptions. For unilateral below the knee amputees, the rate of oxygen consumption is 20-30% higher (Herbert et al., 1994; Molen, 1973) and for above knee amputees there is an additional 25% increment (James, 1973; Waters & Mulroy, 1999) with reference to intact subjects. Conventional prostheses despite their damping and compliance features have not provided a metabolic advantage for amputees (Lehmann et al., 1993; Torburn et al., 1990; Colborne et al., 1992; Huang et al., 2000; Thomas et al., 2000). In addition to higher metabolic consumptions, lower limb amputees show a reduction in their self-selected speed and in consequence they present overall diminished endurance.

For above knee amputees, a particular source of pathological gait for above knee is the lack of accurate control of the knee joint during the swing phase. During this phase, the knee cannot be totally free because it will extend too rapidly with a sudden stop hitting the boundary in hyperextension. In contrast, the knee joint cannot be too rigid that it doesn't permit flexion or extension; this will result in an increase of the amount of energy required by the hip muscles to move the prosthesis as a single piece. To prevent these extreme cases, several prosthetic knees that behave as a damper have been developed using friction mechanisms, hydraulic or, pneumatic or electronically controlled systems. Some have been designed as variable damping coefficient depending on the angle, speed and direction of motion. These mechanisms have partially solved some of the problems associated with abnormal gait patterns in amputees (Whittle, 1991).

A major cause of abnormal gait for transfemoral amputees is the need to walk with the knee in full extension during single stance support, since they cannot oppose to an external flexion torque around the knee axis. To prevent this, passive artificial knees with higher stiffness are generally employed. The inconvenience with higher stiffness in the knee joint during the stance phase is that the location of the center of gravity is dramatically affected, increasing the energy needed to walk. Although amputees adapt to this circumstance, this type of walking is energetically demanding for all of patients (Whittle, 1991).

For below the knee amputees the inability to articulate their ankle joint generates an abnormal gait, including gait asymmetries, lower self-selected speeds and higher energy requirements (Winter & Sienko, 1988; Molen, 1973; Colborne, et al. 1992). Losing the capacity to actively plantarflex at the end of the stance phase of walking avoids having a powered push off, thus creating the need of lifting the leg sooner to clear the ground, since the effective length of the leg is reduced compared to a normal limb. The human ankle joint is essential to walking as it provides a significant amount of net positive work over the stance period of walking, especially at moderate to fast walking speeds (Winter, 1983; Palmer, 2002; Gates, 2004). There are some commercial prostheses that have a spring-like behavior that help store some energy during hill strike and stance phase and releasing it at toe-off. Even though these prostheses have certain compliance and help function as initial and terminal rockers due to their shape, they cannot provide net positive work which makes them not functional enough to replicate normal ankle's flexibility and actuation (Whittle, 1991).

5.1 State of the Art in Lower Limb Prostheses

Modern transfemoral prostheses can be classified into three major groups: passive, variable-damping, and powered. Passive prosthetic devices do not require a power supply for their operation, and are generally less adaptive to environmental disturbances than variable-damping or powered prostheses.

Variable-damping knees have been some of the most significant advances in active prostheses technology. These knees require a power source to modulate damping levels and adapt to different modes of gait, whereas powered prosthetic knees are capable of performing non-conservative positive work. Variable-damping knees offer several advantages over mechanically passive designs, including enhanced knee stability and adaptation to different ambulatory speeds (Flowers, 1972; Stein & Tepavic, 1990; Kitayama et al, 1992; Zahedi, 1993; Herr & Wilkenfield 2003; Johansson et al, 2005). Examples of commercially available variable-damping knees include the Blatchford Endolite Intelligent Prosthesis, the Otto Bock C-leg, and the Össur Rheo.

From these examples one of the most relevant devices is the C-leg. This knee uses a microcomputer to adjust the damping characteristics of its hydraulic joint in order to adapt to patient’s walking speed, in addition to detect and prevent stumbling, allowing safer ramp and stair descent. A second example of a microcontroller based knee is the Össur’s Rheo Knee, developed originally at MIT. This knee prosthesis actively controls a magnetorheological-based fluid that varies damping ratios to allow speed and terrain adaptation.

Although variable-damping knees offer some advantages over purely passive knee mechanisms, they are nonetheless incapable of producing positive mechanical power and therefore cannot replicate the positive work phases of the human knee joint for such activities as sit-to-stand maneuvers, level-ground walking, and stair/slope ascent ambulation. Not surprisingly, transfemoral amputees experience clinical problems when using variable-damping knee technology. For example, amputees have asymmetric gait patterns, slower gait speeds, and elevated metabolic energy requirements compared to non-amputees (Johansson et al, 2005).

A challenging design problem has been developing a commercially-viable powered prosthesis that is human-like in its weight, size and strength while still being energetically-economical and noise-free. 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 (Kapti & Yucenur , 2006, Fite et al 2007, www.Ossur.com].   Such direct-drive designs, however, require high electrical power consumption to fully emulate the mechanical behavior of the human knee joint even during level-ground ambulation. 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 structures, in a manner comparable to highly economical walking machine designs (McGeer, 1990; Wisse, 2004; Endo et al, 2006) or simpler mechanical knee designs with extension assist compliant elements (Radcliffe, 1977).

The development of powered foot-ankle prosthesis for transtibial amputees is less far advanced. Ossur has introduced the first commercially available “powered” ankle prosthesis named “Propio Foot”, which does not provide net power during the gait. Instead it can actively adjust dorsiflexion angle to avoid stumbling during walking and to allow a better sitting posture (Koniuk, 2001). Au and Herr at MIT introduced the world’s first powered foot-ankle system capable of providing an improved metabolic economy to below-knee amputees. This prosthesis is capable of varying joint impedance during stance and capable of providing sufficient instantaneous power output and torque during push-off in order to propel the amputee during level-ground walking (Au and Herr, 2008; Au et al, 2008). Hitt et al, have built a active robotic ankle prosthesis with anterior-posterior and medio-lateral actuation (Hitt et al, 2006). Collins & Kuo introduced controlled energy storage and release prosthesis (CESR) for below knee amputees, capable of efficiently storing energy during stance and adequately timing its release in order to help amputees improve their gait. (Collins and Kuo, 2010). Transfemoral prosthesis that includes both powered knee and ankle system are limited. Sup et al have built a tethered, electrically powered knee and ankle prototype (Sup et al, 2008) and more recently presented an electrically powered self-contained active and ankle prosthesis (Sup et al, 2009).

5.2 Control Strategies

A major challenge for lower limb powered prostheses is the control strategy by which an amputee is able to direct their behavior. It is essential to have a control interface that allows the patient to efficiently control the action and reaction of the active prosthetic device in a safe and reliable manner. In addition, the control interface should permit identifying the motion intent of the patient in order to reduce a constant volitional and cognitive effort.

Current control solutions have been based on automatically detecting different activity modes (such as walking, sitting, standing, etc.) using the onboard sensory information. In the case of prosthetic knees, some approaches have proposed the use of an "echo- control" in which the intact limb is instrumented in order to guide the behavior of the artificial limb (Flowers & Mann, 1977; Stein, 1983; Grimes, 1979; Bedard & Roy, 2003). Among the disadvantages of this approach we can highlight the additional instrumentation of the sound-limb, the potential limited use to unilateral amputees and the fact that the patient has to continuously be reacting to the prosthesis behavior instead of interacting with the natural dynamics of the leg and the environment in a more natural manner. In the case of powered foot-ankle prosthesis, authors have suggested the use of finite-state controllers in addition to lower level torque, impedance and position controllers (Au et al, 2008; Fite et al 2009).

Another method of control has considered electromyographic (EMG) signals as high-level control commands for the active prostheses (Horn, 1972; Peeraer et al., 1990; Saxena & Mukhopadhyay, 1977; Triolo et al., 1988; Myers & Moskowitz, 1981). Researchers have demonstrated that electromyography signals from the residual limb muscles can be integrated with kinematic and kinetic sensor information for state control of a powered a lower limb prosthesis (Au et al., 2008; Hung & Mun, 2005). Recent work has explored the use of controllers that are based on muscle-reflex models in order to enhance adaptation to environmental disturbances such as speed transients and terrain variations (Eilenberg & Herr 2010). Futhermore, as an alternative to echo control approaches, Varol et al. have used patter recognition techniques that complement finite state machine impedance controllers for a powered knee and ankle prosthesis (Varol et al, 2008, 2010).

The development of control strategies for powered limb prostheses that include active knee and ankle-foot devices is still a very recent area of research, thus allowing the exploration of novel frameworks for the advancement of sophisticated human-machine integration systems that are biologically inspired.

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7 Biographies

Ernesto Carlos Martinez-Villalpando

Martinez-Villalpando received his B.Sc. in electrical engineering from Universidad Panamericana in Mexico (2001), and S.M. in Media Arts and Sciences from MIT (2006). During undergraduate degree and before coming to MIT, Ernesto worked on the development of pneumatically powered legged robotic systems and had several participations representing Mexico at international competitions sponsored by the Institute of Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers (SAE). He is currently pursuing his Ph.D. in the Media Arts and Sciences at MIT's Media Laboratory conducting his research at the Biomechatronics Group. His work focuses on the biomimetic design and control of actively powered prosthetic legs. His research areas of interests include rehabilitation technologies, system dynamics and control and robotics. During his time at MIT Ernesto has been involved in student leadership roles as part of the Mexican Student Association (ClubMex) and the Science and Engineering Business Club. In addition to his academic career, Ernesto has participated in competitive soccer for several years, having played at semi-professional level in Mexico, and recently representing MIT in the Massachusetts State League 1st division.

<u>**Doctoral Committee**</u>

Hugh Herr
Associate Professor, Media Arts and Sciences
Associate Professor, MIT-Harvard Division of Health Sciences and Technology
Director of the Biomechatronics Group

Professor Herr holds a joint appointment between MIT's Program in Media Arts and Sciences and The Harvard-MIT Division of Health Sciences and Technology. He is the principal investigator of the Biomechatronics Group at MIT's Media Laboratory. He received his BA in physics from Millersville University of Pennsylvania, an MS in mechanical engineering from MIT, and a PhD in biophysics from Harvard University. Prior to coming to the Media Lab, Herr was assistant professor at the Department of Physical Medicine and Rehabilitation, Harvard Medical School. Herr's research interests include biomechanics, biological motion control, and the advancement of human rehabilitation and augmentation technology.

Russell Tedrake
Assistant Professor at MIT's Department of Electrical Engineering and Computer Science.

Professor Tedrake is a member of the Computer Science and Artificial Intelligence Lab. He received his B.S.E. in Computer Engineering from the University of Michigan, Ann Arbor, in 1999, and his Ph.D. in Electrical Engineering and Computer Science from MIT in 2004, working with Sebastian Seung. After graduation, he spent a year with the MIT Brain and Cognitive

Sciences Department as a Postdoctoral Associate. During his education, he has spent time at Microsoft, Microsoft Research, and the Santa Fe Institute.

Professor Tedrake's research group is interested in underactuated motor control systems in animals and machines that are capable of executing dynamically dexterous tasks and interacting with uncertain environments. When the design of these control systems is intimately related to the mechanical designs of their machines, we can use tools from machine learning and optimal control to exploit this coupling when classical control techniques fail. Current projects include robust and efficient bipedal locomotion on flat terrain, multi-legged locomotion over extreme terrain, flapping-winged flight, and feedback control for fluid dynamics.

Daniel Frey
Associate Professor AT MIT'S Mechanical Engineering and Engineering Systems Department

Professor Frey's research concerns robust design of engineering systems. Robust design is a set of engineering practices whose aim is to ensure that engineering systems function despite variations due to manufacture, wear, deterioration, and environmental conditions.

Professor Frey has received numerous awards and honors. These include the Junior Bose Award for Excellence in Teaching in 2006, a best paper award from INCOSE in 2005, an NSF CAREER award in 2004; the MIT Department of Aeronautics and Astronautics Teaching Award in 2000; the Everett Moore Baker Memorial Award for Outstanding Undergraduate Teaching at MIT in 1999; and an R&D 100 Award in 1997. He also received the Joint Service Commendation Medal for his service in the armed forces in 1991.

Prof. Frey is a member of the American Society of Mechanical Engineers (ASME), the American Statistical Association (ASA), the International Council on Systems Engineering (INCOSE), and the American Society of Engineering Education (ASEE). He holds a Ph.D. in Mechanical Engineering from MIT, an MS in Mechanical Engineering from the University of Colorado and a BS in Aeronautical Engineering from Rensselaer Polytechnic Institute.