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| 14. ABSTRACT<br>The goal is to design the <i>Spring Ankle with Regenerative Kinetics (SPARKy)</i> which seeks to develop a new generation of powered prosthetic devices based on the Robotic Tendon actuator. This actuator is a lightweight motor and transmission in series with a helical spring that significantly minimizes the peak power requirement of an electric motor and total system energy. The Robotic Tendon has kinetic advantages and stores and releases energy to provide SPARKy users with 100% of required push-off power and ankle range of motion comparable to able-bodied ankle motion while maintaining a form factor that is portable to the wearer.<br>In the second year, we developed and tested a transtibial prosthesis that supports continuous unstructured walking for up to 2.8 hours. A pilot study with 2 subjects tested the device. All components are worn and are lightweight and portable. In the third year, jogging on a treadmill will be demonstrated. |                  |                                 |                                         |                                                          |                                              |
| 15. SUBJECT TERMS<br>Transtibial Prosthesis, regenerative, spring, wearable robot                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                  |                                 |                                         |                                                          |                                              |
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## Table of Contents

|                                   | <u>Page</u> |
|-----------------------------------|-------------|
| Introduction.....                 | 4           |
| Body.....                         | 5           |
| Key Research Accomplishments..... | 14          |
| Reportable Outcomes.....          | 16          |
| Conclusion.....                   | 17          |
| References.....                   | 18          |
| Appendices.....                   |             |

## Introduction

### **"SPARKy – Spring Ankle with Regenerative Kinetics" to build a new generation of transtibial prostheses**

**Keywords:** Transtibial Prosthesis, regenerative, spring, wearable robot

The goal is to design the *Spring Ankle with Regenerative Kinetics (SPARKy)* which seeks to develop a new generation of powered prosthetic devices based on the Robotic Tendon actuator. This actuator is a lightweight motor and transmission in series with a helical spring that significantly minimizes the peak power requirement of an electric motor and total system energy. The Robotic Tendon has kinetic advantages and stores and releases energy to provide SPARKy users with 100% of required push-off power and ankle range of motion comparable to able-bodied ankle motion while maintaining a form factor that is portable to the wearer.

**Objective:** The SPARKy Team using several unique technologies developed at Arizona State University's Human Machine Integration Lab will build a new generation of smart, active, energy-storing, transtibial prostheses that will support a Military amputee's return to active duty.

**Military Relevance:** Military amputees have unique requirements not found in the general amputee population. Military amputees are typically highly active and young. Their profession requires that they perform physically demanding dynamic tasks under severe conditions. Current state-of-the-art devices that are commercially available and in research do not address their unique requirements. SPARKy is the only device of its kind designed to address the technologically challenging requirements of the highly active Military amputees. SPARKy is very powerful and efficient. This will allow the amputee to carry heavy loads while walking at speeds up to 2 m/s. The mechanical design addresses the demanding nature of the service member's environment and conditions. For example, the complete electronics and power train package can easily be removed in the case of a malfunction in a field condition, so that the device transforms into a conventional prosthesis.

**Public Purpose:** A transtibial prosthetic device that satisfactorily mimics able-bodied gait can be used by the general public. Because of the prevalence of diabetes, the number of below-the-knee amputees will increase greatly. In the first year, we found that the subject's health improved because he was briskly walking on a treadmill with a powered prosthetic device.

## Body

### The **SPARKy** Project (Spring Ankle with Regenerative Kinetics)

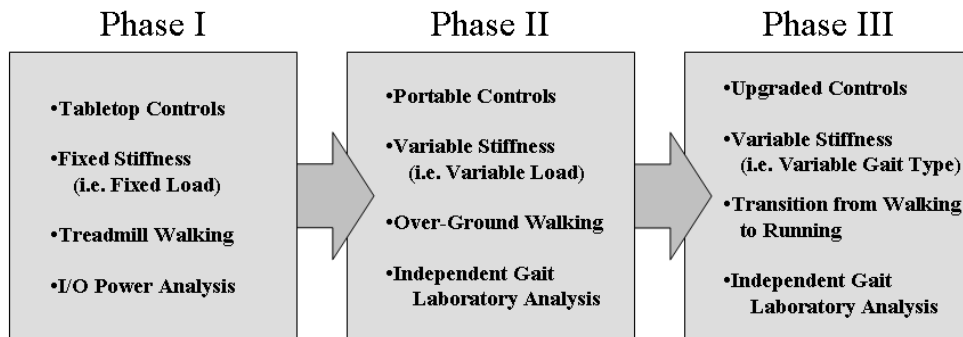
Even today's most sophisticated microprocessor controlled foot-ankle prosthetic devices are passive. They lack internal elements that actively generate power, which is required during the "push-off" phase of normal able-bodied walking gait. Amputees must rely upon the limited spring-back available within the flexed elastic elements of their prostheses to provide power and energy and thus must modify their gait through compensation. Consequently, lower limb amputees expend 20-30% more metabolic power to walk at the same speed as able-bodied individuals. A key challenge in the development of an active foot-ankle prosthetic device is the lack of good power and energy density in current actuator technology. Human gait requires 250W of peak power and 36 Joules of energy per step (80kg subject at 0.8Hz walking rate). Even a highly efficient motor such as the RE75 by Maxon Precision Motors, Inc. rated for 250W continuous power with an appropriate gearbox would weigh 6.6 Kg. This significant weight is only the actuator and transmission. It does not include the electronics or the batteries.

In the first year, we designed the *Spring Ankle with Regenerative Kinetics (SPARKy)* which uses a new generation of powered prosthetic devices based on the Robotic Tendon actuator. This actuator is a lightweight motor and lead screw in series with a helical spring that significantly minimizes the peak power requirement of an electric motor and total system energy. The kinetic advantages of the Robotic Tendon will be shown along with the electro-mechanical design and analysis that will provide SPARKy users with 100% of required push-off power and ankle range of motion comparable to able-bodied ankle motion while maintaining a form factor that is portable to the wearer.

In the second year, we developed and tested a transtibial prosthesis that will support continuous unstructured walking for up to 2.8 hours. A pilot study with 2 subjects tested the device. An independent gait laboratory will compare gait symmetry and metabolic consumption of SPARKy versus the subject's conventional prostheses. All components are worn and are lightweight and portable.

In the third year, we are developing a transtibial prosthesis that will transition from walking to jogging on a treadmill. We are designing new controllers this year studying different types of microprocessors. We will continue our testing at Washington University at St. Louis.

## SPARKy Project Overview



### **Phase 2. To develop, test and demonstrate a transtibial prosthesis for over ground unstructured walking (Months 13-24):**

- a. Design and build SPARKy 2a with the capability to support continuous, unstructured walking for up to 2.8 hours. Mechanical tunability and sensor feedback will allow for variations in load, speed, and environment within the bounds of walking. All componentry will be lightweight, self-contained, and portable. (Months 13-20).

SPARKy 2a has been designed and built. Testing of the mechanical design is on going. A microprocessor has been chosen and code has been ported to the microprocessor. The microprocessor unit has been attached to the device and drives a brushed RE40 DC motor.

- b. Bounds of walking (up to 2 m/s) will include walking on flat even surfaces, walking on inclines/declines, and ascending/descending stairs

We are able to walk continuously over ground and can walk up and down slopes and stairs. Walking up a slope and ascending stairs needs to be improved, adding extra propulsion. The propulsion walking down stairs needs to be reduced.

- c. Test and iterate the design with two selected transtibial amputees at Arizona State University.

A second subject has been recruited and a new socket has been manufactured. The second subject has successfully worn SPARKy 2a.

- d. Testing will include motion capture and oxygen consumption measures and will be independently conducted by another research team at Washington University, Saint Louis, MO. (Months 21-23).

SPARKY 1a has been delivered to Washington University on January 11, 2009 for initial fitting and testing. The testing has started and will be completed by September 2009.

e. Demonstrate SPARKy II to Brooke Army Medical Center. (Month 24).  
Demonstrated SPARKy II on October 22, 2009.

**Phase 3. To expand the capabilities of SPARKy II so that the device supports treadmill jogging (Months 25-36):**

a. Modify hardware and upgrade control software for SPARKy II, which will allow the device to support the transition from walking to jogging and permit continuous jogging (2.5 to 4 m/s for up to 1 hour). (Months 25-32).

We are working in conjunction with LTC Joseph Hitt to develop a jogging prosthesis. Jogging was first demonstrated on April 16<sup>th</sup> and April 23<sup>rd</sup> at West Point.

b. Test and iterate the design with selected transtibial amputees. Again, the task will include independent motion capture and oxygen consumption tests at Saint Louis University Hospital, Saint Louis, MO. (Months 33-35).

In process

c. Demonstrate SPARKY III to MARP and TATRC. (Month 36).

In process, Program Line Review on July 27<sup>th</sup>, 2010.

## Phase 2 Deliverables

### Deliverables:

1. Design and construction of SPARKy 2a - **Completed**
2. Develop a rate gyro based controller for over ground walking - **Completed**
3. Test able bodied subjects walking on flat even surfaces, inclines/declines, and ascending/descending stairs – **In Process**
4. Using able bodied test data, a controller will be developed for over ground walking that includes inclines/declines and ascending/descending stairs – **In Process**
5. Develop a compact microprocessor - **Completed**
6. Develop a compact brushless DC motor amplifier – **Stopped working on this item**
7. Port Matlab code to microprocessor **Completed**
8. Test SPARKy 2a on two transtibial amputees at Arizona State University  
Conduct and Independent Motion Capture and Oxygen Consumption Test. **In Process**

## Phase 3 Deliverables

|                                                                                                    |                     |                                                                                                                  |                                   |
|----------------------------------------------------------------------------------------------------|---------------------|------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| <b>3.0 Design, Build, Test and Demonstrate SPARKy III</b>                                          | <b>Months 12-36</b> | Support transition from walking to jogging and continuous jogging (2.5 to 4 m/s for up to 1 hour).               |                                   |
| 3.1 Upgrade Prosthesis Componentry for Running                                                     | <b>Months 25-26</b> | Support running without powered element.                                                                         | material PhD student              |
| 3.2 Design, Build and Test Adjustable Robotic Tendon for Running                                   | <b>Months 25-28</b> | Interface with prosthesis. Show DOF using SPARKy II control software.                                            | material 2 PhD students machining |
| 3.3 Design, Select/Build, Package and Test Wireless and Portable Electronic Components for Running | <b>Months 26-29</b> | Interface with prosthesis and Adjustable Robotic Tendon. Show functionality using SPARKy II control software.    | Robotics Group                    |
| 3.4 Assemble Hardware                                                                              | <b>Month 29</b>     | IAW Hardware Specs/drawings. Supports limb to limb symmetry.                                                     | PhD student                       |
| 3.5 Design, Develop and Test Control Scheme                                                        | <b>Months 26-30</b> | Show logical output signal to motor based on sensor input signals.                                               | 2 PhD students                    |
| 3.6 Integrate System Hardware, Software and Control                                                | <b>Months 31-32</b> | IAW System Specs.                                                                                                | 2 PhD students                    |
| 3.7 System Performance Tests and Iterations                                                        | <b>Months 33-34</b> | Support continuous jogging on a treadmill for up to 1 hour. Mechanical tunability and sensor feedback will allow | Arise Prosthetics 2 PhD students  |



|                                                             |                 |                                                                                                                                                                                                                |                                              |
|-------------------------------------------------------------|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|
|                                                             |                 | variation in load, speed, and environment. Support transition from walking to running. All componentry will be self-portable (within prosthesis or fanny pack.)                                                |                                              |
| 3.75 Independent Motion Capture and Oxygen Consumption Test | <b>Month 35</b> | SPARKy III should require 20-30% less metabolic power than amputees supported by commercial foot-ankle devices and allow similar functionality as two commercial devices, one for walking and one for running. | Dr. Jack Engsberg, Motor Analysis Laboratory |
| 3.8 System Demonstration                                    | <b>Month 36</b> | Using selected amputee, show continuous treadmill jogging.                                                                                                                                                     |                                              |
|                                                             |                 |                                                                                                                                                                                                                |                                              |

### Phase 3 Deliverables

#### Deliverables:

9. Design and construction of SPARKy 3a
  - a. Developing an ankle in conjunction with West Point
10. Develop a rate gyro based controller for treadmill jogging
  - a. Jogging was demonstrated at West Point on April 23<sup>rd</sup>, 2010
11. Develop a compact microprocessor
  - a. Investigating new microprocessors
12. Develop a compact brushless DC motor amplifier
  - a. Currently dropped
13. Port Matlab code to microprocessor
  - a. Using Matlab, Real Time Workshop, MPLAB from Microchip, and the Kerheul Toolbox
14. Test SPARKy 3a on two transtibial amputees at Arizona State University
  - a. In process
15. Conduct and Independent Motion Capture and Oxygen Consumption Test.
  - a. In process

### Progress for Months 24-36

#### Activity 3.1 Upgrade Prosthesis Componentry for running.

We are currently using two RE40 motors with lead screws.

#### Activity 2.2 Design, Build and Test prosthesis for running.

A new foot was designed at West point and fabricated.

**Activity 3.3** Design, Select/Build, Package and Test Wireless and Portable Electronic Components

Thierry Flaven has selected the dsPIC 33 microprocessor. We have purchased a Demo board, MPLAB, and the Kerheul Matlab blockset. We have ported the Matlab code over to the dsPIC microprocessor board.

**Activity 3.4.** Assemble Hardware

We designed a standalone dsPIC 33 board that controls a brushed DC motor controller.

We dropped the EC Powermax motor and are using the RE40 motor. We have assembled all of the hardware.

**Activity 3.5.** Design, Develop and Test Control Scheme

Matthew Holgate has designed a Tibia Based controller that runs a continuous control algorithm. It can determine gait percent in the first 0.001 seconds of gait initiation. We use the phase angle of the tibia to determine gait percent. The polar length of the phase vector determines stride length. By knowing stride length and gait percent, we can determine the person's desired walking speed. Over ground walking has been demonstrated using this controller.

The controller was adapted to permit jogging.

**Activity 3.6.** Integrate System Hardware, Software and Control

We have integrated the electronics, software to the robot.

**Activity 3.7.** System Performance Tests and Iterations

We have completed preliminary testing at West Point.

**Activity 3.75.** Independent Motion Capture and Oxygen Consumption Test

We took SPARKy 1a to Washington University on January 11, 2009 for initial testing and fitting.



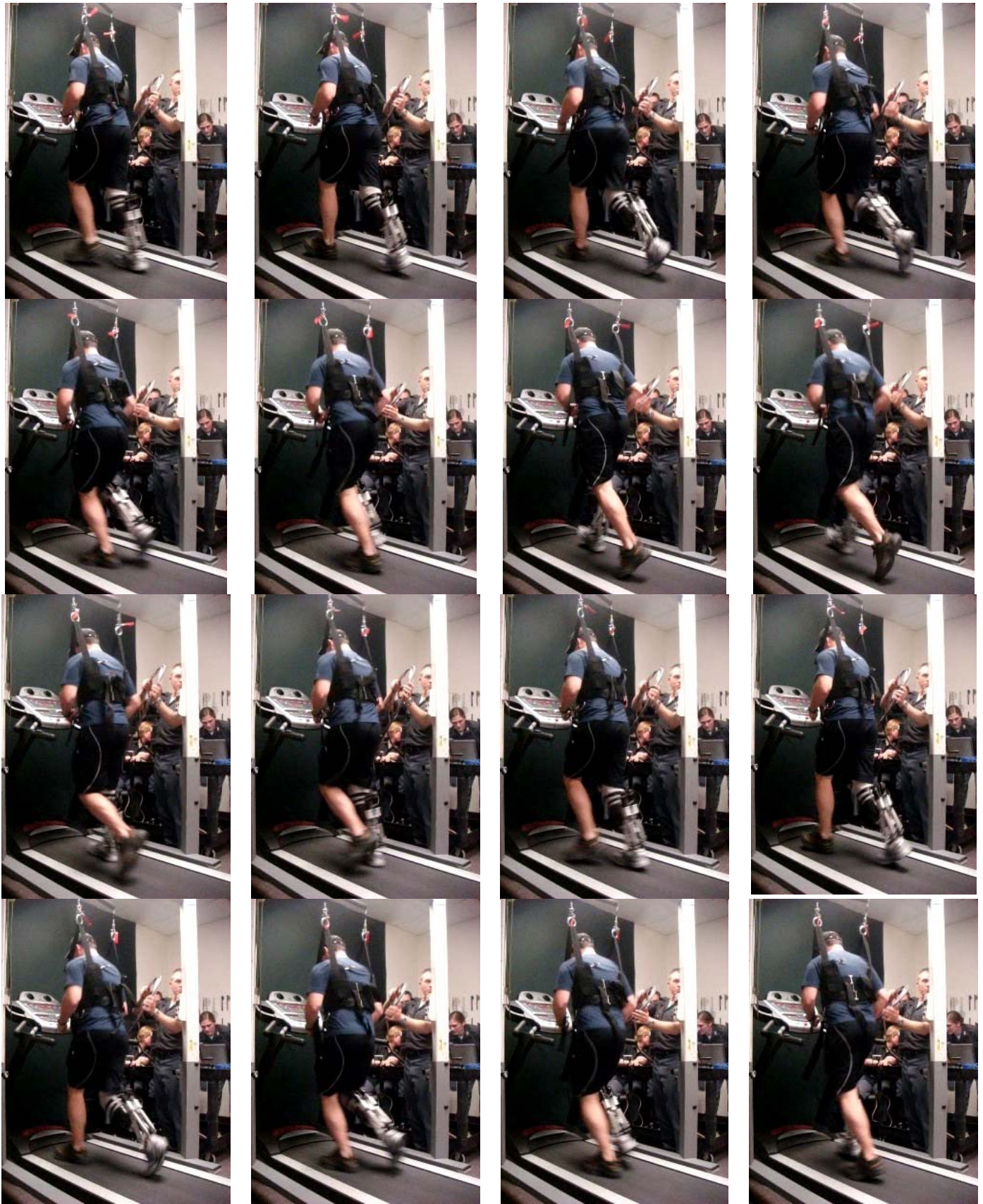
**Figure 1:** Subject is walking over ground on a flat surface.



**Figure 2:** Subject is walking on an inclined surface where the angle is constantly changing. Two small batteries are carried at the waist.



**Figure 3:** Subject is able to ascend and descend stairs.



**Figure 4:** Jogging at West Point

## Key Research Accomplishments:

Our powered ankle devices include the following characteristics:

- User has full range of sagittal ankle motion comparable to able-bodied gait. (23 degrees of plantar-flexion, 7 degrees of dorsiflexion.)
- User has 100% of the required power for gait delivered at the correct time and magnitude.
- The peak output power is 3-4 times larger than the peak motor power allowing a reduction in motor size and weight.
- Provide the user the flexibility to easily remove and install the Robotic Tendon to allow SPARKy to be used as a “powered and computer controlled” prosthesis or a “standard” keel and pylon prosthesis
- Based on lightweight, energy storing springs
- Allows a highly active amputee to regain high functionality and gait symmetry
- A demonstration of a powered, transtibial prosthesis was performed on November 2<sup>nd</sup>, 2007 at The Center for the Intrepid, Brooke Army Medical Center.

### Phase 2:

- Roller screw transmission was very robust and lightweight.
- A compact microprocessor was developed.
- Over ground walking was demonstrated.
- Walking on inclines and declines was demonstrated.
- Ascending and descending stairs was demonstrated.

SPARKy's biggest advantage lies in the fact that we are storing energy in a spring uniquely chosen for an individual. If one chooses the correct stiffness, the spring can be adjusted by the motor to allow for a 3 to 4 times power amplification. Because we have a large power amplification, we can use a small motor allowing a very large sized user to walk slow or walk at a very fast pace. Currently, we are only using 55 Watts of a 150 Watt motor so that we can easily power large individuals and can power fast walking.

We are using a fully intact keel that will absorb the heel strike impact and allow for correct rocker motion over the heel. The Robotic Tendon can be detached so that it can



be easily removed reverting back to a standard, passive carbon fiber keel. This feature can provide an alternative if the electronics fail in a field condition.

We are focused on developing the most durable, versatile, and powerful walk/run prosthetic ankle that meets the goals of a highly functional Military amputee. Because of our power amplification, we can easily walk very fast and have confidence in building a jogging device for Year 3.

## Reportable Outcomes

- Manuscripts
  - two PhD dissertations,
  - one MS thesis
  - four conference papers were published
  - two journal paper was published
- Popular Press – multiple web pages and newspaper articles discussed research
- Presentations – presented research at Dynamic Walking 2008 and 2009
- Demonstrations – Brooke Army Medical Center, Center for the Intrepid, November 2007, October 22, 2009

|                                                                           |                        |                        |
|---------------------------------------------------------------------------|------------------------|------------------------|
| Joseph Hitt                                                               | Mechanical Engineering | Graduated May. 2008.   |
| Dissertation: A Robotic Transtibial Prosthesis with Regenerative Kinetics |                        |                        |
| Ryan Bellman                                                              | Mechanical Engineering | Graduated August 2008. |
| Mechanical and Conceptual Design of a Robotic Transtibial Prosthesis      |                        |                        |
| Matthew Holgate                                                           | Mechanical Engineering | Graduated Dec. 2009.   |
| Dissertation: Control of a Robotic Transtibial Prosthesis                 |                        |                        |



## Conclusion

Significant advances have been achieved towards creating a computer-controlled, powered transtibial prosthesis that can actively support a user in their normal environment and conditions. Low power, high energy consumption, and sophisticated control methodology are key challenges towards realizing a smart, powered prosthesis. In Phase 1, the SPARKy project was able to develop a prosthesis that could supply high peak power to the user at push off in a light weight and energy efficient device.

The key outcomes included:

1. the user has full range of sagittal ankle motion comparable to able-bodied gait. (23 degrees of plantar-flexion, 7 degrees of dorsiflexion, and
2. the user has 100% of the required power for gait delivered at the correct time and magnitude.

The device provides the user 100% of the ankle power and ankle joint movement similar to able-bodied gait. This unique device is one of the most powerful and efficient devices of its kind.

The analyses and test data show that the motor power can be amplified to provide the user 100% of the required power. We showed a power amplification of the output power compared to the input power of 3 to 4 times. This power amplification allows the downsizing of the actuator to a portable level. For example, a small 150 W motor in combination with a transmission and spring provides 200 W to 400 W during testing. This size and weight of the system is to a level that is comfortably portable to the user while powerful enough to support an 80 kg subject up to his maximum walking speed of 1.8 m/s (4 mph). The data suggests that there is enough power available to support even larger users at such speeds.

In Phase 2, the SPARKy project developed a very lightweight prosthesis that was used in over ground walking. The roller screw design was very successful because it was a very robust and lightweight transmission. We ported all of the code to a dsPIC 33 microprocessor. Finally, this project exceeded our expectations in terms of the device performance. Our new control methodology and embedded microprocessor control allowed our Phase 2 device to move from the laboratory to the unstructured and highly dynamic environments that include stairs, inclines/declines and over ground walking.

These demands are very challenging but our successful Phase 1 and 2 research efforts provide the team high confidence that a walk/run device is possible.

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