CAREER: Biomechanics and Energetics of Human Locomotion with Powered Exoskeletons

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ABSTRACT: Previous studies from our laboratory have demonstrated that the choice of control algorithm greatly affects how a human adapts to a robotic lower limb exoskeleton. We have shown that proportional myoelectric controllers have distinct advantages over kinematic based controllers in healthy humans. However, many neurologically impaired patients that could benefit from a robotic lower limb exoskeleton do not have sufficient muscle activation patterns for robust myoelectric control. Our long term goal is to develop an artificial neural oscillator that can provide adaptive control for robotic lower limb exoskeletons and other robotic assistive devices for human locomotion. As a first step towards this goal, we used computer simulations to assess the stability and robustness of various neural oscillator algorithms coupled with dynamic systems. Due to the pendular nature of human walking mechanics, our dynamic systems included damped pendulums and a three-dimensional passive dynamic walker. We used a Hopf oscillator as our artificial neural oscillator providing neural control to the actuators. Overall results indicated that the Hopf oscillator could entrain to the resonant movement dynamics of the mechanical system with sufficient proprioceptive feedback. Our future work will examine methods to shape the timing and profile of the Hopf oscillator output to more closely mimic human muscle activation patterns. After coupling the revised Hopf oscillator to more complex dynamic walking models, we plan on testing their implementation on the robotic lower limb exoskeletons in our laboratory.

INTRODUCTION

At the University of Michigan Human Neuromechanics Laboratory, we have built robotic lower limb exoskeletons for assisting human locomotion. This work was sponsored by an NSF CAREER Award to Daniel P. Ferris with the intent of determining how robotic assistance affects the metabolic cost of human walking. By providing mechanical assistance at different lower limb joints, it is possible to calculate the relative apparent efficiency of the musculotendon work produced about the joints. Results from the ongoing projects have demonstrated that the control algorithm affects how the human wearer adapts their gait mechanics to the powered assistance. We have also shown that the powered assistance can reduce the metabolic cost of walking in healthy individuals, but that the storage and return of elastic energy in the Achilles tendon greatly increases the apparent efficiency of ankle joint mechanical work. To aid in the mobility and rehabilitation of indivduals with neurological disabilities, it would be advantageous to have controllers that are adaptive and did not rely on a robust neurlogical control signal from the wearer.

With the long term goal of creating artificial neural oscillators that can serve as adaptive controllers for our robotic lower limb exoskeletons, Alexandra Voloshina travelled to Professor Auke Jan Ijspeert's Biologically Inspired Robotics Group at the Swiss Federal Institute of Technology at Lausanne (EPFL). Alexandra worked with Prof. Ijspeert's research group to develop computer simulations of various artificial neural oscillators and physics-based models of human walking based on passive dynamic walkers. The Biologically Inspired Robotics Group has developed novel and elegant techniques for adaptive control using artificial neural oscillators to control simulations of legged robots and legged robots. Because of the unique successes of the Biologically Inspired Robotics Group in Switzerland, we strongly believed that working with them would greatly advance our development of artificial neural oscillator controllers for robotic lower limb exoskeletons. Alexandra was finishing up her undergraduate degree in biomedical engineering at the time of our proposal for an IREE supplement. She was working in the Human Neuromechanics Laboratory in conjunction with Monica Daley, an NSF Bioinformatics Postdoctoral Research Fellow, on computer simulations of neuromechanical systems of legged locomotion. Alexandra was going to begin her doctoral studies in the School of Kinesiology at the University of Michigan the following year under the guidance of Daniel Ferris. Her dissertation research will focus on neuromechanical computer simulations of legged locomotion and artificial neural oscillator based controllers for robotic lower limb exoskeletons. As such, she was the ideal choice to travel to Switzerland to collaborate with Prof. Ijspeert and his research group. Alexandra joined the Biologically Inspired Robotics Group from February 2008 to May 2008 to work on the project.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

The first stage of the project was to compare different types of oscillators as potential controllers on a simple mechanical system. We constructed a simulation of a simple damped pendulum in Webots Dynamics software and coupled it to several different artificial neural oscillators using proprioceptive feedback and a feedforward torque control signal. The oscillators included Hopf, Matsuoka, and van der Pol oscillators. We performed analyses to determine the stability of entrainment over a range of different oscillator parameters (Figure 1). Based on the results, we settled on a Hopf oscillator for our artificial neural oscillator.

The second stage of the project was to develop a simple mechanical model for simulating human walking dynamics. Based on the similarity between human gait and passive dynamic walkers, we chose to construct a simulation in Webots that emulated passive dynamic walkers (Figure 2). We began with a simple passive dynamic walker without knees that walked down a sloped surface. Then we progressed to a dynamic walker with knees and more biologically shaped feet. The ankles were held fixed. The four legs allowed the walker to have lateral stability preventing it from falling sideways.

The third stage of the project was to couple the Hopf oscillator to the dynamic walker using proprioceptive feedback of hip position and feedforward control over hip torque. Although we did not finish this stage of the project during the visit to Switzerland, the advances made during the trip will allow us to contine working on the artificial neural oscillator controller. After producing a stable gait over level terrain, we plan on transferring the controller to a hip exoskeleton for testing. The hip exoskeleton is constructed and undergoing experimental testing with a kinematic based controller at present.

During Alexandra’s stay in Switzerland, she regularly participated in events of the Biologically Inspired Robotics Group. This included seminars, lab meetings, and discussion on ongoing projects. Lab members were invaluable in teaching Alexandra how to use the Webots software, perform parameter searches for stability analyses, and couple the artificial neural oscillators with the physical systems in the computer simulations. After her short stay, Alexandra was able to present on the results at a meeting in the Netherlands (1). The visit layed the groundwork for a lasting collaboration between Prof. Ijspeert’s research group and the Human Neuromechanics Laboratory at the University of Michigan. Alexandra will continue working on the project and will likely make at least one more trip to Switzerland to interact with the Biologically Inspired Robotics Group. We envision that the project will develop into several published research articles.

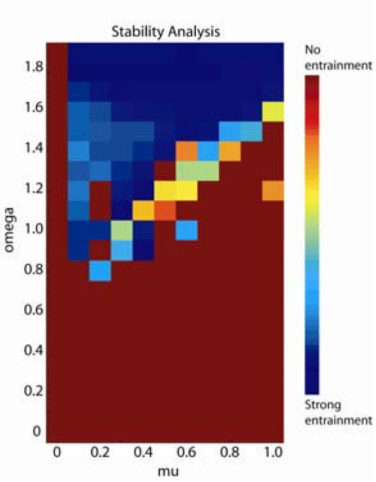

Figure 1 – Analysis of stability for a simple pendulum coupled to a Hopf artificial neural oscillator. The two main parameters of the Hopf oscillator (μ and ω) were altered to determine their effect on entrainment to the pendulum dynamics.

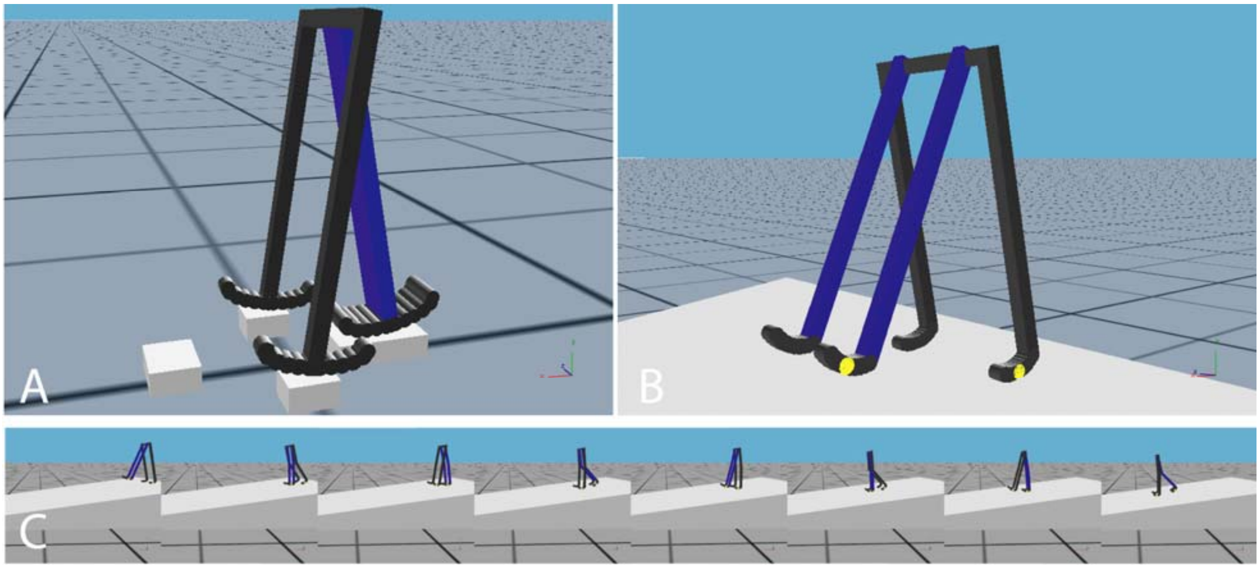

Figure 2 – A) First iteration of the passive dynamic walker with no knees. The blocks were used so the toes would not interfere with walking during swing phase. B) Second iteration of the walker with knees and slightly altered feet curvature. This passive walker walked down the slope without active actuation. C) Video frames showing the walker moving down the slope.

BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

Alexandra Voloshina is an underrepresented graduate student in science and engineering. The IREE award enabled her to learn from one ofhte world's foremost experts in robotic control with artificial neural networks. It also allowed the University of Michigan Human Neuromechanics Laboratory to develop an ongoing collaboration with the Biologically Inspired Robotics Group at the Swiss Federal Institute of Technology at Lausanne (EPFL). The EPFL is one of Eurpoe's premier sites for research in engineering and computer simulation. The three month visit greatly enhanced Alexandra's understanding of these areas from the perspective of the EPFL collaborators. This collaboration will be continued throughout Alexandra's dissertation research and could lead to major breakthroughs in artificial neural oscillator control for robotic lower limb exoskeletons. While the original scope of the NSF CAREER Award was to examine the coupling between the biomechanics and energetics of human locomotion, the IREE award expanded that scope to consider neural control.

DISCUSSION AND SUMMARY

The IREE Supplement provided funds to enable a promising doctoral student to begin an innovative research project for her dissertation. The project brings together U.S. experts in robotic lower limb exoskeletons with Swiss experts in biologically based controllers for legged robots. The project will continue over the next 4-5 years. During this initial visit to Switzerland, Alexandra became well versed in how to use the Webots software, tested the relative stability of different artificial neural oscillators, and developed simple models of human walking dynamics. She also developed a strong rapport with Prof. Ijspeert and his laboratory staff. We envision that the collaboration will lead to several published journal articles in the near future. We recommend that future IREE travelers take time during their stay to outline work that can be begun after the visit in the host laboratory. That was particularly helpful in our experience.

ACKNOWLEDGEMENTS

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REFERENCE

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BRIEF BIOGRAPHIES OF RESEARCHERS

Alexandra S. Voloshina received her B.S. in biomedical engineering from the University of Michigan in 2007. She is currently a doctoral student in the School of Kinesiology at the University of Michigan. Her long term research interests are in developing computer simulations of neuromechanical systems and control algorithms for robotic exoskeletons.

Daniel P. Ferris received his B.S. in Mathematics Education from University of Central Florida in 1992, his M.S. in Exercise Physiology from University of Miami in 1994, and his Ph.D. in Human Biodynamics from University of California, Berkeley in 1998. He worked as a post-doctoral researcher in the UCLA Department of Neurology from 1998 to 2000, and in the University of Washington Department of Electrical Engineering from 2000 to 2001. He is currently an Associate Professor at the University of Michigan, Ann Arbor, MI, in the School of Kinesiology, Department of Biomedical Engineering, and Department of Physical Medicine and Rehabilitation. He studies the neuromechanical control of human locomotion in health and neurological disability. One focus of those studies is to build robotic lower limb exoskeletons for assisting gait rehabilitation.