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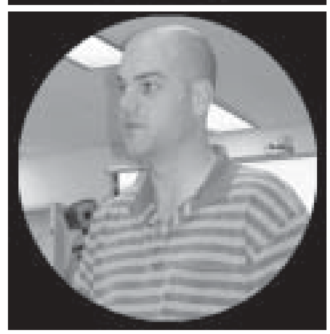




A showcase of student work in Prosthetics and Orthotics

CONTENTS

A Showcase of NURERC Students' Research

"Mentorship of new talent and research is the bedrock for future improvements and innovations in Prosthetics and Orthotics."

An important aspect of our work at Northwestern University's Rehabilitation Engineering Research Center (NURERC) is to inform and educate other professionals and the public about our research. This issue of *Capabilities* features the projects of our graduate students. Hailing from varied backgrounds and interests, these young researchers are united by a determination to develop better prostheses and orthoses and thus enhance the lives of those who live with physical disability.

NURERC is fortunate to have inspired, dedicated faculty whose ongoing projects attract young, talented individuals who are eager to learn and work collaboratively. The engineering-based program has thirteen students of whom five are in the masters program and eight are in the doctoral program. Their research is supported by important funding agencies such as the Whitaker Foundation Graduate Fellowship in Biomedical Engineering, National Defense Science and Engineering Graduate Fellowships, National Consortium for Graduate Degrees for Minorities in Engineering and Science (GEM), National Science Foundation (NSF) and National Institute on Disability and Rehabilitation Research (NIDRR). Others participate in vital, collaborative research funded by Veterans Affairs or the National Institutes of Health. Still others have fellowships from Northwestern University and provide essential services as Research Assistants and Teaching Assistants. As ever, the opinions expressed in *Capabilities* are those of the authors and do not necessarily reflect those of the funding organizations.

NURERC faculty and students come from diverse backgrounds that include engineering, physiotherapy and physical anthropology, while others are certificated prosthetists and/or orthotists. All are committed to educational excellence and productivity through rigorous collaboration and individual hard work. Communication with others from different intellectual and cultural backgrounds further augments our students' intellectual inquiry and discovery.

This breadth of interest, training and experience benefits NURERC research projects, which are never conducted in sterile isolation. Rather, active discourse and interaction are fundamental to the process our students use to design and develop projects. Through this collaborative process, they learn and contribute important ideas, methods and testing, ultimately enhancing products that become available to Prosthetics and Orthotics practitioners and consumers.

Mentorship of new talent and research is the bedrock for future improvements and innovations in Prosthetics and Orthotics. We are delighted to showcase the research of our students at NURERC. Please enjoy this issue of *Capabilities* where you will learn about the innovative work and interesting backgrounds of NURERC's outstanding, young engineering students.

~R. J. Garrick, Ph.D.~
Editor

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Muscle Synergies as an EMG Pattern Classification Paradigm for Multifunctional Myoelectric Devices

A. Bolu Ajiboye, M.S.

(The Ruth L. Kirschstein National Research Service Award (NRSA) Pre-doctoral Fellowship, sponsored by the National Center for Medical Rehabilitation Research (NCMRR) under the National Institutes of Health (NIH), supported this work.)

A. Bolu Ajiboye

Bolu Ajiboye received the dual B.S.E. degree in biomedical and electrical engineering and a minor in computer science from Duke University, Durham, NC, in 2000, the M.S. degree in biomedical engineering under Dr. Dudley S. Childress, and Dr. Richard F. *ff.* Weir, in 2003, from Northwestern University, Evanston, IL, where he is currently working toward the Ph.D. degree, under Dr. Weir, in the Prosthetics Research Laboratory. His research interests lie in the areas of neuromuscular control of human movement and myoelectric control of upper-limb prostheses. He is currently a Kirschstein National Research Service Award Predoctoral Training Fellow of the National Institutes of Health.

Bolu Ajiboye's work demonstrates that a pattern of EMG values can provide a synergy-based pattern recognition system for multifunctional myoelectric controls.

Introduction

There exist at least three modes of control of myoelectric devices. The first, currently implemented in standard two-site myoelectric trans-radial prostheses, is based on a one-to-one mapping of input sites to controlled functions. A second focuses on the ability of pattern recognition algorithms, using tools such as artificial neural networks and fuzzy logic systems [1], to extract features from a limited set of electrode sites and map this activity to a larger number of functions.

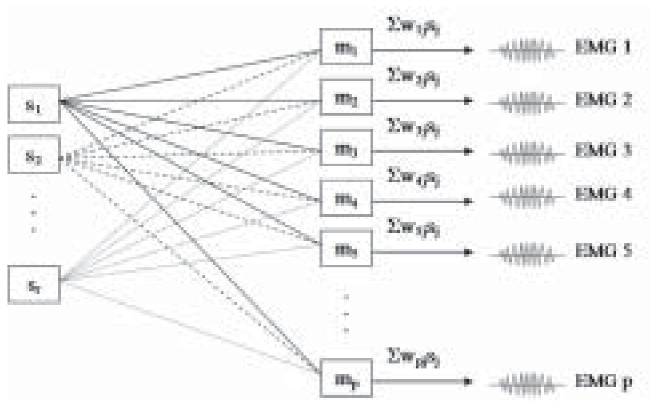

Figure 1: Nodal Representation of Synergy Composition Model. The EMG recorded from each muscle is a weighted sum of the inputs from each synergy node.

The third potential mode of control is based on the use of synergistic muscle groups. There is some evidence to suggest that the intact CNS organizes muscles into synergistic groups to coordinate the many degrees-of-freedom involved in control [2, 3]. Such an organizational method could simplify physiological control of complex systems such as the human hand. However, it has not been shown if these muscle synergies can be used within a control paradigm for multifunctional myoelectric devices.

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Model

To use muscle synergies as a paradigm for EMG pattern recognition for myoelectric control, one must first be able to determine what muscle synergies are used to construct the controllable movements. Figure 1 shows a nodal representation of the synergy model. Each muscle $m_{1..p}$ receives an input from each synergy node $s_{1..r}$, presumably located in the supraspinal and/or spinal systems [4]. The observed electromyography (EMG) samples $o_{1..n}$ recorded from each muscle is a weighted sum of the synergistic inputs. Mathematically, this is represented as

$$\begin{array}{c|c} & o_1 \;\cdots\; o_n \\ \hline \begin{matrix} m_1 \\ m_2 \\ \vdots \\ m_p \end{matrix} & \left[\begin{matrix} & & \\ & V & \\ & & \\ & & \end{matrix}\right] \end{array} = \begin{array}{c|c} & s_1 \;\cdots\; s_n \\ \hline \begin{matrix} m_1 \\ m_2 \\ \vdots \\ m_p \end{matrix} & \left[\begin{matrix} & & \\ & W & \\ & & \\ & & \end{matrix}\right] \end{array} \times \begin{array}{c|c} & o_1 \;\cdots\; o_n \\ \hline \begin{matrix} s_1 \\ s_2 \\ \vdots \\ s_r \end{matrix} & \left[\begin{matrix} & & \\ & H & \\ & & \\ & & \end{matrix}\right] \end{array},$$

where V is the recorded signals, W is the synergy (weighting) matrix and H is the input matrix. Hence, to discern the muscle synergies used to construct a movement, the matrices W and H must be estimated, given only the set of EMG signals. Two ways to do this are non-negative matrix factorization (NMF) and independent component analysis (ICA).

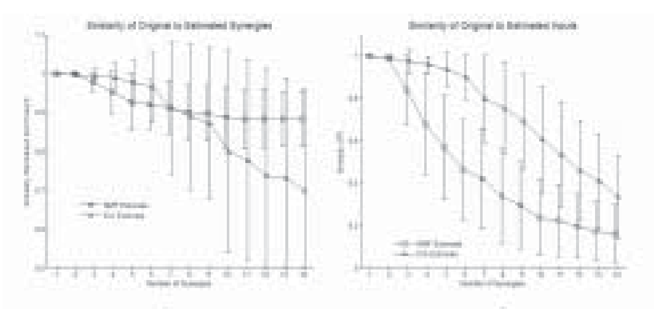

Figure 2: NMF and ICA Estimation of (a) Synergies and (b) Inputs

Simulation Results

To assess how well NMF and ICA estimate the synergy matrix W and the input matrix H, known W and H matrices were randomly generated, and then combined to generate simulated noiseless EMG data (V). Then, given only the EMG matrix, both NMF and ICA were used to estimate the original W and H matrices. The number of original synergies r was allowed to vary from *1 to p* (the number of muscles), and the success of NMF and ICA were assessed in each scenario. Figure 2 reports how well each algorithm was able to estimate the original synergy (W) and input (H) matrices for each number of original synergies, using the dot product and statistical R^2 similarity metrics. The fidelity of both algorithms in estimating the synergy matrix decreased with increasing number of synergies, with ICA outperforming NMF at fewer synergies, but NMF performing better with more synergies. ICA did a better job than NMF of estimating the input matrices with more synergies, although neither seemed to do very well for $r > 6$. Also of note is that the variances of the similarities of the ICA synergy estimates were much larger than those of the NMF estimates, while the input estimates of ICA generally showed less variance than those of NMF.

Discussion

The first step in implementing a synergy-based pattern recognition system for multifunctional myoelectric control is to demonstrate that the implemented estimation algorithms can accurately estimate the components the CNS uses to construct the EMG signals. The simulations described demonstrate that, given just a pattern of EMG values, the original synergies and inputs can be well discerned, for a system with a small number of synergistic components. Furthermore, because of the low variance in error exhibited in the estimations, recognition of the synergistic components seems to be repeatable. This is a necessary property for any recognition algorithm. Future implementation of this method for EMG pattern recognition requires establishing a database of synergies and inputs for various movements. Recorded real-time EMG patterns then can be decomposed into their respective synergy components, which can be compared to this database to discern users' intended control actions.

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Lending a Helping 'ARM': Relief and Rehabilitation in Armenia

A. Bolu Ajiboye, M.S.

(I appreciate those who supported my participation in the ARM project.)

In June 2005, I spent ten days in Armenia helping the Armenia Relief Mission (ARM). Founded by Dr. Steve Kashian and his wife Rozik, ARM is a non-profit organization that provides aid to the people of Armenia. After a devastating earthquake in December 1988 that resulted in 25,000 dead, 50,000 injured, and 100,000 homeless [1], Dr. Kashian frequently visited Armenia as a medical missionary providing medical care and delivering pharmaceuticals. In Vanadzor City, he helped establish a medical clinic that provides free medical care to local Armenians and employment for several Armenian doctors, nurses, and pharmacists.

Recently, the Village of Northbrook, IL donated a community playground to ARM. In 2004, volunteers constructed one section of the playground at the Vanadzor medical clinic; and in 2005 I joined six ARM volunteers to build a second section at a nearby state-run orphanage. The third section of the donated playground will be built in Armenia's capital, Yerevan, where ARM purchased property to establish an orphanage. The site used to be a recreational retreat for the Communist Party when the former Soviet Union ruled Armenia. Our goals were twofold: 1) to reconstruct the second section of the playground at the Vanadzor orphanage; and 2) to rehabilitate the dilapidated cabins, called *domiks*, which ultimately will become the kitchen and living quarters at the Yerevan orphanage.

I observed that the Armenians we met were very relationship-oriented, in contrast to the task-oriented interactions typical of our American culture. During our stay, we incorporated both approaches: building the playground was an important task, but equally significant was building relationships. In terms of tasks, we erected the playground at the Vanadzor orphanage and significantly rehabilitated one of the *domiks* at the Yerevan orphanage site. In terms of relationships, we forged bonds with the children and other Armenians that have lasted until now. Several of the children wrote to us expressing that while they love the playground, even more, they enjoyed our companionship and attention. I went to Armenia knowing that I would give my time and physical energies, but I quickly recognized that my work was profoundly rewarded by human interaction and life experience.

Surrounded by children, A. Bolu Ajiboye (right, back) worked with Armenia Relief Mission (ARM) volunteers to build a playground at a state-run orphanage in Vanadzor, Armenia.

My volunteer work added to already existing relief connections between the Rehabilitation Institute of Chicago (RIC) and Armenia. The 1988 earthquake caused many severe injuries, including loss of limbs. In 1989, Dr. William Walsh (founder of the international relief organization, Project Hope) coordinated doctors and prosthetists from Children's Memorial Hospital and the RIC, to provide physical

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Prosthetic Hand for Able-Bodied Subjects (PHABS) and the Effects of Controller Delay on Prosthesis Performance

Todd Farrell, M.S.

(This work was funded in part by the National Institute on Disability and Rehabilitation Research (NIDRR) of the Department of Education under grant number H133E030030; the National Institutes of Health under Grant 1 R01 EB01672-01; and the Department of Veterans Affairs, Rehabilitation Research and Development Service and is administered through the Jesse Brown Veterans Affairs Medical Center, Chicago, IL.)

Below-elbow prosthesis users who use externally powered devices most often are fit with a prosthetic hand that will provide only a single motion (e.g., opening/closing of the hand). While this returns some of the function that was lost by the amputation, the prosthesis user no longer is able to control movements of the wrist or vary the type of grasp that the hand produces (an individual will use different types of grasp to pick up a soda can as opposed to holding a key).

One direction of the upper-limb group at NUPRL is to design a prosthesis that recognizes patterns of muscle activity in the residual limb and relates this muscle activity to movements of the prosthesis, thus enabling it to move and grasp in many different ways. One of my projects examines the use of implanted electrodes that provide very specific muscular activity measurements from individual muscles in the forearm, as opposed to the gross measurements obtained from electrodes that are placed on the surface of the skin. Another project, the work that I will discuss here, examines the effect of a prosthesis controller delay on the performance of the prosthesis.

Multifunctional prosthesis controllers have shown that they can better predict the intended movement of the user when longer time segments of muscle electrical activity (as measured by the electromyogram or EMG) are examined [1]. However, there is a time limit beyond which the delay necessary to collect and analyze EMG data causes the control of the prosthesis to become cumbersome. In an extreme example, one could imagine the hardships introduced by a five second delay, causing the user to wait five seconds before the prosthesis would respond to a command. This would make proficient control of the device nearly impossible. A trade-off exists between examining as much EMG data as possible, enabling the controller to interpret more correctly the intended movement of the user, versus minimizing the time

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Todd Farrell

Background: Currently, I am a 6th year graduate student in biomedical engineering. I grew up in Valatie, NY (about 30 minutes south east of Albany) and received my bachelor's degree from the Catholic University of America in Washington, DC.

Future Goals: I have been accepted by the medical school at the University of Pittsburgh where I plan to begin my medical studies in August, immediately after I defend my Ph.D. thesis at Northwestern University. I would like to find a job where I can pursue both research and clinical work.

Personal Interests: My personal interests include coaching youth basketball as well as participating in a variety of sports. I also play in a rock band with fellow graduate students/faculty/staff. Recently, I've started to brew my own beer at home.

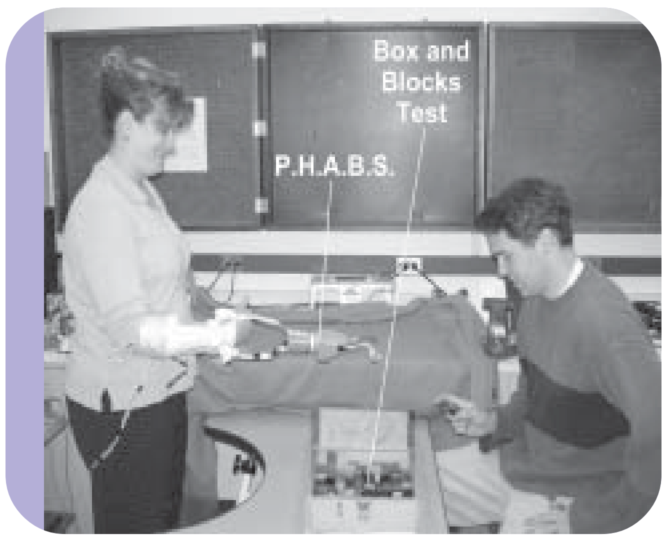

Figure 1: Todd Farrell (right) times volunteer subject, Laura A. Miller, Ph.D., CP (left), who is performing the Box and Blocks Test with the Prosthetic Hand for Able Bodied Subjects (PHABS).

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between the intention of movement and the actual movement of the prosthesis. Therefore, we designed experiments to define the greatest amount of controller delay that does not significantly affect prosthesis performance and that can be dedicated to EMG collection and processing.

We created the **P**rosthetic **H**and for **A**ble-**B**odied **S**ubjects (PHABS) (Figure 1) to allow able-bodied subjects to operate a prosthetic terminal device and to allow us to examine the effects of controller delay on prosthesis performance [2]. The Box and Blocks Test (Figure 1) was used as the measure of prosthetic performance [3]. It is a sixty-second timed test in which subjects were instructed to use PHABS to pick up blocks from one compartment, transport them across the barrier and release them in the opposite compartment as quickly as possible.

Subjects performed three trials of the Box and Block Test with two different prehensors (‘fast’ and ‘slow’) at seven levels of controller delay (0 to 300 ms in 50 ms increments). Results showed that as the controller delays become larger, the Box and Block Test scores tended to decrease. The results of post-hoc tests on a repeated measures ANOVA analysis showed that, with both the ‘fast’ and ‘slow’ prehensors, controllers with a delay at or above 150 ms had statistically significantly lower scores on the Box and Block Test than the shortest delays of 0 and 50 ms. This indicates that controller delays as small as 150 ms will have a negative impact on prosthesis performance. Thus, designers of prosthesis controllers should limit EMG data acquisition and processing to less than 150 ms.

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Lending a Helping ‘ARM’: Relief and Rehabilitation in Armenia

A. Bolu Ajiboye, M.S.

rehabilitation to several Armenian children. Dr. Armen Kelikian (now at Illinois Bone and Joint Institute), Dr. Yeongchi Wu (now at Center for International Rehabilitation), Jack Uellendahl, CPO (now at Hanger Prosthetics & Orthotics Inc.), and others worked as a team to perform reconstructive surgeries and fit the children with body-powered prosthetic arms. Their rehabilitative efforts enabled the children to achieve the activities of daily living [1].

Relevant to my work in prosthetics research at NURERC, while in Vanadzor I met Armen Sarkissian, a young man who had experienced a vehicle accident and trans-humeral amputation. A former sports trainer, Mr. Sarkissian could not support himself and his family, so Dr. Steve Kashian and I pledged to help him obtain a prosthesis and rehabilitation training. Mr. Sarkissian could not pay for a prosthesis or training, but Dr. Kashian and I found Stephan Manucharian, CPO, and Armen Sarkisyan, CPO, both Armenian prosthetists, who offered their services and prosthetic components to Mr. Sarkissian at no cost. Now, Dr. Kashian and I are seeking donors to underwrite Armen Sarkissian’s trip between Vanadzor, Armenia and Mr. Sarkisyan’s prosthetic clinic in Moscow, Russia.

ARM’s work in Armenia is not yet complete. In a few years, ARM envisions the Yerevan orphanage will be fully staffed and operational. I look forward to helping ARM accomplish its vision by returning to Armenia this summer to help rehab *domiks* and landscape the orphanage grounds. Also, I hope to see Armen Sarkissian using a functional prosthetic arm, again able to pursue his livelihood and support his family.

Reference

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Series Elastic Actuators: Providing Safe Power in Electric Prostheses

Jonathon Sensinger, M.S.

(A National Defense Science and Engineering Graduate Fellowship, the Department of Veterans Affairs, Rehabilitation Research and Development Service administered through the Jesse Brown VA Medical Center, Chicago, and the National Institute of Disability and Rehabilitation Research of the United States Department of Education under grant H133E030030 supported this work.)

High fidelity versions of simple, electromechanical motors have high performance levels; so often they are used for interaction with people. The performance of such motors, however, must be balanced against the safety of the user and his environment. In order to optimize both parameters, it is desirable to examine safety independently of performance. One independent metric for measuring safety is impedance.

Impedance defines the relationship between the kinematics (position, speed, and acceleration) of an object and the resulting forces. For example, a spring exerts a force when you shorten it (F=kx), whereas a mass exerts a force when you accelerate it (F=ma). Most objects have stiffness and inertia. To ensure low forces, a robot must either have low magnitudes of motion or low impedance. Because high levels of performance are proportional to the ability to move fast, inhibiting motion is undesirable. As a result, low impedances are desired in robots that interact with humans to minimize unplanned forces.

Many term these classical robots as having low-impedance if the actuator's impedance is low within the operating range of the robot. However, it is precisely above the operating range where conventional robots, even high fidelity force robots, lose their low impedance and thus become hazardous to people in unplanned collisions. The problem is exacerbated by the inherent properties of electric motors, which require high gear ratios. In turn, these high gear ratios significantly amplify the inertia of the actuator, creating high impedance systems. Perhaps the most common remedy in conventional robotics is to soften the blow of the robot with a compliant cover. However, as Zinn et al. have illustrated [1], more than five inches of cushioning would be needed to generate sufficient compliance to make a robot such as the Puma 560 safe when interacting with people. This bulkiness is unacceptable for many human-robot applications.

One solution to this problem has been the intentional introduction of compliance in the robot, a concept made popular by Pratt et al. [2], who termed such an actuator a "series elastic actuator." Increasing the compliance increases the force fidelity and the controllable bandwidth of the actuator, while limiting the impedance to the stiffness of the spring. It negatively affects performance by decreasing the maximum frequency of torque oscillations at a given torque magnitude.

Figure 1: Prosthetic elbow.

Our research has attempted to harmonize the desired features of series elastic actuators, namely their inherent safety and force fidelity, with a conservative power source required in prosthetics. Traditionally, this has been done by including a non-backdrivable transmission, which only draws energy when movement of the prosthesis occurs. Non-backdrivable transmissions have never been popular in force control,

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even in the realm of series elastic actuators, but there are no inherent conflicts between their use and safe, high fidelity force control. We have found that adequate force bandwidth may be achieved with the inclusion of a non-backdrivable transmission. Currently we are integrating these concepts into a prosthetic elbow shown in Figure 1. A more detailed discussion may be found in [3].

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Jonathon W. Sensinger

Jonathon Sensinger received the B.S. degree from the University of Illinois in Chicago, USA, in 2002 and the M.S. degree from Northwestern University in 2005. He is investigating nonbackdrivable impedance control for use as a control paradigm in prosthetics. He enjoys backpacking, kayaking, and reading to his wife and new daughter.

(Left to right) Jon Sensinger is shown with subject, Jesse Sullivan, and advisor, Richard F. *ff.* Weir, Ph.D., working on a haptic implementation of a series elastic actuator.

NEWS FROM THE DEPARTMENT OF VETERANS AFFAIRS

VA Investigators Working to Advance Osseointegrations

Joel Kupersmith, M.D.

(Joel Kupersmith, M.D., is Chief Research and Development Officer at Veterans Affairs)

Prostheses with Titanium Anchor in Bone

Osseointegration, a surgical technique for anchoring lower-limb prostheses directly to the bone in the residual limb, may carry significant advantages over current attachment methods. But there are potential drawbacks to the technique, and researchers will have to overcome major challenges before it becomes accepted in the United States. Department of Veterans Affairs scientists—in particular, teams at our Providence, RI, and Salt Lake City sites—are in the forefront of this effort.

Developed in Sweden and now used more widely in Europe, osseointegration involves threading the artificial leg onto a titanium bolt that is implanted in the bone of the residual limb and protrudes through the skin. This is a paradigm shift from methods used for the past half-century, in which a rigid plastic or fiberglass socket is custom-molded to fit over the residual limb, like a thumb in a thimble. Even with the use of soft liners over the residual limb to ease friction and absorb perspiration, conventional methods often cause tissue breakdown and extreme discomfort for the user.

Advantages and Challenges

European amputees who have successfully undergone osseointegration report several advantages. For example, they say they do not feel the increased weight of their prosthesis, and have better control over it. And they experience no socket-related skin irritation.

Osseointegration is not without its challenges, however. It requires two surgeries and a relatively long rehabilitation period—at least 18 months. And since there is a "foreign" object permanently piercing the skin, the risk of infection is always present. This can be controlled through rigorous personal hygiene and antibiotics, but infections that do occur can involve serious consequences: bone loss, loosening of the implant, and a possible need for re-amputation of the limb at higher, less functional level.

Prosthetics Technology and Tissue Engineering

The main thrust of VA research in this area, then, is to learn how to prevent infection. In one of many projects at our recently established Providence-based Center of Excellence for Rebuilding, Regenerating and Restoring Function after Limb Loss, scientists will try to grow skin cells that will fuse with the titanium, forming a natural seal around the bolts to minimize the chance of infection. Dr. Clyde Briant, a metals expert, will experiment with different titanium alloys to find a combination strong yet porous enough for cells to bond to, while his colleague Dr. Jeffrey Morgan, a tissue-engineering specialist, will alter human skin cells to create cells capable of multiplying and spreading on metal. In addition to its application in osseointegration, this work could lead to improvements in other medical devices inserted in the skin, such as catheters and shunts.

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Along with this VA-supported research, Dr. Roy Bloebaum, director of VA's Bone and Joint Research Laboratory in Salt Lake City and a professor of bioengineering, orthopedics and biology at the University of Utah, is working on two Department of Defense grants totaling $4.3 million to develop novel anti-bacterial compounds to enhance the safety of osseointegration. Dr. Bloebaum's goal is to make osseointegration an "infection-free" procedure.

Osseointegration Report at AAOP 2006

Dr. Bloebaum and clinical colleague Ed Ayyappa, a prosthetist at the VA Desert Pacific Healthcare System, will be delivering a presentation on osseointegration at the annual meeting of the American Academy of Orthotists and Prosthetists in March 2006 in Chicago. The work of these talented scientists is integral to our overall program to advance prosthetics care and technology, and we look forward to their continued progress.

(This article was coordinated by Robert M. Baum.)

Robert M. Baum

Robert M. Baum is Program Manager for Prosthetics and Clinical Logistics.

NURERC and *Capabilities* sincerely appreciate Mr. Baum's ongoing collaboration and cooperation in writing, coordinating, and facilitating quarterly research contributions from and about Veterans Affairs.

Please contact him with your suggestions for future articles:

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ORTHOPAEDIE + REHA-TECHNIK Tradeshow

ORTHOPAEDIE + REHA – TECHNIK's International Trade Show and World Congress for Prosthetics, Orthotics and Rehabilitation Technology will be held in Leipzig, Germany from May 10 through 13, 2006. For the first time, the United States of America will be a partner nation for this event. The trade fair will feature hundreds of exhibitors. Topics at the meeting will include all aspects of prosthetics and orthotics, mobility aids, surgical, medical and homecare appliances, as well as diagnostic systems. Presentations by more than 200 speakers will provide an opportunity for continuing education. For more information, please visit their website at www.ot-forum.de

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The Effect of Trunk Flexion on Standing and Walking

Devjani Saha, B.S.

subjects. Instead, they may be compensatory mechanisms that shift the body's COM toward a more stable position closer to the base of support. Trunk flexion also resulted in a decrease in mechanical energy transfer during gait, as well as an increase in oxygen consumption while standing.

By investigating the relationship between trunk posture and the ability to maintain balance in able-bodied individuals, we hope to improve our understanding of some of the functional consequences associated with spinal pathologies. Furthermore, the results of this study can be used to help surgeons develop outcome measurements to gauge the efficacy of spine treatments.

The Role of Spinal Motion in Walking

Regina Konz, M.S.

(Funds from Medtronic Sofamor-Danek, Inc., the National Institutes of Health training grant 5T32HD07418-10, and the National Institute on Disability and Rehabilitation Research of the United States Department of Education under grant H133E030030 supported this work.)

Our understanding of the spine's role in walking is limited currently because typical models either disregard the upper body entirely or consider the trunk as a *single*, rigid structure. Data on segmental spinal movements associated with walking are scarce. Exploring how spinal motion contributes to walking forms the basis of my doctoral dissertation. Drs. Dudley Childress, Steven Gard, and Stefania Fatone, and Ms. Rebecca Stine and I are collaborating with Drs. Stephen Ondra and Aruna Ganju, surgeons from the Northwestern University Feinberg School of Medicine's Department of Neurological Surgery, on two studies: (1) Analysis of Able-Bodied Spinal Motion During Walking, and (2) Analysis of Pathologic Spinal Motion During Walking. The overall purpose of these studies is to increase our understanding of the spine's role in walking and to determine the effects of limiting spinal motion on walking in both able-bodied adults and adults with spinal pathologies. By furthering our understanding of the relationship between spine motion/restriction and the rest of the musculoskeletal system in locomotion, we hope to gain a broader understanding regarding the implications of disease and treatment.

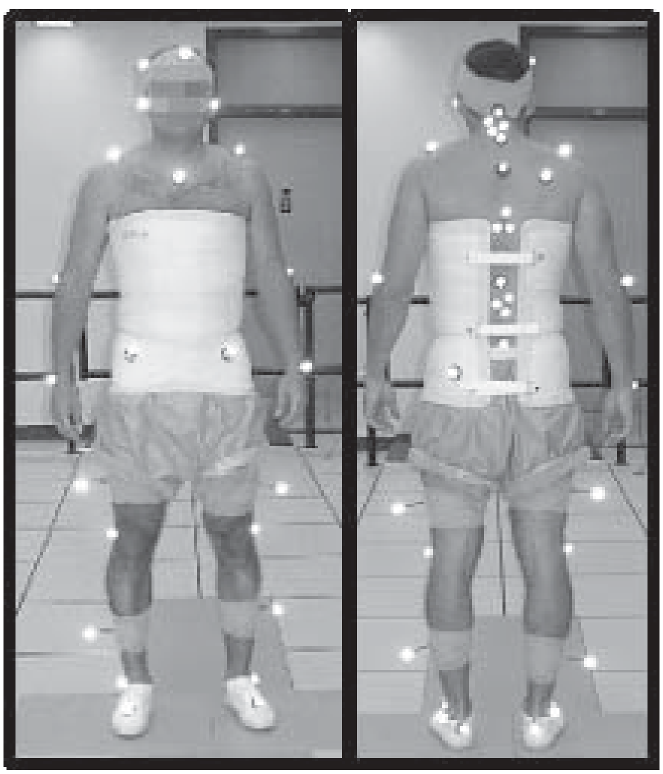

Figure 1: An able-bodied subject wearing a fiberglass body jacket.

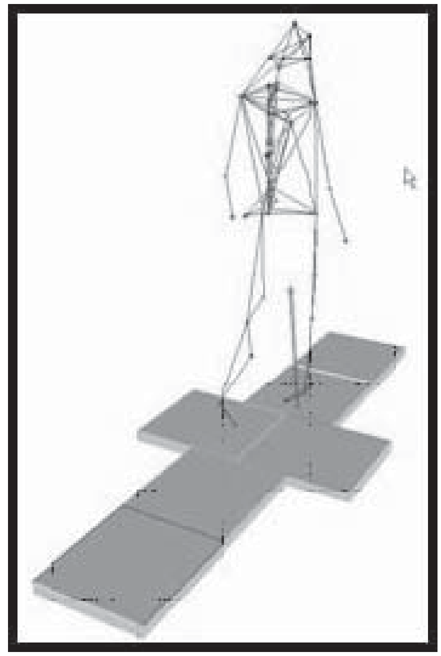

Figure 2: Stick figure showing the locations of retro-reflective markers used to analyze lower limb and spine motions during walking.

We have developed a multi-segment kinematic spinal model to analyze spinal motion during walking. In the first study, spinal motion was restricted by the application of a customized, fiberglass body jacket, similar to a Thoraco-Lumbo-Sacral Orthosis (TLSO). A TLSO is intended to treat a variety of conditions affecting the spine, such as instability, spinal fractures, and post-operative spinal support. Spinal orthoses achieve their objectives primarily by restricting movement of the spine. Data were collected from ten able-bodied subjects walking with and without spinal restriction. Pelvic obliquity and rotation range of motion (ROM) were significantly reduced across all walking speeds ($p<0.001$), while pelvic tilt ROM was significantly

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reduced at only the fastest speeds (p=0.017). Hip abduction/adduction ROM was significantly reduced with spinal restriction across all speeds (p<0.001), while hip flexion/extension ROM significantly increased at only the slow and slowest speeds (p<0.001 and p=0.023).

The reduction in pelvic rotation may explain the trend toward shorter step lengths taken by individuals when restricted by the TLSO. To achieve faster walking speeds with restricted spinal motion, cadence was increased. Additionally, the first peak of the magnitude of the vertical ground reaction force (GRF), the transient of this force, the fore-aft GRF, and the medial-lateral GRF were analyzed, with no differences observed between restricted and unrestricted conditions. Thoracic axial rotation ROM significantly decreased with spinal restriction (p<0.001). A trend toward decreased ROM also was observed for thoracic lateral bending and both lumbar axial rotation and lumbar lateral bending ROM. Further, cervical lateral bending, cervical flexion/extension, and thoracic flexion/extension ROM significantly *increased* with spinal restriction (p=0.019, p<0.001, and p<0.001). Therefore, while our results indicated that the TLSO reduced spinal motion as intended, it had unanticipated, detrimental effects on gait.

In persons with spinal pathology, the spine's dynamic compensatory abilities may be exceeded, requiring the use of orthoses or surgical intervention. While these methods correct deformity, they also alter normal spinal motion. It is unclear what effect, if any, this may have on an individual's gait. In our second study, gait data from subjects with spinal pathologies are being collected. Subjects requiring spinal surgery will undergo gait analysis both pre- and six months post-operatively. Data from the first analysis will be compared to the post-operative data.

While relatively few compensatory actions were observed in lower body and spine motion during walking in the healthy able-bodied people, persons with spinal pathology may not be able to compensate in these same ways. Further, increased spinal motion at levels adjacent to spinal constraints may pre-dispose individuals to additional degenerative changes. Limited spine and pelvic motions may also have implications for reduced shock absorption, possibly subjecting adjacent levels to greater shock forces. An awareness of the effects of restricted spinal motion will enable clinicians to monitor patients for potential problems resulting from decreased spine and pelvic motion during walking.

Regina Konz analyzes the spine's compensatory abilities in healthy, able-bodied people and in those with spinal pathology.

Regina J. Konz

Ms. Konz is a Ph.D. candidate in Biomedical Engineering at Northwestern University. She has a B.S.E. (1996) in Biomedical Engineering, University of Iowa, an M.S. (1998) in Mechanical Engineering, University of Iowa. Her M.S. Thesis was titled "The Pathomechanism of Spondylolytic Spondylolisthesis: In Vitro & Finite Element Assessments."

Her personal interests include being mother of three children: Jacob 4 years, Alyssa 2 years and Madeline 4 months.

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The Effect of Trunk Flexion on Standing and Walking

Devjani Saha, B.S.

(Funds from Medtronic Sofamor-Danek, Inc., and the National Institute on Disability and Rehabilitation Research of the United States Department of Education under grant H133E030030 supported this work.)

For humans, upright trunk posture is considered a major evolutionary hallmark; however, this posture is inherently unstable and disturbances to this system come at a very high cost. In upright posture, the spine is aligned so that the head and trunk fall directly over the pelvis. Changes in spinal alignment resulting from spinal pathologies may displace the trunk center of mass (COM) with respect to the body's base of support. Sufficient displacement of the trunk COM may adversely affect the body's ability to maintain upright posture and balance. Compensatory mechanisms that are metabolically expensive may be necessary to restore balance.

Devjani Saha focuses on how anterior trunk alignment affects energetics during standing and walking.

Devjani Saha

Ms. Saha received her Bachelors degree in Bioengineering at the University of Pennsylvania. Currently, she is working on her Masters degree in Biomedical Engineering at Northwestern University. Her research focuses on trunk posture and balance.

Abnormal spinal alignment can occur due to age related degeneration of the spine or as a result of spinal pathology. Previous studies of spinal pathologies have concentrated primarily on the pathophysiology of the disease. However, the functional implications of postural changes that occur with these pathologies are not well understood. In order to improve our understanding of how spinal malalignment affects the ability to maintain balance, I am investigating how alterations in trunk orientation in the sagittal plane affects balance, body kinematics, kinetics, and energetics during standing and walking. The focus of my research is on anterior trunk flexion, a common characteristic of several spine pathologies, including kyphosis and lumbar flatback.

To ensure that the main factor affecting balance is trunk orientation, only able-bodied subjects with no history of spinal pathology were recruited for this study. Kinematic marker data and kinetic force plate data were collected during static standing, and walking while maintaining three different trunk postures: upright, and approximately 25° and 50° of trunk flexion with respect to the vertical. Also, energy expenditure data were collected during the static standing trials.

Alterations in lower body kinematics were observed in both trunk-flexed conditions. An increase in the degree of ankle plantarflexion and knee hyperextension occurred during standing with trunk-flexed postures. A crouch gait pattern, characterized by increased stance phase knee flexion and ankle dorsiflexion, often was exhibited during trunk-flexed walking. Spinal surgeons, who are associated with our laboratory, have commented that crouch gait tendencies are common among kyphotic patients. The data suggest that these changes may not necessarily be a direct consequence of the pathology, since they also occur in able-bodied

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A Study in the Modulation of Step Length: Inherent, Learned and Assisted

Pinata Hungspreugs Sessoms, M.S.

(The National Institute on Disability and Rehabilitation Research of the United States Department of Education under grant H133E030030 supported this work.)

Step length, the distance traversed during one step of gait, is a common measurement taken during gait analyses. It allows one to determine asymmetries between the two legs, compare differences between subjects, and also compare intra-subject differences for changing parameters such as increasing walking speed or wearing different types of prostheses. Yet there has been little investigation of step length specifically and how people are able to alter it when they are walking.

Persons with unilateral lower limb amputation typically take a longer step with their prosthesis than they do with their sound leg. A better understanding of how step length is modulated, may allow us to determine why step length asymmetry occurs in persons with unilateral lower limb amputation; and how we can modify prostheses to improve symmetry. This would help to decrease risk factors associated with gait asymmetry (Skinner and Effeney 1985; Giakas *et al.* 1996; Horvath *et al.* 2001); increase the aesthetics of the person's gait; and allow persons with unilateral lower limb amputation to walk farther using the same amount of effort. For example, using data taken from a study by Underwood *et al.* (2004) of individuals having a unilateral below-knee amputation and wearing a SAFE prosthetic foot, the average step length difference between the sound and prosthetic limb was measured to be 1.18 inches (3 cm). If the step length of the sound side could be restored, an increase of approximately 98 feet (30 m) would be expected for every mile (1609 m) walked. This is more than a quarter length of a football field. Research into step length may even be beneficial for persons without an amputation. An example would be competitive race walkers, who may wish to walk farther and faster over a given time.

This research project investigates the means by which we are able to modulate and increase our step length, whether it is by inherent, learned, or assisted methods. People appear to increase their step length *inherently* by several different means: increasing hip flexion and extension; increasing ankle-foot rollover arc length; rotating sagittally (side view) about the ball of the stance leg foot (to increase the contact time of the stance leg and allow further hip flexion and extension); and increasing pelvic rotation. Not all persons may utilize every one of these methods, so being able to *learn* these, or possibly other methods of increasing step length, may help them to take even longer steps. Step length also might be increased using specially designed prosthetic or orthotic components. These *assisted* methods, in particular some method for foot lengthening, are being examined to determine the effectiveness of assistive devices to increase step length. It is possible that by utilizing many or all of these

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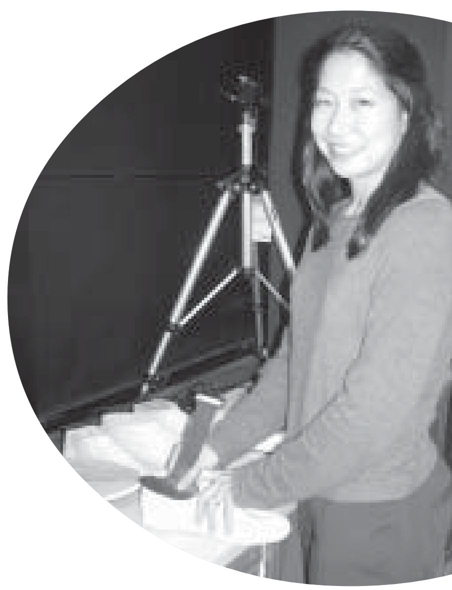

Pinata Sessoms develops a model of kinematic differences that may improve discrepancies in prosthetic step length.

Pinata Sessoms

Ms. Sessoms earned a Master of Science in Biomedical Engineering (2000) at Northwestern University; and a Bachelor of Science and Engineering (1998) in Biomedical Engineering, (Cum Laude) at Duke University. In 2001, she was an Intern at Honda Fundamental Research Laboratory. Her personal interests include travel/exploration, scuba diving and golf.

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parameters, one should be able to take longer strides and possibly increase walking speed.

Also, this research project may help us understand what factors determine one's natural step length. A detailed model involving all lower limb joints is being created to perform a sensitivity analysis of each joint's contribution to step length. This model will allow us to determine what kinematic differences may contribute to the step length discrepancies exhibited by persons with amputation. Once we have identified the sources that lead to the shorter step lengths of persons walking with prostheses, we can develop prosthetic components or training techniques that can improve their gait. Overall, we are trying to develop a better understanding of gait and establish methods by which gait can be enhanced or improved.

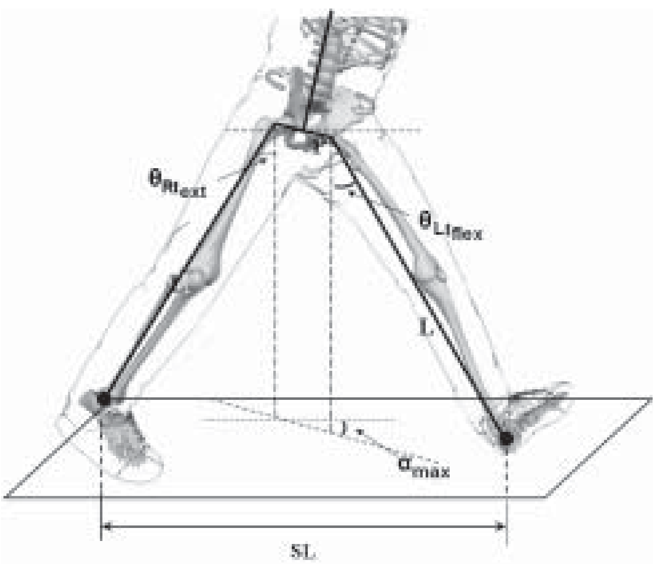

Figure 1: Drawing shows how hip flexion (θ) and pelvic rotation (α) contribute to the step length.

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Characterization of the Shock Absorption of the Able-bodied Locomotor System, with Application to Amputee Gait

Yiorgos (George) Bertos, M.S.

(The National Institute on Disability and Rehabilitation Research under Grant H133E030030 supported this work.)

Purpose

Lower-limb amputees experience high forces that are transmitted through their prostheses to their trunk during walking. These shock forces not only are uncomfortable and unhealthy, but also may contribute negatively to the quality of gait. We believe shock absorption is a fundamental aspect of normal and pathological walking which, if not set properly, can result in poor and injurious gait. We also believe that the current prostheses and orthoses on the market may not supply the right shock absorption to the persons who walk with them. One of the reasons for this is that there is no clear understanding of the basic science in terms of shock absorption during normal and pathological walking.

We believe that using engineering analysis, models and experiments to investigate shock absorption during normal and amputee walking will improve our understanding of this important aspect of gait and may contribute significantly to the science of prosthetics and orthotics. Our purpose is to use this acquired theoretical knowledge to design and test prototype prostheses and orthoses and, ultimately, to improve the comfort and gait of the persons wearing them.

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Methodology

In order to characterize properly the mechanical impedance of able-bodied subjects, we collected gait analysis and accelerometer data from 7 able-bodied walkers walking at self-selected, slow and fast walking speeds.

In order to characterize the vertical mechanical impedance of the locomotor system of each subject, we assumed a second order model [1] (Figure 1), for the unknown shock absorption mechanism. Based on

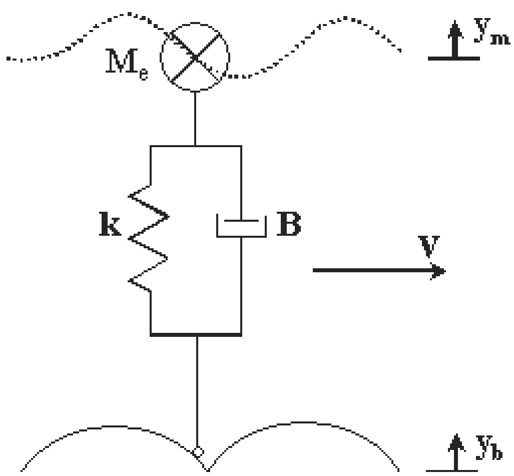

Figure 1: Able-bodied human walking was modeled with a 2^{nd} order mechanical vibration system. y_b is the vertical trajectory of a rocker-based inverted pendulum walking machine with no shock absorption. y_m is the vertical trajectory of the Body Center of Mass of one able-bodied subject. M_e is the equivalent subject's body mass; k is a linear stiffness element; B is a linear viscous damping element; and v is the steady state forward velocity of walking.

the kinematic data, we can estimate what the vertical path of the Body Center of Mass (BCOM) would be if there was no shock absorption and use this as the input to our identification method. We use the vertical BCOM trajectory (which contains all shock absorption mechanisms) as output of the identification method. This identification method can estimate the values of the second order system, which makes the given output and the estimated output (based on the model) to be as close as possible.

We used simulations to validate the identification method. To further validate the identification method, we constructed a mechanical model, the "walking wheel" (Figure 2).

Results

For one able-bodied subject [1], the fitting of the model to the data was satisfactory. The Variance Accounted For (VAF), which is indicative if the fit of a model ranged from 75-80% for low speeds to 90-95% for normal and fast speeds. Our results support the theory that the damping ratio ζ [$=B/2(M_e k)^{1/2}$] is

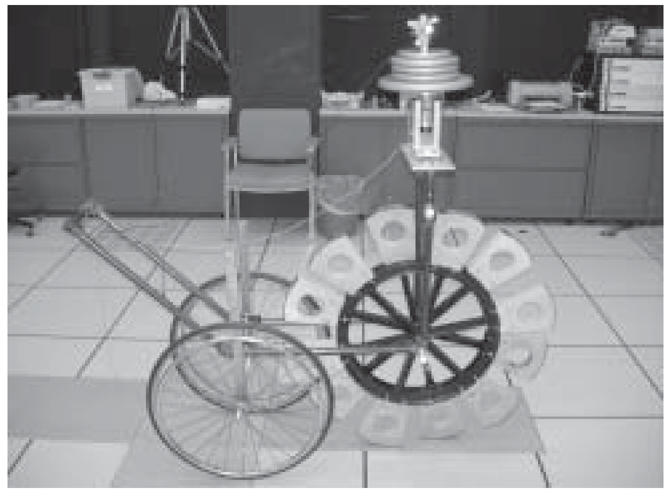

Figure 2: "Walking wheel" mechanical model used to validate the proposed identification method.

fairly constant (ζ = 0.4 - 0.7) across different walking speeds. Stiffness k appears to increase linearly with walking speed (r^2=0.95), being around 6 kN/m at 1.2 m/sec. Damping B appears to increase with the square root of walking speed, (r^2=0.75). During able-bodied walking the system appears to be underdamped ($0<\zeta<1$), having a high performance from a control theory standpoint (fastest response with minimum ripple) with damping ratio ζ between 0.4 and 0.7. The results also show that the locomotor system of able-bodied walkers acts like a mechanical low-pass filter with cutoff frequency to be very close to the stepping frequency.

The next step will be to characterize the shock absorption of a bilateral transfemoral amputee and theoretically calculate an optimum shock absorption component which, if placed in a series configuration to the amputee's prosthesis, will bring the total amputee shock absorption closer to the shock absorption values

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of a similar able-bodied subject. Then, two prostheses with the prescribed mechanical impedance values will be constructed and incorporated into the transfemoral amputee's prostheses. Thereafter, it will be possible to compare the resultant gait to the gait that lacks a shock absorption mechanism.

The walking wheel model validated our identification method because, based on input and output data, it correctly predicted the values of the stiffness and damping that already were known but not used in the estimation of these values. We continue to work on this valuable model in order to develop a theory of shock absorption during walking.

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George Bertos investigates ways to improve shock absorption during ambulation for wearers of prostheses and orthoses.

Yiorgos (George) Bertos

George Bertos will complete his Ph.D. this year for Northwestern University's Department of Biomedical Engineering. He completed his M.S. at Northwestern University in 1999. In 1994, he received a degree in electrical and computer engineering from National Technical University of Athens, Greece. He enjoys listening to eclectic music, traveling back to Greece and spending time with his wife and two daughters. His goals include designing smart prostheses for amputees.

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An Investigation of Shock-Absorbing Prosthetic Components for Persons with Transfemoral Amputations

Sara R. Koehler, M.S.

walking. Walking speed, cadence, and single-support phase symmetry remained unchanged. Step lengths were found to be more symmetric when subjects walked with the 3R60 Knee compared to the TT Pylon, although no significant differences were observed from baseline. Stance-phase knee flexion was not considerably increased with the 3R60 Knee. Ground reaction forces were consistently higher on the sound limb, and this loading asymmetry did not change with the addition of either SAC. Furthermore, impact forces on the prosthetic limb were not significantly attenuated.

Based on these results, there is little evidence to suggest that either prosthetic device enhanced shock absorption when subjects walked on flat, level surfaces in the laboratory, although subjective feedback suggests that SACs may provide increased comfort during faster walking speeds and high-impact activities. Transfemoral amputees typically have a considerable amount of compliance in the soft tissue of their residual limb so that the addition of a SAC may only have a small effect on the overall stiffness of the prosthesis-residual limb combination. In future studies, additional metrics may be needed to better characterize the shock-absorbing capacity of these components.

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An Investigation of Shock-Absorbing Prosthetic Components for Persons with Transfemoral Amputations

Sara R. Koehler, M.S.

(The Department of Veterans Affairs, Whitaker Foundation Graduate Fellowship Program, and the National Institute on Disability and Rehabilitation Research under Grant H133E030030 funded this work.)

One of the primary functions of the lower limbs is to manage impact forces acting upon the body during walking. Normally, shock absorption is provided from step to step through soft tissue compression of the heel and coordinated movements of the ankle, knee, and pelvis. However, people with transfemoral amputations lack many of these anatomical shock absorbers, making them susceptible to higher impact forces on their prosthetic side at joints proximal to their amputation. Insufficient shock absorption may also contribute to gait asymmetries and compensatory gait patterns. To address these limitations, shock-absorbing components (SAC) have been designed to decrease the stiffness of the prosthetic limb and improve walking performance. The purpose of this study was to compare the effect of two different SACs, an Endolite Telescopic-Torsion (TT) Pylon and an Otto Bock 3R60 Knee, on the gait patterns of ten unilateral, transfemoral amputees walking over a range of self-selected speeds. While the TT Pylon is designed to decrease prosthetic stiffness through axial compression of the shank segment, the 3R60 Knee is designed to permit up to 15° of cushioned stance-phase knee flexion. Therefore, although both of these components are intended to enhance shock absorption, their designs and operation are distinctly different.

In this study, quantitative gait analysis was used to evaluate spatial-temporal parameters (walking speed, step length, floor contact patterns), selected joint angles and moments, and ground reaction forces for subjects' prosthetic and sound sides. Comparisons were made between the two SAC conditions and a baseline measurement in which subjects wore their conventional prosthesis. Although subjects indicated that both SACs were more comfortable for walking compared to their baseline components, few quantitative gait measures indicated that either SAC provided a measurable benefit to the user during level

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Sara Koehler adjusts an Otto Bock 3R60 knee designed to manage impact forces during gait.

Sara Koehler

Ms. Koehler is pursuing her Ph.D. at Northwestern University's Prosthetic Research Laboratory. She completed her Master's Degree in the Department of Biomedical Engineering at Northwestern University and received her Bachelor's Degree in Engineering at the Department of General Engineering, University of Illinois, Urbana-Champaign. Her personal interests include cooking, Salsa dancing and cycling along Lake Michigan.

The Effect of Prosthetic Ankle Motion on the Gait of Persons with Bilateral Transfemoral Amputations

Lexyne L. McNealy, B.S.

(Funds from the National Institute of Disability and Rehabilitation Research under Grant H133E030030, the National Institute of Child Health and Human Development under Grant Number R01HD042592, and the National Science Foundation Graduate Research Fellowship Program supported this project.)

Introduction

Several studies describe the qualitative nature of rehabilitation programs for bilateral transfemoral (TF) amputees (1-5). These studies, however, fail to provide any significant information about the quantitative aspects of the gait of persons with bilateral TF amputations. Increased ankle motion in the sagittal and transverse planes may improve the gait of these individuals while providing a more versatile prosthesis, but this has yet to be investigated. This study investigated the gait of persons with bilateral TF amputations who walked with four different prosthetic ankle configurations. The primary aim was to examine and quantify changes in gait resulting from the various prosthetic ankle joints. Quantification of gait parameters for persons with bilateral TF amputations can help improve the functionality of prosthetic devices available to this population.

Lexyne McNealy studies prosthetic ankle configurations to determine how increased ankle motion in the sagittal and transverse planes may improve the gait of persons with bilateral transfemoral amputations.

Lexyne McNealy

Ms. McNealy is a fourth-year graduate student in the Department of Biomedical Engineering at Northwestern University. In 2002 she completed both a B.S. in Physics at Spelman College and a B.S. in Biomedical Engineering at Boston. She enjoys cooking, travel and reading.

Methods

Four male subjects with bilateral TF amputations were recruited for the study. The average age of the participants was 41 years while the average weight was 68 kg. One subject had amputations due to congenital deformity, while three subjects had amputations due to trauma. All subjects used their prostheses daily.

Four gait analyses were completed to examine the prosthetic ankle motion of the study participants. In the Baseline gait analysis, each subject walked at three self-selected speeds with two Seattle LightFoot2 prosthetic feet included in his prostheses. Then each subject was fit randomly with either of two sets of prosthetic ankle units: the MultiFlex Ankles or the Torsion Adapters. After another two-week period, the subject returned to VACMARL and repeated the procedure from the first analysis. The second set of ankle units was exchanged for the first set and the procedure was repeated following a third two-week accommodation period. In the Final gait analysis, the subject walked with both the MultiFlex Ankles and the Torsion Adapters. Following each gait analysis, study participants answered subjective questionnaires to assess their opinions of the ankle configurations.

Results

The self-selected walking speeds of the amputee group ranged between 0.31 ± 0.25m/s and 1.00 ± 0.26m/s. The study participants walked slower than the control group, which is in agreement with previous studies (6-8). The amputee groups' speeds

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varied from Baseline values with the MultiFlex Ankle and Torsion Adapter configurations. In the Final gait analysis, the amputee group increased their self-selected speeds compared to those in the Baseline gait analysis. The mean ankle range of motion in the sagittal plane increased in all amputee subjects with the MultiFlex Ankles. There was little difference in ankle motion in the transverse plane while the amputee subjects wore only the Torsion Adapters. In the Final gait analysis, ankle motion of the amputee group increased in the sagittal plane but remained the same in the transverse plane. The study participants exhibited a three-peak vertical ground reaction force (GRF) that was different from the typical two-peak vertical GRF of the control group (Figure 1). The three-peak vertical GRF was apparent at all speeds with each prosthetic ankle configuration.

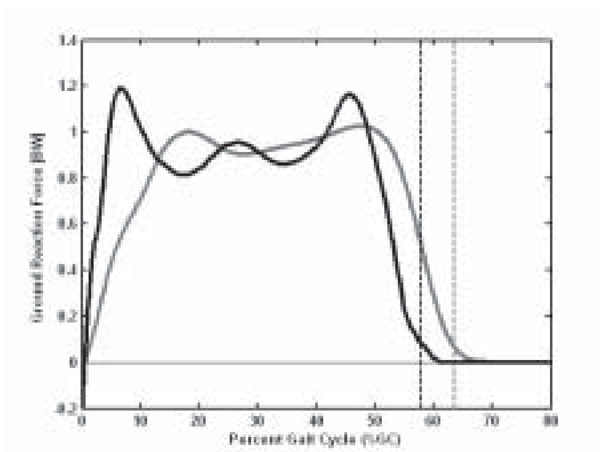

Figure 1. The vertical ground reaction force curve of Subject 1 from the Final gait analysis at his fastest speed is shown in black. The three-peak curve was typical of the amputee subjects while wearing all prosthetic ankle configurations. The able-bodied curve at slowest speed is shown in gray for comparison.

Discussion

Increases in walking speed were due to a combination of cadence and step length. The speed, equal to the product of cadence and step length, was directly related to both parameters across all ankle configurations (Figure 2). The difference in sagittal plane ankle motion was the result of the function provided by the MultiFlex Ankle configuration. The ankle units allowed the amputee group to passively plantarflex and dorsiflex their prosthetic feet in the stance phase of the gait cycle, similar to the control group. The vertical GRF was found to be unique among the study participants. Since the amputee subjects lacked sound legs, they used alternative gait characteristics to compensate for the function of the absent limbs. It is believed that the "extra" peak is a consequence of two gait compensations—hip hiking and excessive hip abduction—used by the amputee subjects during stance. According to the subject questionnaires, three of the participants felt that the combination of the MultiFlex Ankles and the Torsion Adapters increased their comfort level during walking. Three of the subjects also commented that the Final configuration allowed them to walk longer distances compared to the Baseline configuration. The general consensus among the study participants was that the MultiFlex Ankles and Torsion Adapters were beneficial to their prostheses. Thus, these prosthetic options should be considered when fitting prostheses on persons with transfemoral amputations.

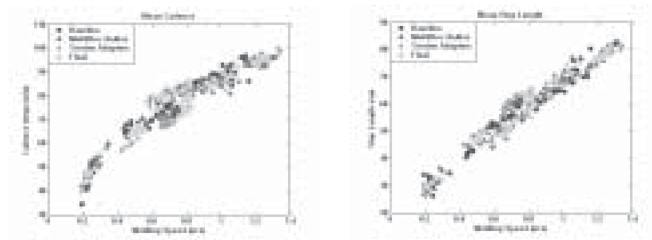

Figure 2. Mean Cadence (left) and Mean Step Lengths (right) of amputee subjects during each of the prosthetic ankle configurations. Both mean cadence and step length increased with speed.

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The Effect of Increased Prosthetic Ankle Motion on the Gait of Persons with Bilateral Transtibial Amputations

Po-Fu Su, M.S.

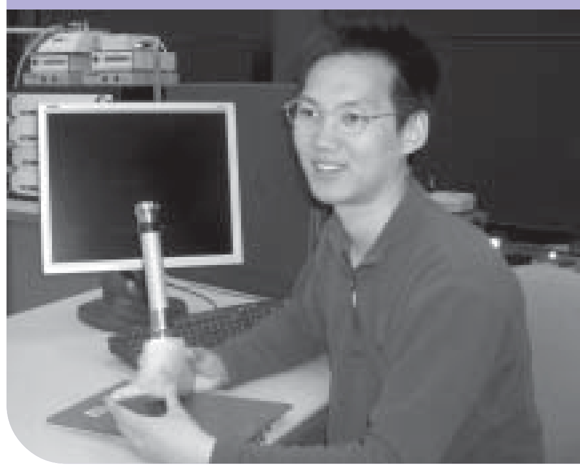
(Funds from the National Institute of Disability and Rehabilitation Research under Grant H133E030030, and the National Institute of Child Health and Human Development under Grant Number R01HD042592 supported this project.)

Increased ankle motion appears to improve the gait of persons with unilateral transtibial (TT) amputation, but the improvements are limited and inconsistent between studies [1,2]. The purpose of the study is to determine if the provision of prosthetic ankle motion in persons with bilateral TT amputations significantly improves their walking performance. The subjects in the study were divided into two groups based on etiology. The TRA group had their amputations due to trauma and the PVD group had their amputations due to peripheral vascular diseases. Analyzing the effects of increased prosthetic ankle motions in persons with bilateral TT amputations enables us to better identify the advantages and disadvantages of the prosthetic components because there are no compensatory actions from a sound leg. Our results may provide information for improving design of prosthetic ankles and feet, and help establish guidelines for prosthetists fitting persons with lower limb amputation.

Endolite Multiflex Ankles (flexion unit) were used in the study to increase ankle sagittal plane motion and Otto Bock Torsion Adapters (torsion unit) were used to provide ankle transverse plane motion. The participants walked with the following prosthetic configurations: Seattle Lightfoot II only; the feet with torsion unit; the feet with flexion unit; with both flexion and torsion units. Quantitative gait analyses were conducted after walking with each configuration for two weeks. At the end of each gait analysis, questionnaires were administered to the research subjects to record their perceptions of walking with the different prosthetic configurations.

Data were collected from 12 people with bilateral TT amputations. The average age of the six TRA subjects was 45.7 years old and was 66.0 years old for the six PVD subjects. When the subjects walked with the flexion unit, they displayed about 6° of increase in the peak-to-peak ankle sagittal plane motion (Figure 1), increased ankle plantarflexion moment and increased ankle energy absorption and return. When they walked with the torsion unit, they displayed only 1° to 2° of increase in the ankle transverse plane rotation (Figure 2). Some of the TT subjects may have felt unstable walking with greater ankle transverse rotation, and they either adopted a walking pattern to avoid increased ankle transverse rotation or they requested the prosthetist adjust the torsion unit to be stiffer. Also, the increased ankle motion may not be used much for straight, level walking. Gait analysis on different floor conditions, or when the subjects performed tasks like turning, may further illustrate the advantage of

Po-Fu Su evaluates walking performance of persons with bilateral amputations and works to improve the design of prosthetic ankles and feet.



Po-Fu Su

Po-Fu Su graduated in 1999 from National Taiwan University, Taipei, with a B.S. degree in Physical Therapy. He is a Ph.D. candidate in the Department of Biomedical Engineering at Northwestern University where he focuses on the performance of prosthetic ankles and feet through biomedical engineering research. He enjoys traveling and watching movies.

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components that increase ankle motions. The increased ankle motion provided by both the flexion and torsion units did not affect the subjects' walking speed or their knee, hip and pelvis motions. The participants reported that they benefited equally well when they walked with the flexion and torsion units, but they preferred the combination of both. These results suggested that increased prosthetic ankle motions in the transverse and sagittal planes are probably both important when prosthetists prescribe prostheses to amputees.

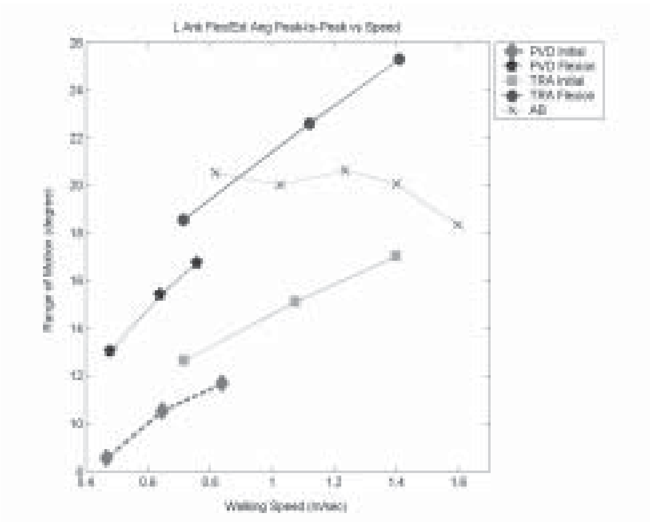

Figure 1: Sagittal plane ankle peak-to-peak-value vs speed for the PVD, TRA and able-bodied subjects walking at various speeds with initial and flexion ankle configurations.

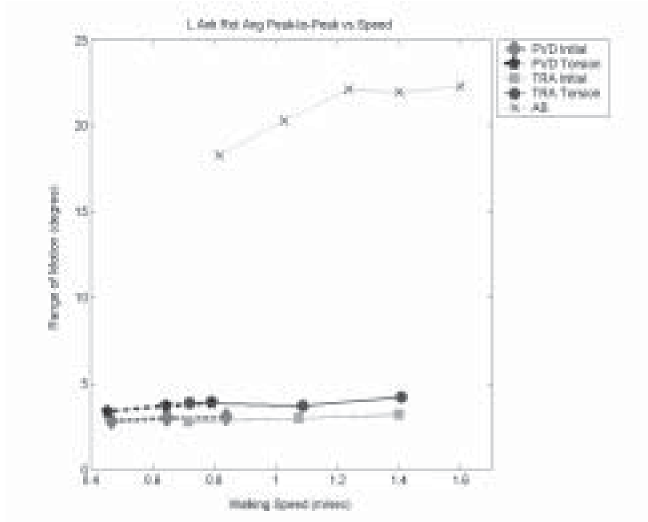

Figure 2: Transverse plane ankle peak-to-peak-value vs speed for the PVD, TRA and able-bodied subjects walking at various speeds with initial and torsion ankle configurations.

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Requirements for Improved Prosthetic Foot/Ankle Function on Uneven Surfaces

Brian L. Ruhe, M.S.

(Funds from the National Institute of Disability and Rehabilitation Research under Grant H133E030030 supported this work.)

Prosthetic alignment is the process of positioning prosthetic components relative to each other and the weight line to reduce moments on the residual limb. Lower limb prostheses are aligned in a clinical setting. These alignments are set to enable standing and walking on flat, level surfaces. However, when standing or walking outside the clinical setting, the user will encounter many uneven surfaces. The standard alignment for flat surfaces, coupled with deficiencies in prosthetic components, prevents lower limb prostheses from conforming to these uneven surfaces. Moreover, these deficiencies require the prosthesis user to make compensations in order to remain stable. These compensations may result in increased energy consumption.

The main objective of this research is to identify and understand the deficiencies in lower limb prosthetic components that result in kinematic compensations employed by users to achieve stability on even and uneven surfaces. Understanding the compensations will lead to modification of prosthetic components, thus eliminating these compensations and improving overall function.

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Previous research has shown that able-bodied persons flex their ankles to match the inclination of the slope that they are standing on (Simeonov et al. 2003). Ankle flexion is not a strategy that persons with amputation can apply when confronted with sloped surfaces. This would require a different alignment of the prosthetic foot. Standing and walking on sloped surfaces with a standard aligned prosthesis may lead to increased instability and energy demands. Schmalz et al. (2002) showed that energy demands increase during ambulation on a mal-aligned prosthesis.

The proposed research will examine the trunk flexion compensations that persons with amputation employ to achieve stability while standing on inclined surfaces. The location of the center of pressure with respect to the position of ankle centers also will be studied. Energy demands will be measured for different testing conditions. Experiments include standing on a ramp at different degrees of inclination for each condition. For each condition, the prosthetic foot will be aligned either in a neutral position or for the inclination of the ramp.

Preliminary data have shown that when the prosthetic foot is aligned to match the inclined surface, the user will stand with a more vertical posture and reduce the amount of trunk flexion. Reduced trunk flexion also is observed in walking trials. This reduced amount of trunk flexion may result in decreased energy demands.

Results from this study will illustrate the need for adaptable prosthetic components. An adaptable prosthetic ankle may improve the overall function of a person with a lower limb amputation by decreasing the compensatory actions while standing and walking on uneven surfaces, and thus reducing energy consumption.

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Brian Ruhe evaluates the benefits of ankle movement for bilateral prosthetic ambulation.

Brian L. Ruhe

Brian Ruhe received his Bachelors of Science degree in Biomedical Engineering from Wright State University in Dayton, Ohio in 1998. At Northwestern University, he earned his Masters of Science degree and now is working toward the Ph.D. degree in Biomedical Engineering.

As a result of an automobile accident in 1993, Brian lost both of his lower limbs above the knee. Since then, his work focuses on understanding gait in order to develop improved prosthetic devices that will help persons with amputations achieve higher function.

In addition to his work at NURERC, Brian is an active athlete. He is a Paralympic Gold medallist as a member of the 2002 United States Ice Sledge Hockey Team. Also, he plays bass in a rock band performing in the Chicago area.

Understanding How Reciprocating Gait Orthosis (RGO) Users Walk

Brett Johnson, B.E.

(Funds from the National Institute of Disability and Rehabilitation Research under Grant H133E030030 supported this work.)

The Reciprocating Gait Orthosis (RGO) was designed in the 1970's with the hope of enabling people with lower limb paralysis to ambulate in an upright position. An RGO consists of two, mechanically linked Hip-Knee-Ankle-Foot-Orthoses (HKAFOs) so that the extension of one hip joint leads to the flexion of the other hip joint. The designers theorized that the reciprocating gait allowed by an RGO would be more efficient than the swing through gait that traditional HKAFOs provided. Surprisingly, the user abandonment rate for RGOs is very high. Many researchers believe that the high-energy cost of walking and the difficulty of donning and doffing the orthosis are the primary causes of the high abandonment rate.

Several studies have investigated the energy cost of using RGOs and reported varying outcomes. Some studies report that in terms of efficiency, no statistically significant difference exists between the RGO and traditional HKAFO [1]. However, all the studies agree that walking with an RGO requires much more energy than able-bodied walking and allows only a fraction of the speed.

The high-energy cost of using RGOs has been well documented, but very little attention has been paid to the kinetics and kinematics. One study looked at the forces acting on the mechanical link between the hip joints. The researchers reported that no force was being transmitted through the mechanical link during swing phase, which was a surprising find since the mechanical link was designed to assist in moving the swing leg [2]. This result implies that there is much more to learn about the dynamics of the gait of RGO users.

This study was designed to investigate in greater detail the kinetics and kinematics of the gait of RGO users. The study is recruiting people with lower limb paralysis who regularly use RGOs and are over the age of six. While subjects walk back and forth over level ground in our gait laboratory, a video motion capture system measures their joint angles, joint velocities, step length, cadence, and body segment velocities. A system of force plates measures the forces acting on the subjects' feet and walking aides, and a specially designed force sensor measures the forces acting on the mechanical link between the hip joints. Surface electrodes measure muscle activity, and a

B. J. Johnson works to improve the energy efficiency of bi-lateral Reciprocating Gait Orthoses (RGOs).

William Brett Johnson

William Brett "BJ" Johnson graduated from Vanderbilt University with a B. E. degree in Biomedical Engineering. Currently he is working on his Master's Degree at Northwestern University and he plans to pursue his Doctorate. In his free time, he studies martial arts, performs with a local *a Capella* group, and enjoys swing dancing.

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spirometer indirectly measures each subject's energy expenditure while walking.

These data will be used to calculate joint forces, moments, and powers, as well as the mechanical energy of each body segment, and may contribute to making RGOs more energy efficient.

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An Investigation of Stance-Control Knee-Ankle-Foot Orthoses

Angelika N. Zissimopoulos, B.S.

(The National Institute on Disability and Rehabilitation Research of the United States Department of Education under grant H133E03003 supported this work.)

Traditional orthotic knee joints utilized in Knee-Ankle-Foot Orthoses (KAFOs) are either locked or unlocked. Recently, a number of new stance-phase control orthotic knee joint designs have become commercially available. These designs differ in their locking/unlocking mechanism, but they all lock during stance to provide stability of the knee and allow free flexion during swing. From an energy standpoint, walking with a locked knee requires costly gait compensations to create adequate ground clearance for the leg during swing phase. Providing a KAFO that stabilizes the knee during stance, but allows knee flexion during swing, should result in a reduction in energy expenditure during walking. Reducing the amount of energy required to walk may improve quality of life for disabled individuals who require a KAFO for safe ambulation as observed through decreased fatigue and greater endurance. However, to date these benefits have not been objectively documented, or quantified.

We aim to: (i) determine if stance-control knee joints improve energy expenditure compared to a locked knee joint during level walking; (ii) evaluate whether stance-control knee joints provide consistent stability of the knee during stance and consistent unlocking for swing; (iii) characterize gait strategies required to operate the stance-control feature by documenting and analyzing lower-limb kinematic and kinetic parameters.

Angelika Zissimopoulos shows a Knee-Ankle-Foot Orthosis (KAFO) that stabilizes during stance but allows knee flexion during swing phase.

Angelika N. Zissimopoulos

Ms. Zissimopoulos received a B.S. in Biomedical Engineering at Northwestern University in 2003. Her research interests include human movement, biomechanics of gait, lower limb orthoses, and rehabilitation engineering. Her personal interests include travel, cooking and Greek folk dancing.

A KAFO, utilizing Horton's Stance Control Orthotic Knee Joint (SCOKJ) (Figure 1), was custom fabricated for each of ten able-bodied subjects. Five able-bodied subjects were trained to walk with the SCOKJ operating in each of its three modes: unlocked, locked and auto (locked during stance, unlocked during swing). Quantitative gait and energy expenditure analyses then were performed with the SCOKJ in the unlocked,

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locked and auto modes, providing kinematic, kinetic, temporal-spatial, and energy expenditure data. The remaining five subjects are at various stages of participation in the study. EVaRT and OrthoTrak software (Motion Analysis Corp., Santa Rosa, CA) were utilized to process and analyze temporal/spatial and lower extremity data. Cosmed K4b^2 software (Cosmed, Rome, Italy) was utilized to process and analyze energy expenditure data.

Energy expenditure data showed that the unlocked mode produced the lowest energy expenditure as expected. However, the results thus far from the auto and locked modes were inconsistent across subjects (Figure 2). Two able-bodied subjects showed the expected results of reduced energy expenditure when the stance control orthosis was used in the auto mode compared to the locked mode.

Figure 1 Horton's SCOKJ

Figure 3 shows the loss of swing phase knee flexion on the right (affected) side with the orthosis in the locked mode (dotted line) and how the knee flexion range becomes more normal when the orthosis is used in the auto mode (compare dashed and solid lines).

Additionally, the gait analyses revealed that using the orthosis in the stance-control (auto) mode produced more normal kinematics at the pelvis. Figure 4 shows that the unlocked and auto modes produced similar patterns of pelvic tilt and obliquity in contrast to the locked mode. From the pelvic obliquity data, it is clear that in the locked mode the subject was hip hiking to create sufficient ground clearance as evidenced by the increased elevation of the right leg during swing phase.

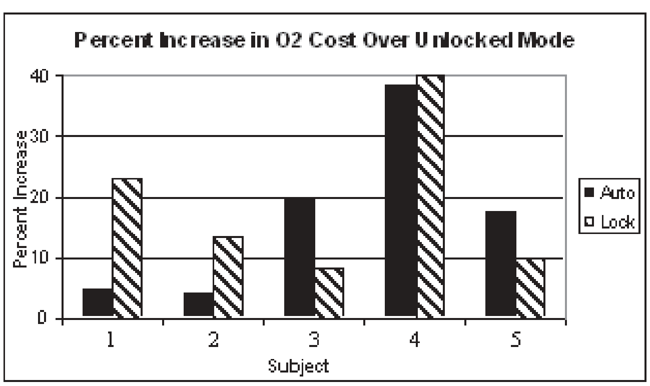

Figure 2: Energy expenditure data for five subjects during treadmill walking. Data is shown as a percent increase in energy expenditure for the locked and auto modes over the unlocked mode.

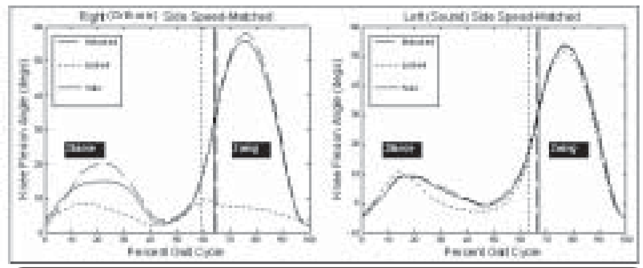

Figure 3: Knee kinematics for a single able-bodied subject during over-ground walking with three speed-matched, orthosis conditions: locked, unlocked and auto.

These preliminary data suggest that stance-control KAFO may be beneficial for patients because they appear to provide knee stability when needed during stance, while allowing for a more normal swing phase and potentially less energy expensive gait than walking with a locked knee.

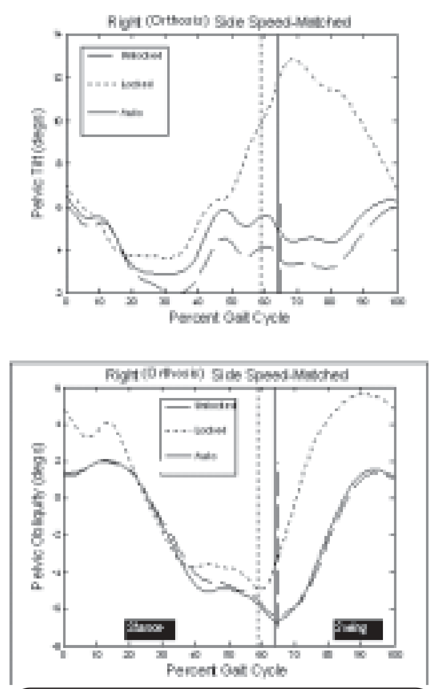

Figure 4: Pelvic kinematics for a single able-bodied subject during over-ground walking with three speed-matched, orthotic conditions: locked, unlocked and auto.

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