Proceedings of
Neuromechanics of Rehabilitation for Lower Limb Loss Symposium (2018)

Abstracts of the Neuromechanics of Rehabilitation for Lower Limb Loss Symposium©
June 11, 2018
Chicago, IL USA

CONTENTS

Foreword

The 2018 symposium, *Neuromechanics of Rehabilitation for Lower Limb Loss,* addresses lower limb loss as a significant disability that impairs human mobility, restricts activity and social participation, and detrimentally impacts balance, maneuverability and energy expenditure.

Neuromechanics, a multidisciplinary, human movement science that combines concepts from biomechanics, motor control and neurophysiology, can yield knowledge about how bionic prostheses, novel physical therapies, and human adaptability can maximize the quality of life for individuals with lower limb loss.

Symposium Aims

The Symposium objectives were threefold: 1) introduce approaches to conducting neuromechanics research on persons with lower limb loss and emphasize; 2) create a dialogue on how neuromechanics research can enhance limb loss rehabilitation; and 3) identify and pursue target areas for future research. The Symposium sought to achieve these aims through 1) a series of scientific presentations, 2) a panel discussion, 3) a poster session, and 4) multiple opportunities for professional networking and information exchange.

Distinguished Speakers

We are pleased to have as the featured guest speaker, Hiroaki Hobara, PhD, Senior Researcher, National Institute of Advanced Industrial Science and Technology (AIST), Japan, who introduced attendees to Japanese research about the neuromechanics of prosthetic locomotion and Paralympic performance.

Our expert speakers and their presentations demonstrate the multidisciplinary nature of neuromechanical research. We appreciate symposium presenters Nicholas Fey, PhD, University of Texas-Dallas, Dallas, TX; Elliott Rouse, PhD, University of Michigan, Ann Arbor, MI; Noah Rosenblatt, PhD, Rosalind Franklin University, North Chicago, IL; and Andrew Sawers, CPO, PhD, University of Illinois, Chicago, IL.

Potential for Global Impact

We appreciate the support of the Japan Society for the Promotion of Science (JSPS) for supporting United States-Japan research programs. Collaborative USA-Japan projects that focus on the neuromechanics of rehabilitation for lower limb loss. These multidisciplinary initiatives have enormous potential to develop novel rehabilitation interventions and technology that will enhance the human condition for those living with lower limb loss. We hope that this symposium will sow the seeds for future collaborative research in the field of Neuromechanics of Rehabilitation for Lower Limb Loss.

R. J. Garrick, PhD
Matthew J. Major, PhD
Symposium Organizers
August 16, 2018

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Acknowledgements

The *Neuromechanics of Rehabilitation for Lower Limb Loss Symposium 2018* would not have been possible without the sponsorship and support of the Northwestern University Prosthetics-Orthotics Center (NUPOC), Department of PM&R, Feinberg School of Medicine; and the Japan Society for the Promotion of Science (JSPS).

We appreciate the symposium speakers, researchers who submitted posters, and registrants who contributed valuable content and spurred discussions.

Contact information has been included with the permission of the symposium participants.

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PROGRAM

THE NEUROMECHANICS OF REHABILITATION FOR LOWER LIMB LOSS SYMPOSIUM 2018

June 11, 2018

CONTINENTAL BREAKFAST

8:30 - 9:00 a.m.

PRESENTATIONS

9:00-9:10 a.m. **Matthew J. Major, PhD**
Assistant Professor, Physical Medicine & Rehabilitation
Northwestern University, Chicago, IL
Welcome, symposium overview, aims, and introductions

9:10-9:35 a.m. **Elliott Rouse, PhD**
Assistant Professor, Department of Mechanical Engineering
University of Michigan, Ann Arbor, MI
The Role of Mechanical Impedance in Human Neuromotor Control and Wearable Robotic Systems

9:35-10:00 a.m. **Andrew Sawers, CPO, PhD**
Assistant Professor, Department of Kinesiology
University of Illinois, Chicago, IL
Falls among Lower Limb Prosthesis Users: Refocusing through an Epidemiological Lens

MORNING REFRESHER

10:00 a.m. - 10:10 a.m.

10:10-10:35 a.m. **Matthew Major, PhD**
Assistant Professor, Physical Medicine & Rehabilitation
Northwestern University, Chicago, IL
How a priori *Knowledge of a Perturbation Impacts Proactive and Reactive Locomotor Strategies of Below-Knee Prosthesis Users*

10:35-11:00 a.m. **Noah Rosenblatt, PhD**
Assistant Professor, Podiatric Surgery & Applied Biomechanics
Rosalind Franklin University, North Chicago, IL
The Effects of Fear of Falling on Balance and Gait: Lessons from Intact Adults and Implications for Prosthetic Design and Rehabilitation

11:00-11:25 a.m. **Nicholas Fey, PhD**
Assistant Professor, Mechanical Engineering; Joint-Bioengineering
University of Texas-Dallas, Dallas, TX
Assessing the Neuromechanical Response of Individuals with Major Lower-Limb Loss during Steady and Non-Steady-State Locomotion

11:25 a.m.-12:10 p.m. **Hiroaki Hobara, PhD**
Senior Researcher
National Institute of Advanced Industrial Science and Technology, Tokyo & Tsukuba, Japan
Active Amputees: Biomechanics of Running-Specific Prostheses

12:10-12:30 p.m. **Mr. Koki Kawano**
International Program Representative, JSPS Office, Washington, D.C.
JSPS Information Session

LUNCHEON
BALDWIN AUDITORIUM FOYER
12:30 noon - 13:30 p.m.

PANEL DISCUSSION
13:30-14:30 p.m. **Drs. Hobara, Fey, Major, Rouse, Rosenblatt** and **Sawers**

CLOSING REMARKS
14:30- 15:00 p.m. **Dr. Major** and **Dr. Garrick**

AFTERNOON REFRESHER
15:00 - 16:00 p.m.

NETWORKING OPPORTUNITY
16:30-18:00 p.m.

Symposium registrants are invited to gather for an un-hosted, post-symposium mixer. Dinner and drinks are at your own expense. All are welcome!

Author Index: Abstracts and Speaker Biographies

ABSTRACT

Assessing the Neuromechanical Response of Individuals with Major Lower-Limb Loss during Steady and Non-Steady-State Locomotion

Nicholas Fey

Individuals with lower-limb amputation commonly experience abnormal gait characteristics and chronic pain. These behaviors restrict mobility and are usually attributed to the use of prostheses that inadequately restore muscular functions. A prevailing assumption in the use of devices to replace or augment human function is that biologically-inspired approaches are optimal. The field of rehabilitation engineering is met with emerging questions such as: to what extent should assistive devices be biologically-inspired; and in what contexts are robotic systems needed.

This presentation will highlight recent efforts to assess how the injection of mechanical energy delivered via robotic, mechanically-active foot-ankle prostheses influence body segment contributions to whole-body balance of individuals with below-knee amputation on even and uneven terrain. Secondly, I will present other efforts to assess the relative contributions of prosthetic knee and/or ankle assistance to the mechanical energetics of transfemoral amputee locomotion. I will conclude by presenting a neuromechanical technique to quantify the quality of the interfaces connecting lower-limb prostheses and their users, and a potential surgical intervention to improve interface quality.

BIOGRAPHY

Nicholas Fey, PhD
Assistant Professor, Mechanical Engineering; Joint-Bioengineering
University of Texas-Dallas, Dallas, TX

Dr. Fey is an Assistant Professor at The University of Texas at Dallas and UT Southwestern Medical Center. After attending college at The University of Texas at Austin, graduating in 2006, 2008 and 2011, with bachelor's, master's and doctorate degrees in Mechanical Engineering, respectively; he pursued research in the Center for Bionic Medicine at the Shirley Ryan AbilityLab (formerly the Rehabilitation Institute of Chicago) and Northwestern University's Feinberg School of Medicine. His research focuses on the biomechanics of human movement and informed design and control of prosthetic and orthotic technologies for human assistance, with an emphasis on demanding forms of human locomotion.

He has studied transtibial amputees and above-knee amputees and the application both conventional and robotic knee-ankle-foot prostheses for enhanced mobility. He holds appointments in Bioengineering and Mechanical Engineering at UTD and Physical Medicine and Rehabilitation at UT Southwestern, and directs the Systems for Augmenting Human Mechanics Lab, co-located at UTD and UT Southwestern.

ABSTRACT

Active Amputees: Biomechanics of Running-Specific Prosthesis

Hiroaki Hobara

Background and Aim

Lower extremity amputation often leads to a reduction in physical activity levels, which can in turn lead to weight gain, depression, anxiety, increased risk of cardiovascular and other chronic diseases, and an overall reduction in quality of life. Current challenges in providing appropriate rehabilitation to assist individuals with lower extremity amputation (ILEAs) in adapting to new physical conditions and demanding physical activities largely lie in the lack of knowledge regarding the biomechanical and physiological characteristics of this patient population in active contexts. Especially, running-specific prostheses (RSP) are prevalent in ILEAs, but its biomechanical adaptations remain largely unknown. Therefore, the goal of our 'Active amputees' project is to provide biomechanical evidence of RSPs for ILEAs, prosthetists, clinicians and manufacturers to prescribe individualized prosthetic components and rehabilitation plans for this population.

Approaches

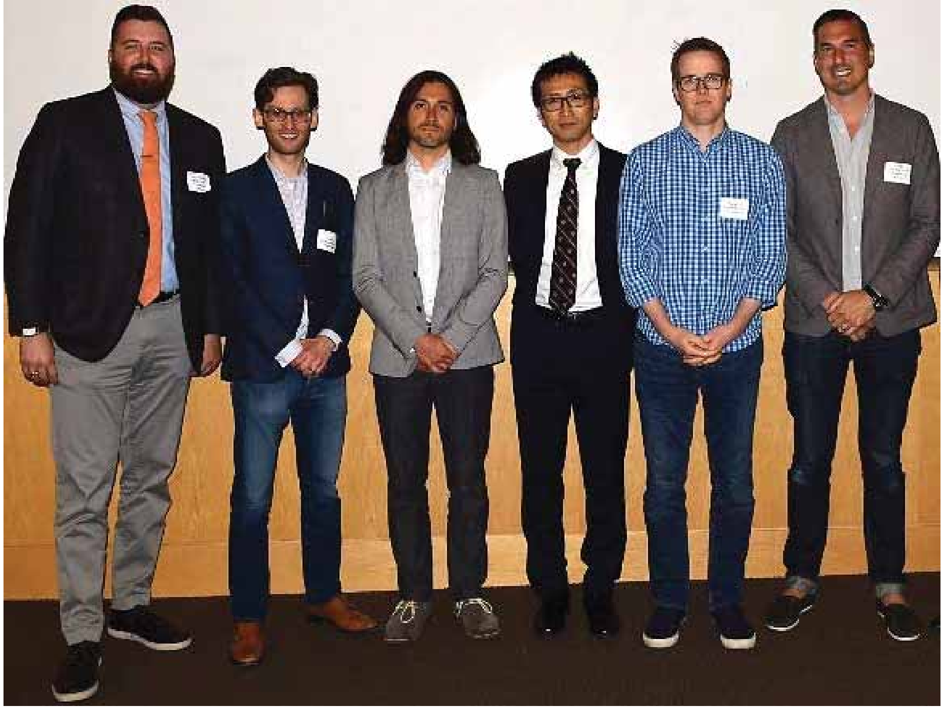
Three-dimensional motion capture is currently the gold standard for analyzing movement adaptations in the field of biomechanics. When combined with force platform data, inverse dynamics techniques can be used to calculate the forces and moments at each major lower extremity joint during running and jumping (the first approach; deep data analysis). Despite the fact that 3-D motion capture is thought to be advantageous to determine biomechanical characteristics of ILEAs, the technique is associated with several constraints (e.g. subject recruitment, constraints for experimental set-up, and environmental dissimilarities to athletic fields). To solve these problems, we also developed a database for spatiotemporal data of sprinters with lower extremity amputations using publicly-available Internet broadcasts (second approach; big data analysis). The average speed, average step length, and step frequency for each ILEA sprinter in 100- and 200-m sprints were calculated using the number of steps in conjunction with the official race time and distance. This technique makes it possible to compare spatiotemporal parameters of ILEAs during actual competitions.

Results

For the first approach, our team revealed that propulsive impulses of ground reaction forces generated by the prosthetic limb, rather than the intact limb, may be the key parameter toward achieving greater sprint velocity in sprinters with unilateral transfemoral amputations. The force production capabilities are mainly associated with joint extension moment in the prosthetic hip joint during the stance phase. For the second approach, we acquired 850 spatiotemporal data from 147 ILEAs in 35 countries. We found that spatiotemporal parameters in sprinters with lower extremity amputations vary according to amputation levels, sex, ethnicity, competition level, and RSP type, but not to body height or amputation side.

Social Implementations

Several sprinters with lower extremity amputations have used our biomechanical data to enhance their athletic performance. Further, our data aid ILEAs in resuming running via proposing effective rehabilitation protocols conducted by physiotherapists and prosthetists. To date, relatively little research has focused on ILEAs who wish to begin running. As a result of our concise feedback, some ILEAs have re-learned how to run using RSPs. These results were achieved not only by researchers, but also by cooperative partnerships among medical doctors, clinicians and prosthesis users.



BIOGRAPHY

Hiroaki Hobara, PhD
Senior Researcher
National Institute of Advanced Industrial Science and Technology, Tokyo & Tsukuba, Japan

Dr. Hobara is a senior researcher at the National Institute of Industrial Science and Technology (AIST), Tokyo, Japan. He completed his doctorate in Human Sciences from Waseda University (2008), and completed his post-doctoral training at NRCD (Japan), and University of Maryland, College Park (USA). His research interests are biomechanics of amputee locomotion, including para-athletes.

ABSTRACT

How *a priori* Knowledge of a Perturbation Impacts Proactive and Reactive Locomotor Strategies of Below-Knee Prosthesis Users

Matthew Major

Locomotor stability is an essential precondition for safe ambulation. Accordingly, people employ a combination of proactive and reactive control strategies to manage walking disturbances. Proactive strategies involve locomotor adaptations derived partially from sensory-based anticipation to prepare for a disturbance, while reactive strategies involve a feedback-driven response to correct errors following the disturbance. Lower limb prosthesis users experience sensory-motor deficits that compromise components of postural control, which may partially explain why over half of community-living lower limb prosthesis users fall each year. However, the impact of these deficits on proactive and reactive control strategies is not fully understood. Lower limb prosthesis users may reasonably emphasize proactive strategies due to lost proprioceptive feedback and active joint control, but with consideration of associated stability costs, such as maneuverability, metabolic energy, and comfort. These sensory-motor deficits and associated stability costs are particularly relevant to the unique challenge of controlling frontal-plane locomotor stability, which requires careful control of center-of-mass dynamics and foot placement.

Previous research has suggested that lower limb prosthesis users increase frontal-plane stability through locomotor adaptations when in environments that continuously challenge stability, but exhibit only minimal proactive adaptations when repeatedly exposed to discrete but temporally-unpredictable lateral perturbations. These findings suggest the importance of contextual information of the environmental disturbance on selecting proactive strategies to influence reactive control demands and stability costs. However, little is known about how lower limb prosthesis users assess risk based on a priori knowledge of a perturbation and the effects of context-based proactive strategies on perturbation response behavior.

The aim of this work was to help answer the questions of: why lower limb prosthesis users select certain proactive strategies, and what the consequences of these strategies are on disturbance response. This study observed the effects of a priori spatiotemporal (timing, direction) knowledge of a lateral perturbation during treadmill walking on the proactive and reactive locomotor behavior of lower limb prosthesis users, and compared this behavior to that of able-bodied controls. The results from this work suggest that providing information on the timing of a perturbation known to be directed towards the impaired (prosthetic) limb encourages proactive strategies to enhance frontal-plane stability on the impaired side just prior to the perturbation instance. Minimal proactive adaptions were observed when timing was unknown. Furthermore, knowledge of perturbation timing resulted in reduced peak displacement of whole-body center-of-mass in prosthesis users, but an increase in time until the center-of-mass was reversed back towards the center of the treadmill. The finding that proactive locomotor adaptations and reactive behavior may be partially dependent on contextual temporal

information (timing) of a lateral perturbation may help explain mechanisms responsible for impaired balance control in lower limb prosthesis users.

The results from characterization studies such as this, which include considerations on motor control, cognitive factors (i.e., contextual risk), and biomechanics, may inform the design of balance-targeted training paradigms and prostheses to compensate for sensor-motor deficits in persons with lower limb loss. The ultimate aim of this research is to enhance locomotor stability for safe ambulation and support long-term rehabilitation outcomes to maximize quality of life of lower limb prosthesis users.

BIOGRAPHY

Matthew Major, PhD
Assistant Professor, Physical Medicine & Rehabilitation
Northwestern University, Chicago, IL

Matthew Major, PhD, is a Research Health Scientist at the Jesse Brown VA Medical Center in Chicago, IL, and an Assistant Professor of Physical Medicine and Rehabilitation at Northwestern University in Chicago. He has been working in these institutions since 2010, but performing rehabilitation science research for over twelve years. He earned Bachelor of Science and Master of Science Degrees in Mechanical Engineering from the University of Illinois at Urbana-Champaign, and earned a PhD in Biomedical Engineering from the University of Salford, Manchester in the United Kingdom. Prior to completing a postdoctoral fellowship at Northwestern University in Rehabilitation Engineering, he conducted research as a Whitaker International Fellow in England and a National Science Foundation Graduate Scholar in Japan.

Dr. Major’s research is currently funded through a U.S. Department of Veterans Affairs Career Development Award and several grants from the U.S. Department of Defense, National Science Foundation, and National Institutes of Health. His research focuses on improving mobility and function of individuals with neurological and musculoskeletal pathology through rehabilitation technology and therapeutic intervention.

He manages the Prosthetics and Orthotics Rehabilitation Technology Assessment Laboratory (PORTAL) of the Northwestern University Prosthetics-Orthotics Center (NUPOC). He also instructs for the NUPOC Master’s in Prosthetics and Orthotics clinical education program. He is a member of the American Academy of Orthotists and Prosthetists (AAOP) and the American Society of Biomechanics, and regularly presents his research findings at national and international scientific and clinical conferences. Dr. Major is an editorial board member of the Journal of Prosthetics and Orthotics, and a member of the Research Committee for the Orthotic and Prosthetic Education and Research Foundation.

ABSTRACT

The Effects of Fear of Falling on Balance and Gait: Lessons from Intact Adults and Implications for Prosthetic Design and Rehabilitation

Noah Rosenblatt

Fear of falling, or an overwhelming concern about falls that can lead to activity avoidance, is a prevalent problem in individuals with lower limb loss that can increase fall risk and negatively impact community participation and quality of life. While a considerable amount of research has focused on the impacts of low balance confidence and fear on postural control and gait in intact adults, little is known about the impact in persons with lower limb loss and whether targeted rehabilitative methods can be employed to address fear and alter any dysfunctional neuromechanics.

I will begin this talk by providing a brief introduction to the general construct of fear of falling and clinical scales that can be used to measure both fear of falling and related constructs, and then summarize the existing literature on its prevalence in lower limb prosthesis users and the impact it has on balance, falls and community participation in this population. Next I will describe methods that have been used to evaluate the effects of fall-related fear on neuromechanics of intact individuals and the associated results. I will highlight an example regarding the effects of fear on postural control in healthy subjects to provide a possible implication for prosthetic control. I will conclude by presenting data from an ongoing study testing the effect of a novel rehabilitation protocol, which targets low balance confidence in individuals with transtibial amputation, highlighting the effects on stability and biomechanics of gait.

At the conclusion of this talk, the audience should appreciate the need to consider fear of falling in future research studies and in rehabilitation protocols for lower limb prosthesis users.

BIOGRAPHY

Noah Rosenblatt, PhD
Assistant Professor, Podiatric Surgery & Applied Biomechanics
Rosalind Franklin University, North Chicago, IL

Training and Degrees

BS in Biomedical Engineering
Northwestern University, Evanston, IL, USA
PhD in Biomedical Engineering
Boston University, Boston, MA, USA
Post-Doctoral Fellow University of Illinois at Chicago; Biomechanics Research Laboratory; mentor, Mark D. Grabiner

Current Institutional Positions

Assistant Professor

Center for Lower Extremity Ambulatory Research (CLEAR) at the Dr. William M. Scholl College of Podiatric Medicine; Rosalind Franklin University of Medicine and Science, North Chicago, IL USA

Current Research Interests and Objectives

Maintaining mobility across the lifespan by addressing barriers to activity, with an emphasis on the effects of fear of falling in prosthetic users and obese older adults

Preventing falls in healthy community dwelling-older adults and individuals using lower limb prosthesis

Relevant Publications

N.J. Rosenblatt, T. Ehrhardt. The effect of vacuum assisted socket suspension on prospective, community-based falls by users of lower limb prostheses. Gait & Posture. 55:100-4, 2017.

N.J. Rosenblatt, A. Bauer, M.D. Grabiner. Relating minimum toe clearance to prospective, self-reported, trip-related stumbles in the community; Prosthetics and Orthotics International. 41(4):387-92, 2017.

https://www.rosalindfranklin.edu/academics/faculty/noah-rosenblatt/

ABSTRACT

The Role of Mechanical Impedance in Human Neuromotor Control and Wearable Robotic Systems

Elliott Rouse

To date, wearable robotic systems have not yet realized their full potential, and their impact on the lives of people with disabilities has been limited. One cause for these challenges is that the blueprint used to develop these technologies is flawed. Kinetics and kinematics of locomotion form the basis for the development of wearable robotic systems, and the underlying dynamic mechanical properties, collectively known as mechanical impedance, of human joints is not included in the design and control process. In this talk, I will discuss our approach to identify and incorporate the regulation of mechanical impedance into the development of wearable robots.

Over the past several years, we have completed the estimation of impedance in the able-bodied ankle joint during locomotion. We have used these data to develop a new class of variable-stiffness ankle prosthesis, and have leveraged this technology to gain novel insight into the role of stiffness in ankle-foot prostheses. Finally, I will discuss basic studies on the human sensorimotor system that provide support for the role of impedance properties in the control of gait. Collectively, these studies begin to lay the foundation for the implications of mechanical impedance in locomotor control, and benchmarks for the mechanics of a new generation of prosthetic and wearable robotic systems.

BIOGRAPHY

Elliott Rouse, PhD
Assistant Professor, Department of Mechanical Engineering
University of Michigan, Ann Arbor, MI

Elliott Rouse is an Assistant Professor in the Department of Mechanical Engineering, and Core Faculty of the Robotics Institute, at the University of Michigan. He directs the Neurobionics Lab, whose research focuses on understanding human locomotion using techniques from system dynamics and robotics, and how pathology affects these dynamics. The goal of this understanding is to develop a new class of wearable robotic technologies that impact the lives of people with disabilities. Applications include robotic prostheses, exoskeletons, and technologies that augment human motor performance. He serves on the IEEE Technical Committee on Bio-Robotics, and is on the Editorial Board for the journal Assistive Technology.

ABSTRACT

Falls among Lower Limb Prosthesis Users: Refocusing through an Epidemiological Lens

1Kim, J., 2Major, M.J., 3Hafner, B.J., 1Sawers, A.

1University of Illinois at Chicago, 2Northwestern University, 3University of Washington

More than 50% of lower limb prosthesis (LLP) users report falling at least once a year, placing them at a high risk for adverse health outcomes like reduced mobility and diminished quality of life. Efforts to reduce falls among LLP users have focused on: i) developing clinical tests to assess fall risk, ii) designing prosthetic technology to improve patient safety, iii) characterizing biomechanical balance response, and iv) identifying risk factors for falls.

In contrast, little attention has been paid to the circumstances surrounding falls among LLP users. A better understanding of how and where LLP users fall could help: i) direct treatment to the most prevalent and consequential types of falls, ii) prioritize research needs in areas related to fall assessment, and iii) generate evidence to develop and revise reimbursement policy. The primary objective of this project was to characterize falls circumstances among ambulatory unilateral LLP users.

A secondary analysis of self-report falls data collected in two previous studies was conducted to address the study objective. Two investigators reviewed narrative descriptions of fall events provided by 66 LLP users. Falls were categorized using a novel fall type classification framework that describes the location of the destabilizing force (e.g., base-of-support, center-of-mass), the source of the destabilizing force (i.e., intrinsic or extrinsic), and the ensuing fall pattern (e.g., trip, slip etc.).

Thirty-eight participants (57.6%) reported one or more falls in over the past year, for a total of 90 falls (1.36 falls per participant). Therefore, falls among LLP users appear to remain as frequent today as they were 20 years ago. This suggests that research exploring new approaches to reduce falls among LLP users is warranted.

The base-of-support was the most commonly reported location of a destabilizing force leading to a fall (54%, 49/90 falls). Therefore, LLP users may be more susceptible to base-of-support than center-of-mass falls. Clinical balance tests that probe responses to base-of-support disruptions may improve fall risk assessment. New prosthetic designs that help LLP users successfully avoid and respond to base-of-support disruptions are also needed.

Intrinsic (i.e., personal) factors were more commonly reported as the source of destabilizing forces leading to a fall (58%, 52/90 falls) than extrinsic (i.e., environmental) factors. Intrinsic falls are associated with advanced age (i.e., >75 years old). However, the relatively low mean age of our sample, 50.4 years, suggests this cannot be the case here. Rather, challenges related to prosthetic gait (e.g., control of a prosthetic knee) may be responsible for intrinsic falls. Thus, a greater emphasis on the identification and treatment of personal rather than environmental factors appears warranted.

Slips (26%), followed by trips (22%), prosthetic factors (22%), and incorrect weight shift (15%) were the most commonly reported fall patterns. Owing to the diversity of fall patterns, neither assessment nor treatment can be prioritized based on the prevalence of fall patterns.

This secondary analysis provides an initial account of fall circumstances among LLP users. Data from a larger national sample collected with a structured LLP user-specific fall survey are needed to confirm these results, and identify other circumstances and related fall consequences.

BIOGRAPHY

Andrew Sawers, CPO, PhD
Assistant Professor, Department of Kinesiology
University of Illinois-Chicago, Chicago, IL

Andrew Sawers is an Assistant Professor in the Department of Kinesiology at UIC, where he directs the Locomotor Rehabilitation Lab. Dr. Sawers earned his doctorate at the University of Washington, and completed a post-doctoral fellowship at Emory University. His research focuses on developing novel clinical tests to determine, diagnose, and predict the "who, why, and how" of fall risk in lower limb prosthesis users.

JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE

Research Collaborations with Japan

Koki Kawano
JSPS Office, Washington, D.C.

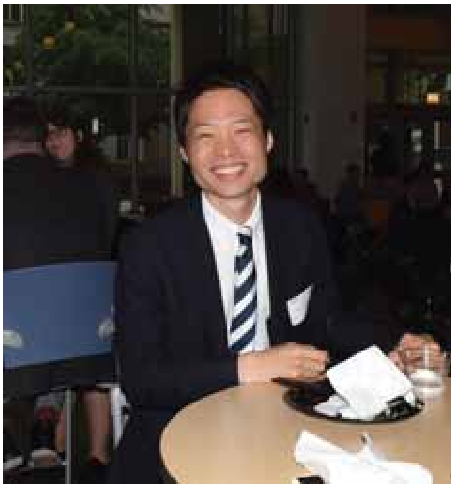
The Japan Society for the Promotion of Science (JSPS), or *Gakushin* for short, is an independent administrative institution, established by national law for the purpose of contributing to the advancement of science in the natural sciences, social sciences and humanities. JSPS plays a pivotal role in the administration of a wide spectrum of Japan's scientific and academic programs. While working within the broad framework of government policies established to promote scientific advancement, JSPS carries out its programs in a manner responsive to the needs of the participating scientists.

JSPS was founded in 1932 as a non-profit foundation through an endowment granted by Emperor Showa. JSPS became a quasi-governmental organization in 1967 under the auspices of the Ministry of Education (*Monbusho*), and since 2001 under the Ministry of Education, Culture, Sports, Science and Technology (*Monbukagakusho*). Over this 70-year period, JSPS has worked continuously to develop and implement a far-reaching array of domestic and international scientific programs. On October 1, 2003, JSPS entered a new phase with its conversion to an independent administrative institution. Henceforth, the JSPS will continue to optimize the effectiveness and efficiency of its management with the goals of improving the quality of services it offers to individual researchers, universities, and research institutes.

JSPS activities are supported in large part by annual subsidies from the Japanese Government. Its main functions are to:

- Foster young researchers,
- Promote international scientific cooperation,
- Award Grants-in-Aid for Scientific Research,
- Support scientific cooperation between the academic community and industry, and
- Collect and distribute information on scientific research activities.

Learn more about JSPS contributions to science at: https://www.jsps.go.jp/english/index.html.



Mr. Koki Kawano

JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE

Research Collaborations with Japan

Index of Symposium Participants

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Scientific Posters
(Alphabetical by first author)

1. Greene M, Adamczyk P. *Joint Effects of a Quasi-Passive Two Degree of Freedom Prosthetic Ankle*.

2. Hisano G, Hashizume S, Murai A, Kobayashi Y, Nakashima M, Hobara H. *Factors Affecting Knee Buckling Risk during Walking in Unilateral Transfemoral Amputees*.

3. Kaluf B, Duncan A, Shoemaker E, Martin T, DiGioia C, et al. *Comparative Effectiveness of Microprocessor Controlled and Carbon Fiber Energy Storing and Returning Prosthetic Feet in Persons with Unilateral Transtibial Amputation: Full Study*.

4. Krausz N, Hargrove L. *Powered Prosthesis Control and Intent Recognition Based on Novel Computer Vision Algorithms*.

5. Li W, Pickle N, Fey N. *Time Evolution of Frontal-Plane Dynamic Balance during Locomotor Transitions of Altered Anticipation and Complexity*.

6. Major M, Shirvaikar T, Stine R, Gard S. *Effects of Wearing an Upper Limb Prosthesis on Standing Balance*.

7. Olesnavage K, Arelekatti M, Prost V, Petalina N, Johnson B, Winter A. *Design of a Low Cost, Mass-Manufacturable Prosthetic Leg for Persons with Amputations in India*.

8. Pickle N, Silverman A, Wilken J, Fey N. *Segmental Contributions to Sagittal-Plane Whole-Body Angular Momentum When Using Powered Compared to Passive Ankle-Foot Prostheses on Ramps*.

9. Shepherd M, Rouse E. *Energy Storage and Return in Prosthetic Feet Is Not Maximal at the Preferred Stiffness*.

10. Shorter A, Rouse E. *Type of Gait Alters Ankle Joint Mechanical Impedance*.

11. Takahashi K, Hashizume S, Namiki Y, Hobara H. *Mechanical Power and Work Profiles during Sprinting in Transfemoral Amputees*.

Joint Moment Effects of a Quasi-Passive Two Degree of Freedom Prosthetic Ankle

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Motivation:

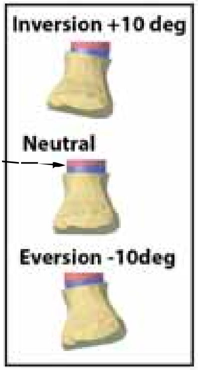
Goal:
Stabilize Gait through Two-Axis Prosthesis Angle Control

Study:
Effects of Foot Angle Changes on Ankle Moments

Prosthetic Ankle Design:

- o Complementary positions --> Neutral
- o Rotate upper and lower angled spacers --> +/- 10 deg alignment, any direction

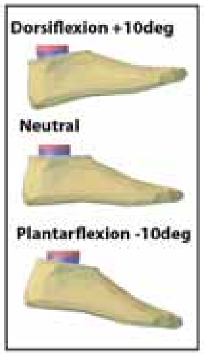
Frontal Angles



Methods:

- o Walking with prosthesis simulator boot
- o Frontal and Sagittal Angles Changes
- o Inverse Dynamics -> Average Ankle Angle & Peak Moment

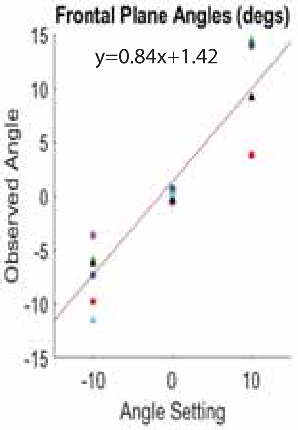
Sagittal Angles

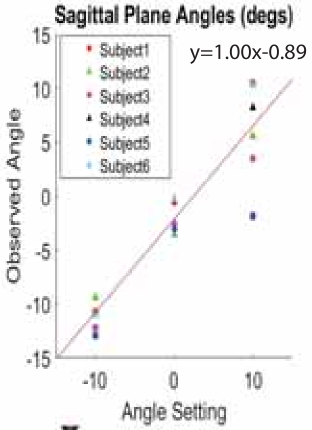


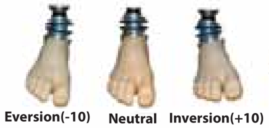
Results:

Observed Ankle Angle

Hypothesis: Observed Angle = Ankle Setting



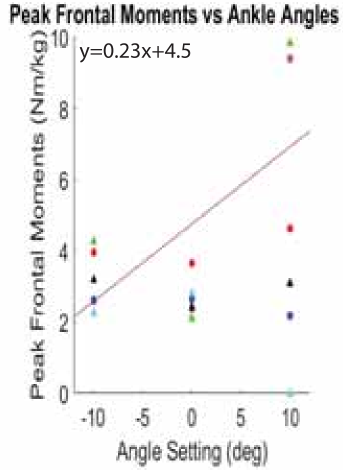


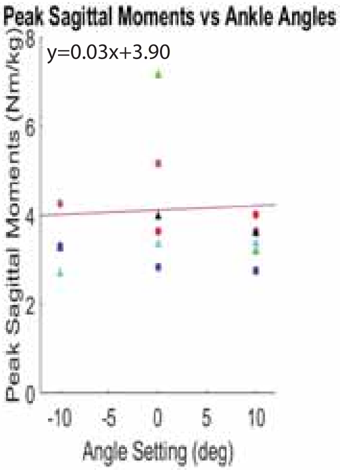


Conclusion: Observed angle matches setting ✓

Peak Ankle Moment

Hypothesis: Peak Moment Proportional to Angle Setting





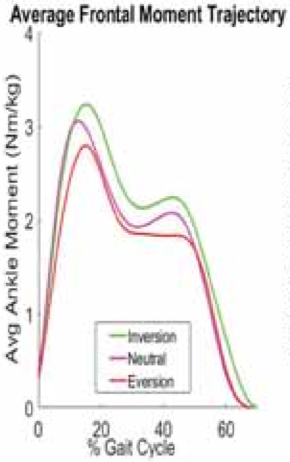
Conclusion:

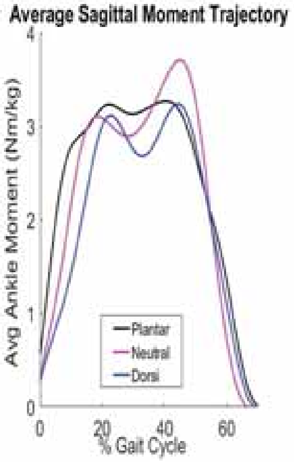
o No systematic moment effect
(*suspected leaning or step width compensation) ✗

Ankle Moment Trajectory

Hypothesis:

- o Plantarflexion -> Earlier increase in moment
- o Dorsiflexion -> Later increase in moment
- o Inversion/Eversion-> Shifts moment higher/lower





Conclusion:

- o Plantarflexed (PF) → earlier increases in ankle moments ✓
- o Dorsiflexed (DF) → delayed the increase of ankle moment ✓
- o Inversion and Eversion (IE) → increased/decreased peak force ✓

Future Work:

Perturbation Training

Amputee Testing

Stability Augmentation

References

[1] *Bauby 2000, JBiomech*
[2] *Kobayashi 2013, JRRD*

Acknowledgements

This work was supported by institutional funds from the University of Wisconsin – Madison and the Wisconsin Alumni Research Foundation.

Factors affecting knee buckling risk during walking in unilateral transfemoral amputees

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Introduction

Transfemoral amputees

- People with above-knee amputation
- Walking mobility is essential for enhancing quality of life.
- Only **20%** can re-learn walking. (specifically to geriatric vascular amputees)

Peng et al 2000, Fletcher et al 2002
Toursarkissian et al 2002

Non-microprocessor knees

Ottobock
3R80

- Passive, mechanical joint
- Widely-used and low-cost solution
- It **cannot** produce extension moment during stance phase voluntarily.

Knee buckling

- Knee buckling induces risk and fear of falling.

Nguyen et al 2014, Nevitt et al 2016

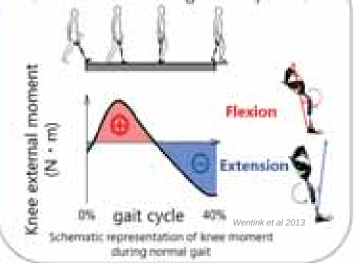
- Prevention of knee buckling is prerequisite for walking using a passive and mechanical knee.

Youtube

Research Question

Knee buckling risk

(Knee external angular impulse)



Wentink et al 2013

Schematic representation of knee moment during normal gait

Demographic data

- Age
- Sex
- Etiology
- Body Height
- Body Mass
- Time since amputation
- Prosthetic use history
- Residual limb length

What factors affect knee buckling risk?

Methods

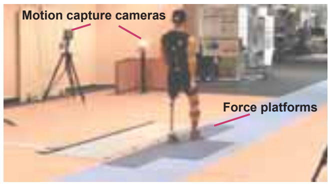
Experiments

- 13 active participants with unilateral transfemoral amputations were recruited.
- All the participants used passive, mechanical knee joint.
- We asked them to perform walking at self-selected speed on a straight 10-m walkway.

Data collection & analysis

- Ground reaction forces data (1000Hz, BP400600_10000PT, AMTI)
- 3D coordinate of markers attached to body (200Hz, VICON, Oxford Metrics Ltd)

Prosthetic knee external flexion-extension moment was calculated by using inverse dynamics.



Statistical analysis

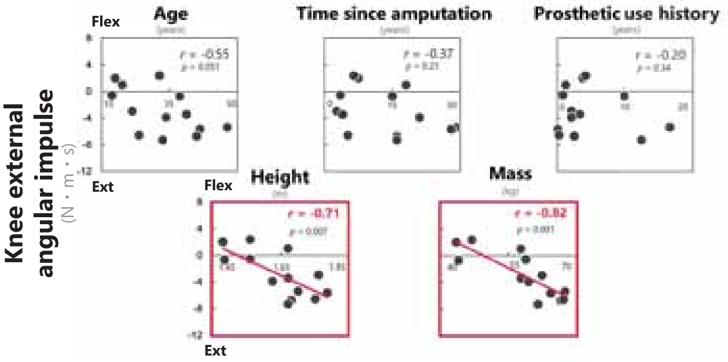
- Pearson's correlation coefficient (*r*)
- Independent *t*-Test

Questionnaires

- Knee buckling and fall history

Results & Discussion

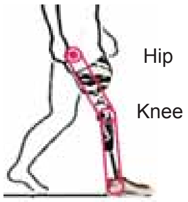
(1) Correlations with demographic data



- Body height and mass were <u>negatively</u> correlated with knee buckling risk.

☞**Knee buckling risk may be affected by participant's body size.**

Explanation 1.
<u>Hip extensor muscle strength</u>



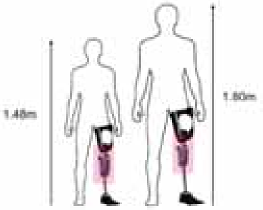
- Active hip internal extension during stance phase can produce external knee extension moment.

Kaufman et al 2007

- The greater body size, the greater hip extensor muscle strength.

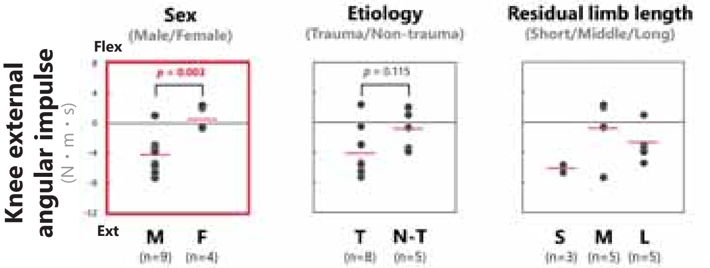
Fukunaga et al 2001, Handsfield et al 2014

Explanation 2.
<u>Relative size of prosthetic knee</u>



- Generally, prosthetic knee size is not adjustable to the body size.
- The greater body size, the smaller relative size of prosthetic knee.

(2) Between-group comparisons

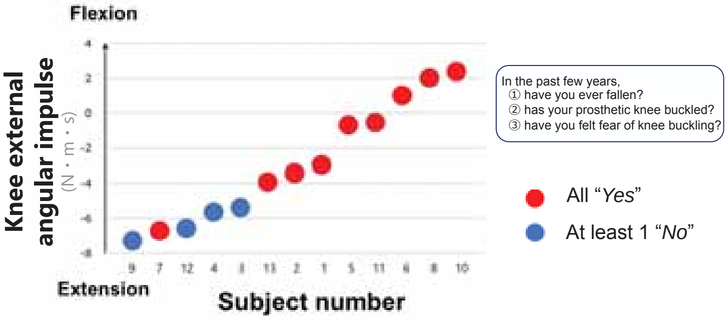


- We found **sex differences** in knee buckling risk during walking.

☞**Females may have a greater risk than males.**

- As shown in results for correlation, body height and body mass negatively correlated with knee buckling risk.
- In the present study, female body height and mass were relatively smaller than males. Hence, females may have relatively higher knee buckling risks than males.

Appendix: Questionnaires for 13 participants



In the past few years,
① have you ever fallen?
② has your prosthetic knee buckled?
③ have you felt fear of knee buckling?

Comparative Effectiveness of Microprocessor Controlled and Carbon Fiber Energy Storing and Returning Prosthetic Feet in Persons with Unilateral Transtibial Amputation: Full Study

Kaluf BD[1], Duncan A[2], Bridges WC[3], Shoemaker E[1], Martin TR[1], DiGioia C[1], Ability Prosthetics and Orthotics, Inc.[1], OrthoCarolina Research Institute[2], Clemson University[3]

Introduction

- Advancements in microprocessor prosthetic ankle - feet (MPA) allow additional functionality for lower limb amputees. Evidence on MPA includes 3D kinematic and kinetic data (Struchkov 2016), gait symmetry (Agrawal 2013), energy expenditure (Darter 2014), and socket pressure (Wolf 2009). Further comparative effectiveness research is needed in larger samples. This study compares differences in patient-reported and performance-based outcome measures and 2D motion capture while walking and standing on a ramp with an energy storing and returning (ESAR) and MPA.

Methods

- Institutional review board (IRB) approved, randomized crossover protocol with ankle-foot configurations consisting of a control ESAR (Pacifica LP) and a MPA (Kinnex, Freedom Innovations, Irvine, CA).
- Subjects: 23 unilateral transtibial amputees enrolled with a mean age of 51 years, mass of 88.92 kg, and 15.4 years since amputation.
- Apparatus: Prosthesis Evaluation Questionnaire – Mobility Subscale (PEQ-MS), Prosthetic Limb User Survey of Mobility (PLUS-M), Activities Specific Balance Confidence (ABC) and Socket Comfort Score (SCS); Amputee Mobility Predictor with Prosthesis (AMPPRO), 6 min Timed-Walk-Test (6min TWT), Physiological Cost Index (PCI); Hill Assessment Index (HAI), prosthesis side ankle and knee angles at initial contact and mid-stance of gait during ramp ascent and descent measured with 2D video motion analysis (PnO Data Live, iPad Air).
- Procedures: Ankle-feet were assembled/aligned to participants' current socket by a certified prosthetist. Markers were placed on the greater trochanter, knee center, lateral malleolus and base of the fifth digit. A 6 ft long ramp with 15 deg slope was used for HAI and 2D motion analysis. Testing was performed after initial assembly and after a 4-week accommodation period.
- Data Analysis: The results were inspected for normality, and found to be normally distributed, one-tailed paired t-tests (with participant being the pairing variable) were performed to compare whether Kinnex had higher mean scores than Pacifica LP. All calculations were performed using the SAS package JMP. All statistical tests used α=0.05.

Results

- Average scores for ABC, PLUS-M T-Score, PEQ-MS and SCS for all ramp conditions are depicted in Figure 1a and 1b. Average AMP, PCI and walking speed are depicted in Figure 2a and 2b. During walking on sloped descent, the Kinnex had a significantly greater knee angle at foot-flat. Kinnex had significantly more stable knee and ankle angles in all standing activities on the ramp.
- When asked, 81% of participants preferred the Kinnex over the Pacifica LP. Negative aspects that participants reported about the Pacifica LP included: less motion, difficult on uneven terrain, less balance, more loads/pressure.
- Participants only reported lighter weight as something they liked about the Pacifica LP. With the Kinnex, participants reportedly liked: better on slopes, better on uneven terrain, more natural, more motion, adjusts to heel height, more comfortable, convenience. Aspects they disliked included: more weight, requires charging, lock inconvenience, battery capacity.

Conclusion

- A fixed 90 deg ESAR ankle can cause loss of balance and limited mobility on uneven terrain. Improvements were seen in mobility in the community (PLUS-M and PEQ-MS) when patients used the MPA compared to the ESAR. SCS was consistently higher with the MPA compared to ESAR when patients stood still and walked on a 15 deg ascending and descending slope. The AMP, PCI, walking speed and HAI did not show a significant difference between the MPA and ESAR. Regarding walking speed and PCI, this highlights that participants did not walk knowingly slower or have greater cost of ambulation when walking with the heavier MPA system. The ABC, AMP and HAI may not have been responsive to the functional benefits of MPA as anticipated.

Significance

- The MPA demonstrated higher patient-reported outcome measure results related to mobility and socket comfort. Knee and ankle angles were more stable while standing on a ramp and knee angles were more stable at foot-flat walking down a slope. Most patients preferred the MPA, and notable reasons for dislike were related to the additional weight and battery charging. These results highlight important benefits of this advanced technology and the findings. This study represents the largest known investigation of MPA and includes the type of outcome measures that clinicians, physicians, patients and payer sources care about.

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Acknowledgements

- This effort was supported by funding from Freedom Innovations LLC and made possible through the dedication of four research prosthetists and four resident prosthetists.

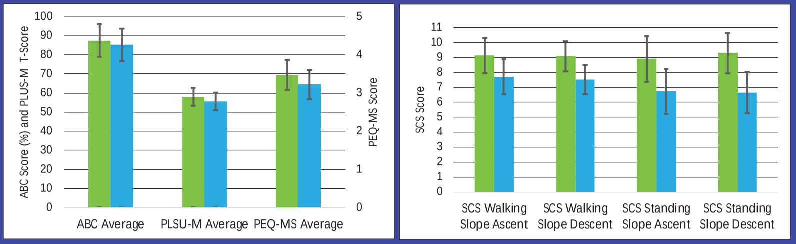

Figure 1. (a) ABC, PLUS-M T-Score and PEQ-MS average scores for Kinnex (green) and Pacifica LP (blue). (b) SCS average scores while walking/standing on slope ascent/descent for Kinnex (green) and Pacifica LP (blue).

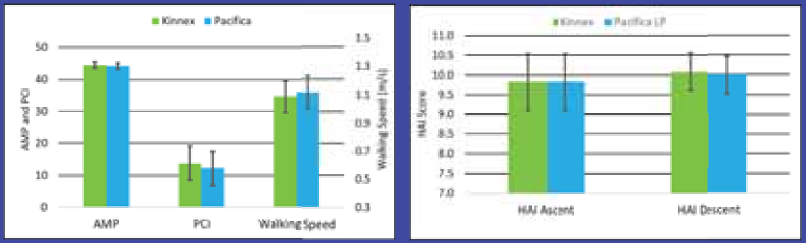

Figure 2. (a) AMP, PCI and walking speed averages for Kinnex (green) and Pacifica LP (blue). (b) HIA average scores while walking slope ascent/descent for Kinnex (green) and Pacifica LP (blue).

Figure 3. Sagittal plane images showing the smaller ankle angle while walking (left) and standing (right) on an ascending ramp using the Kinnex.

Figure 4. Sagittal plane images showing the larger ankle angle while walking (left) and standing (right) on an descending ramp using the Kinnex.

Powered Prosthesis Control and Intent Recognition Based on Novel Computer Vision Algorithms

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Advisor: Levi J. Hargrove, PhD[1-3]

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Introduction

Context: Current research for powered prostheses have used pattern recognition methods incorporating electromyography (*EMG), kinetics,* and *kinematics* to recognize what the user intends to perform.

Error rates for transitions between locomotion modes is 10-20% in the most advanced systems currently [1].

Problem: Intent recognition systems have high inter- and intra-subject variability, due to subject-based data sources varying regularly.

Solution: We propose the addition of *environment-based* data, using 2D and 3D computer vision (CV).

We developed novel algorithms, integrated CV with prosthetic control, and completed preliminary testing to determine feasibility for prosthesis intent recognition and control.

Proposed System

- We propose a **high level controller** that will predict the desired locomotion mode based on a **fusion** of:
  - Depth data from the environment (Camboard Pico Flexx)
  - Kinetics and kinematics (Powered Knee Ankle Prosthesis)
- Two fusion approaches will be evaluated: a machine learning method and a fuzzy logic method.
- Locomotion mode specific mid/low level controllers will be used to estimate motor commands.

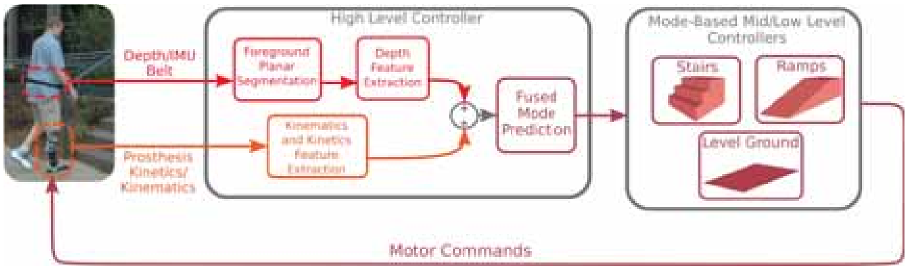

Figure 1. Diagram showing the proposed system with inputs from the depth sensor/IMU and the Vanderbilt transfemoral prosthesis. Individual mode-based mid/low level controllers will be used.

Integrated Prosthesis Study

Setup

- Eventually 10 able-bodied subjects and 10 amputee subjects will complete the protocol.
- Walking trials including level-ground walking, stair ascent/descent, and ramp ascent/descent.
- A depth sensor [2] and an inertial measurement unit (IMU) were worn on a belt at the waist were synchronized with a transfemoral prosthesis, and controlled using a custom software package.
- The experimenter controls the prosthesis locomotion mode during training trials.
- **All processing/control must be completed within 30 ms to prevent trips/falls.**

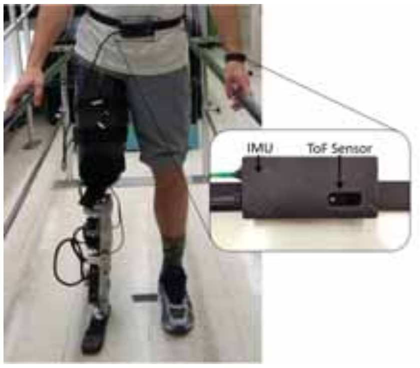

Figure 2. Able-bodied subject wearing the depth sensor/IMU belt unit and transfemoral prosthesis with a custom made bypass socket.

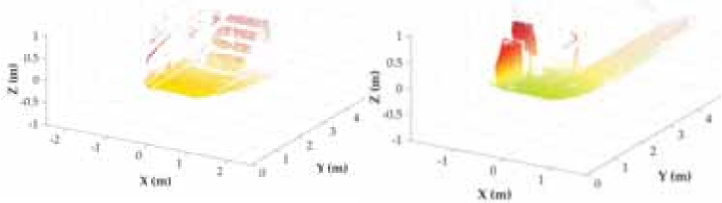

Figure 5. Raw point clouds collected during ambulation with the prosthesis (l-r stair, ramp).

Novel Depth Algorithm

- A novel algorithm was developed to segment regions from the raw depth data, extract features, and estimate the desired locomotion mode.
- The overall system will utilize a fusion of EMG, kinetics, and kinematics as well as Vision features.
- Multiple fusion approaches are being evaluated.

Figure 3. Walking circuit for data collection, including multiple stairs, a ramp, and elevated platforms.

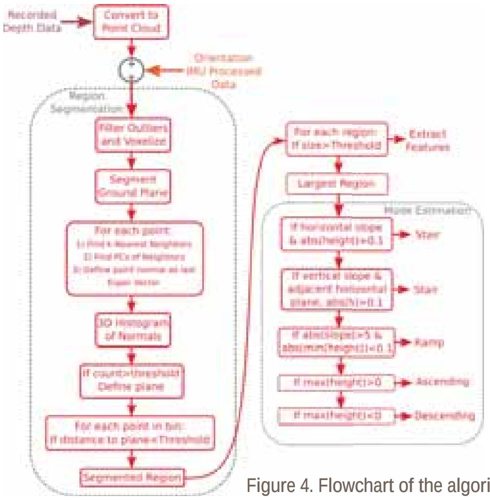

Figure 4. Flowchart of the algorithm developed to perform region segmentation, feature extraction, and mode estimation based on the depth and IMU data.

Preliminary Testing

- Preliminary data collection/testing has been completed with two able-bodied subjects.
- Synchronization was evaluated to ensure controller lag of <30 ms.
- Algorithm validation to ensure adequate segmentation of environmental objects.
- Feasibility of depth-approach demonstrated in [3] with **98.8% frame accuracy.**

Figure 6. Segmented stairs superimposed on RGB image.

Future Directions

- Completion of testing and analysis of data from all able-bodied and amputee subjects.
- Evaluation of inter- and intra-subject variability of different data sources across days.
- Testing and comparison of fusion approaches.
- Online implementation.
- Testing of other control algorithms using vision (i.e. double support phase testing [4]).

Figure 7. Segmented shank used for double support controller.

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Time evolution of frontal-plane dynamic balance during locomotor transitions of altered anticipation and complexity

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Introduction

- **Transitions** between locomotion modes are fundamental activities of daily life, arising under both anticipated and unanticipated cognitive states.
- How the unimpaired human neuromuscular system manages specific user and environmental factors of transitions to maintain dynamic balance is unknown.
- New insights are needed to inform how we assess balance deficits of fall-prone individuals, and to inform device interventions targeting specific destabilizing scenarios.
- **Whole-body angular momentum** (*H*) is highly-regulated in 3D to maintain dynamic balance[1-4].

Purpose: Apportion the effects of task anticipation, cutting style and complexity on the **time evolution of frontal-plane dynamic balance** during locomotor transitions of healthy, unimpaired individuals.

Hypothesis: *H* will be larger during unanticipated transitions of increased complexity.

Methods

Protocol

5 healthy, able-bodied individuals
- 27.7 mean (3.8 std. dev.) years
- 52.6 (5.0) kg
- 1.68 (0.09) m

Environmental factors
- Overground straight-line walking
- Crossover, sidestep
- 45º cut, 45º cut/stair-ascent

User-specific factor
- Task anticipation

10 total locomotor conditions
1. A-STR, anticipated straight-line walking
2. A-CO, anticipated crossover
3. A-SS, anticipated sidestep
4. A-CO-S, anticipated crossover/stair-ascent
5. A-SS-S, anticipated sidestep/stair-ascent
6. UA-STR, unanticipated straight-line
7. UA-CO, unanticipated crossover
8. UA-SS, unanticipated sidestep
9. UA-CO-S, unanticipated crossover/stair-ascent
10. UA-SS-S, unanticipated sidestep/stair-ascent

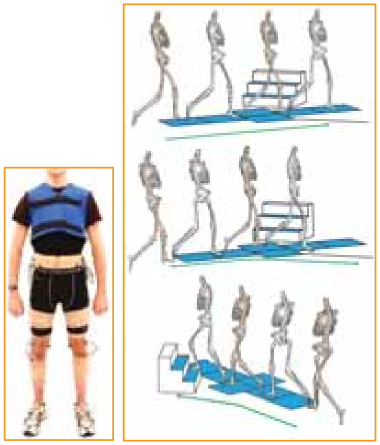

Figure 1: Representative subject (left) and kinematic model of a subject preforming straight walking (right, top), sidestep cut (right, middle), and crossover cut to stair ascent transitions (right, bottom), using the right (trailing) leg.

Sources of Data

- 10-camera motion capture system (Motion Lab Systems, Inc.) tracked positions of 42 reflective markers (Fig. 1).
- 8-segment kinematic and inertial model of each subject (Fig. 1)

Analysis

- *H* about the body's center-of-mass calculated was calculated via kinematic relationship:

$$\vec{H} = \sum_{i=1}^{8} [I_i \vec{\omega}_i + (\vec{r}_i - \vec{r}_{COM}) \times m_i(\vec{v}_i - \vec{v}_{COM})]$$

- *H* was normalized by body mass and height for each participant.
- Consecutive maxima and minima of frontal-plane *H* during two full gait cycles spanning the transitions and straight-line walking were computed.
- ANOVA with main effects of anticipation (anticipated, unanticipated), complexity (cut, stairs, straight walking), and style (sidestep, crossover)
- *Post hoc* comparisons when ANOVA indicated significant main or interaction effects
- α=0.05

Results

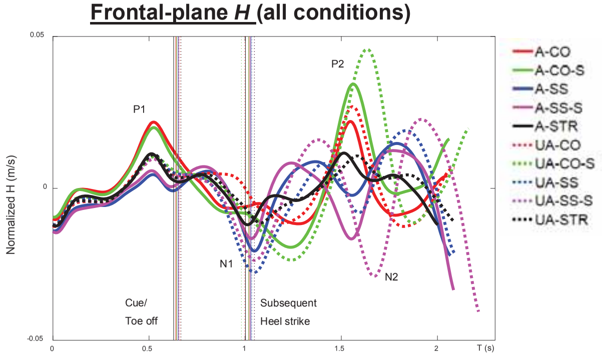

Figure 2: Frontal-plane *H* during two consecutive strides of *trailing leg* (Fig. 1). Auditory cue was given at the first toe off of *trailing leg* in unanticipated conditions.

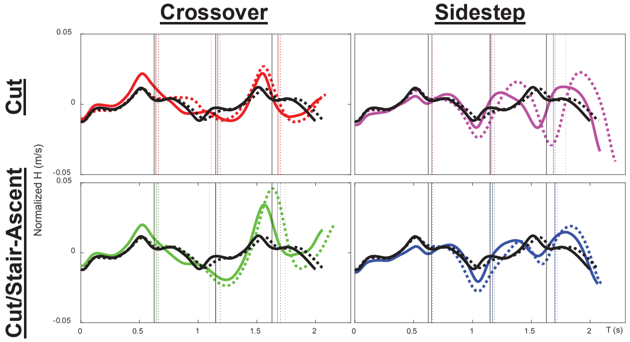

Figure 3: Frontal-plane *H* during two consecutive strides of *trailing leg* (Fig. 1). Vertical lines indicate the first toe off of the trailing leg (also cue onset in unanticipated conditions), toe off of the leading leg, and the second toe off of the trailing leg, chronologically. Please note the share legend from Fig. 2.

			P1	N1	P2	N2
Anticipated	**Straight**		12(1)	-12(2)	12(1)	-12(2)
Unanticipated	**Straight**		11(1)	-11(2)	12(1)	-11(2)
Anticipated	**Crossover**	Cut	22(5)*^^{a}	-13(2)	22(4)*^	-9(2)*^
		Cut/Stair	21(4)*^^{a}	-20(3)*^	35(3)*^^{c}	-2(2)*^
	Sidestep	Cut	5(2)*^	-21(3)*^	9(1)*^	-3(3)*^
		Cut/Stair	6(2)*^	-17(3)*^	9(3)	-17(3)^^{c}
Unanticipated	**Crossover**	Cut	11(1)	-12(3)	27(5)*^	-13(1)
		Cut/Stair	11(1)	-25(3)*^	47(6)*^^{bc}	-12(5)^{b}
	Sidestep	Cut	11(1)	-29(5)*^^{a}	9(7)	-9(5)
		Cut/Stair	10(1)	-25(8)*^^{a}	16(1)*^^{b}	-31(5)*^^{bc}

Table 1: Mean (standard deviation) P1, N1, P2, N2, ×10-3 m/s of *H* condition. * represents significant differences compared with anticipated straight walking. ^ represents significant differences relative to unanticipated straight walking. ^{a} shows the largest magnitude of frontal-plane *H* in anticipation by cutting style interaction. ^{b} shows the largest magnitude of frontal-plane *H* in anticipation by complexity interactions. ^{c} shows the largest magnitude of frontal-plane *H* in cutting style by complexity interaction.

Conclusion

- Anticipatory changes in *H* influenced by style, not complexity. Healthy individuals prioritize directional changes over impending changes in walking surface.
- Our hypothesis was largely supported—For matched complexities and styles, unanticipated states produced largest peak *H*. Transitions under unanticipated states produced harmful downstream effects, especially on stairs.
- However, specific combinations of contextual factors showed unique magnitudes of dynamic balance.

Implications regarding locomotor transitions

Anticipatory modifications, rapid adjustments following the interruption of task planning and subsequent management of downstream adverse effects *all* appear to be functionally important. These abilities could be targeted with training and/or device rehabilitative interventions to assess and/or assist balance-impaired individuals.

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EFFECTS OF WEARING AN UPPER LIMB PROSTHESIS ON STANDING BALANCE

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Introduction

- Whole-body composition influences postural control with the arms playing a key role in the regulation of standing balance [1, 2].
- Nearly half of persons with upper limb (UL) loss fall once per year [3] and prosthesis use may impose a postural disturbance [1,3].
- Understanding the effects of wearing an UL prosthesis on balance may inform intervention strategies to enhance postural control.

Purpose: Evaluate the acute effects of wearing an UL prosthesis on standing balance, particularly the impact of matching the mass of the impaired (prosthetic) limb to the sound limb.

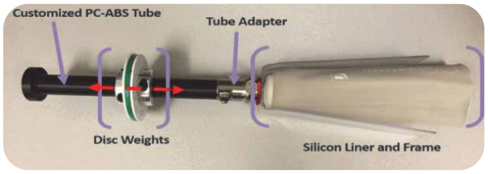
Methods

- **Design:** Repeated-measures study; 11 subjects with unilateral UL loss (8 transradial/3 transhumeral; 50±18yrs; 175.1±7.4cm; 79.6±22.6kg).

Experimental Protocol

Three trials of 30 seconds of quiet standing under **three prosthesis conditions:**

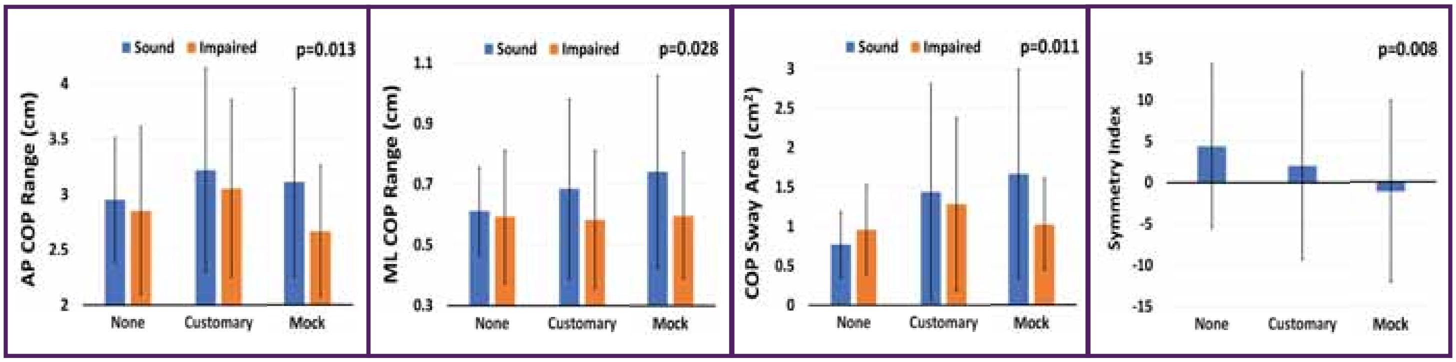
1) Without wearing a prosthesis;
2) Wearing the subject's customary prosthesis; and
3) Wearing a mock prosthesis that matched the mass of the impaired (prosthetic) limb to the sound limb.



Equipment and Data Analysis

- **Equipment**: 2 embedded force plates that collect instantaneous Center-of-Pressure (COP) location.
- **Measures**:
  - Mean COP anterior-posterior/medial-lateral (AP/ML) range, and sway area for each side (impaired, sound).
  - Sway area estimated using the Khachiyan Ellipsoid Algorithm with a tolerance of 0.001 cm.
  - Symmetry Index estimated weight distribution between sides (>0=sound side bias; <0=impaired side bias).
- **Fallers** defined as falling at least once in past 12 months.
- **Mixed ANCOVAs** performed on COP range, sway area, and Symmetry Index (side*condition*Faller/Non-Faller group).

Results



Anterior-Posterior COP Range *Medial-Lateral COP Range* *COP Sway Area* *Symmetry Index*

Error Bars = 95% Confidence Interval; p-values correspond to between-condition analyses

Conclusions

- Wearing an UL prosthesis may improve weight symmetry in persons with unilateral UL loss, but generally increased COP excursion.
- Increased COP excursion reflects greater sway of the whole-body center-of-mass and increased demands on postural control [4].
- No difference in COP parameters were significant ($p \geq 0.07$) between subjects categorized as Fallers or Non-Fallers.
- Further research is needed to explore relationships between COP excursion and fall risk in persons with UL loss.

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Acknowledgements

We thank John Brinkmann, CPO, for helping design the mock prosthesis and Suzanne McConn, MSc, for assistance with data collection. Work was supported by the U.S. Dept. of Veterans Affairs (#1I21RX001388 & 1IK2RX001322) and NU Undergraduate Research Assistant Program.

Design of a Low Cost, Mass-Manufacturable Prosthetic Leg for Persons with Amputations in India

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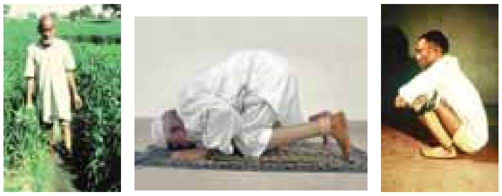
Collaborating Institutions:
BMVSS, Jaipur, India
Northwestern University, Chicago, IL

Opportunity

- 30 million people in developing countries need a lower limb prosthesis[1]
- Jaipur Foot is a low cost solution for prosthetic demand in India
- Jaipur Foot has inconsistent quality, suboptimal production rates, does not meet international standards, is not optimized for walking

The goal of this work is to create a low cost, mass-manufacturable lower leg prosthesis that meets or exceeds the performance of the Jaipur Foot



Amputees wearing the Jaipur Foot for different activities.

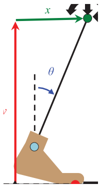
LLTE – A New Design Tool for Feet

Lower Leg Trajectory Error (LLTE) [2]

- Evaluates the functionality of passive foot designs
- Treats the foot as a compliant structure under typical walking loads and compares the kinematics to able-body data
- Maps a prosthetic foot's mechanical design to biomechanical performance

This tool enables optimization to:

- Better replicate able-bodied gait and loading
- Tune to readily available, affordable polymers
- Tune performance to specific patients' body weight, size, and activity level



Acknowledgments

This work is supported by the Tata Trusts. We thank Mr. D.R. Mehta, Dr. Pooja Mukul, Dr. M.K. Mathur at BMVSS and Dr. Matthew J. Major and Rebecca Stine, M.S., at Northwestern University and JBVAMCMARL for their continued support.

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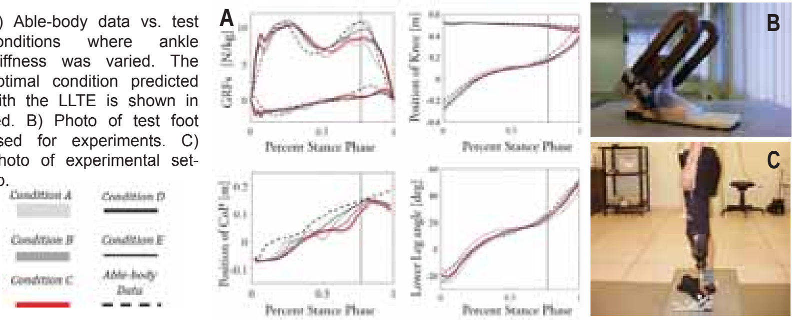
Demonstrating Validity of the LLTE-based Design Tool

Optimal and suboptimal feet of varying stiffness were built and tested on a transtibial amputee

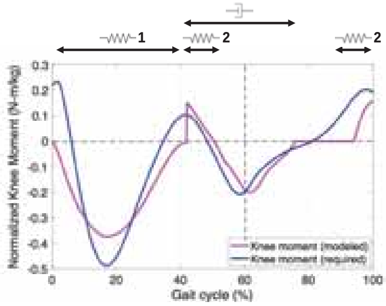
A) Able-body data vs. test conditions where ankle stiffness was varied. The optimal condition predicted with the LLTE is shown in red. B) Photo of test foot used for experiments. C) Photo of experimental set-up.



Results suggest that LLTE links the prosthetic foot mechanical design to its biomechanical performance and could be used as a design objective to optimize prosthetic foot designs.

Knee Design Process

- Determine the required knee torque to reproduce able-body kinematics based on user height and weight
- Model the torque profile using passive components, such as springs and dampers
- Two springs and a viscous damper engaged with proper timing can approximate the target profile



Target knee torque profile over the gait cycle (blue line) and model approximation using two springs and a damper (pink line). Black arrows at the top indicate the ideal timing for engaging the damper and springs 1 and 2.

Prototypes

Prosthetic foot designed through LLTE optimization. Can be injection molded for under $10 USD.

"Works-like" knee prototype with springs and dampers that engage at different times within the gait cycle.

Future Work

- Develop a durable cosmetic shell for the foot
- Field test prototypes in India
- Collect more dynamic data to refine our models
- Optimize the foot for other walking tasks

Photos from preliminary field tests of the foot prototype (left) and the knee prototype (right).

Segmental Contributions to Sagittal-Plane Whole-Body Angular Momentum When Using Powered Compared to Passive Ankle-Foot Prostheses on Ramps

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MOTIVATION

Below-knee amputation affects dynamic balance on ramps[1]

Soleus, gastrocnemius, and passive prostheses contribute to **trunk and leg** motion differently during walking[2-4]

Powered ankle-foot prostheses generate net positive mechanical power, unlike passive prostheses (Fig. 1), but do not consistently reduce metabolic cost[5,6]

Whole-body angular momentum (*H*) can identify altered balance strategies[1,7-9], and be decomposed into individual **segmental contributions**[10,11]

As assistive device hardware and control algorithms continue to evolve, so too must methods of **targeted assessment** incorporating time-series data

Certain segments may be **more affected** by prosthetic ankle power generation

Hypotheses

1) **Differences in prosthetic leg contributions to *H* during mid-stance and mid-swing**
2) **Interaction effect between prosthesis and slope in trunk contributions to *H***

Figure 1: Example of a passive energy storage and return prosthesis (left, Ossur) and the BiOM powered prosthesis (right).

METHODS

Subjects

8 individuals with unilateral transtibial amputation
7 male/1 female, 96 (SD=8) kg, 1.8 (SD=0.1) m, 31 (SD=5) years old

Devices

Passive prosthesis: clinically prescribed
Powered prosthesis: BiOM (BiOM, Inc.)
Average acclimation period of 43 (SD=18) days with BiOM

Protocol

Walked up and down 16-foot long ramp (Fig. 2)

- 0°, ±5°, ±10°
- Fixed speed (Froude number 0.16)

Whole-body kinematics from 57 retroreflective markers

Processing

Marker trajectories low-pass filtered with 6 Hz cutoff
13-segment model of each participant

- Passive prosthesis shank mass reduced 30%, moved 30% proximal
- Computed contributions to whole-body angular momentum from arms, trunk, and legs (Fig. 3)

$$\vec{\boldsymbol{H}}_{\boldsymbol{i}} = \left(\vec{\boldsymbol{r}}_{\boldsymbol{i}} - \vec{\boldsymbol{r}}_{\boldsymbol{body}}\right) \times \boldsymbol{m}_{\boldsymbol{i}}\left(\vec{\boldsymbol{v}}_{\boldsymbol{i}} - \vec{\boldsymbol{v}}_{\boldsymbol{body}}\right) + \boldsymbol{I}_{\boldsymbol{i}}\vec{\boldsymbol{\omega}}_{\boldsymbol{i}}$$

- *H* values normalized by body mass, height, and mean velocity

Analysis

Statistical Parametric Mapping (SPM)[12]

- ANOVA with main effects of slope, prosthesis type
- Post-hoc pairwise comparisons when significant main or interaction effects were found
- Family-wise error rate of α=0.05 maintained by computing critical threshold *F** or *t** using Random Field Theory

Figure 2: Adjustable ramp and motion capture system at the Center for the Intrepid, Brooke Army Medical Center.

Figure 3: Body segments for which contributions to whole-body angular momentum were analyzed: arms (upper and lower arm), trunk (head, torso, pelvis), and legs (thigh, shank, foot).

RESULTS

SPM ANOVA Results

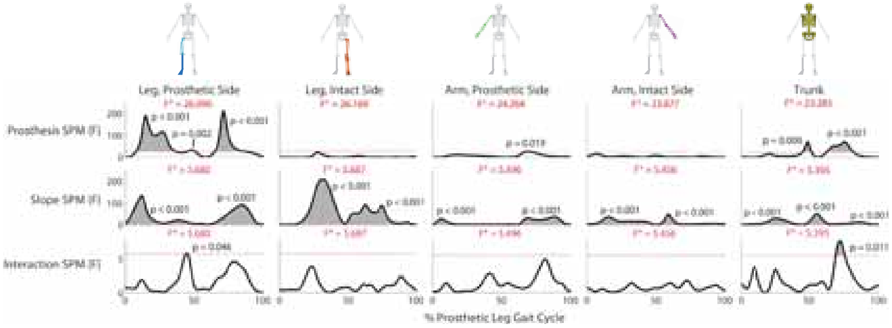
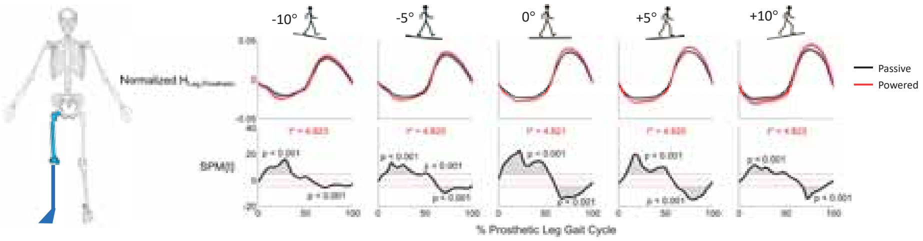


Figure 4: ANOVA results for the main effects of prosthesis type (top row) and slope (middle row) as well as the interaction effect (bottom row) for all segments. The plotted values are the SPM{*F*}, which is the *F*-statistic as a function of time. The critical threshold (*F**) needed to achieve significance is indicated for each test. Shaded regions indicate significant effects.

Pairwise Comparisons for Prosthetic-Side Leg



Pairwise Comparisons for Trunk

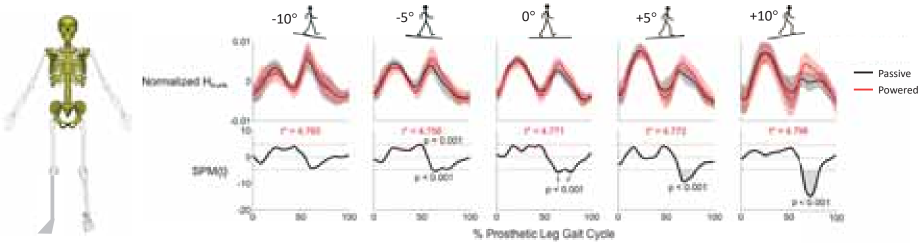


Figure 5: Pairwise comparison results for prosthetic-side leg (top set of plots) and trunk (bottom set of plots) contributions to whole-body angular momentum (*H*). Within each set of plots, the top row shows mean (±SD in shaded regions) contributions to *H* with the passive and powered prostheses, and the bottom row shows the SPM{*t*}, which is the student's *t*-value as a function of time. The critical threshold (*t**) needed to achieve significance is indicated for each pairwise comparison. Shaded regions indicate significant differences between passive and powered prostheses. Positive (negative) SPM{*t*} indicates that the contribution from the passive prosthesis was more (less) positive compared to the powered prosthesis.

CONCLUSIONS

Ramp angle affects segmental coordination

- Main effect of slope for all segments
- Changes in arm coordination only occurred during certain portions of the gait cycle

Powered prosthesis increases magnitude of prosthetic leg contributions to *H*

- Increase during early- and mid-stance may be related to controlled plantarflexion in powered prosthesis
  - Similar to increased leg braking in compliant passive prosthesis[3]
- Increase during swing possibly due to ankle power generation aiding leg swing initiation

Powered prosthesis increases trunk contributions to *H* when walking uphill

- Suggests powered prosthesis partially replicates function of soleus, which primarily contributes to trunk[1,2]
- Demonstrates mechanical coupling among all body segments

Implications for prosthesis design and clinical rehabilitation

Design of robotic assistive devices should account for effects on segmental contributions to dynamic balance, not just local joint mechanics (e.g., ankle moment) or metabolic cost.

ACKNOWLEDGMENTS AND REFERENCES

The authors thank Jennifer Aldridge Whitehead, Kelly Ohm, and Audrey Westbrook for their assistance with data collection and processing. This work was supported by NIH NICHD Award No. R03HD075946, DoD Award No. W81K00-09-P-1129, and discretionary research funds from Dr. Fey.

The views expressed herein are those of the authors and do not reflect the official policy or position of Brooke Army Medical Center, the U.S. Army Medical Dept. the U.S. Army Office of the Surgeon General, the Dept. of the Army, Dept. of Defense, the U.S. Government, of the National Institutes of Health.

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Energy Storage and Return in Prosthetic Feet is Not Maximal at the Preferred Stiffness

Max K Shepherd[1,2,3], **Elliott J Rouse**[1,4]

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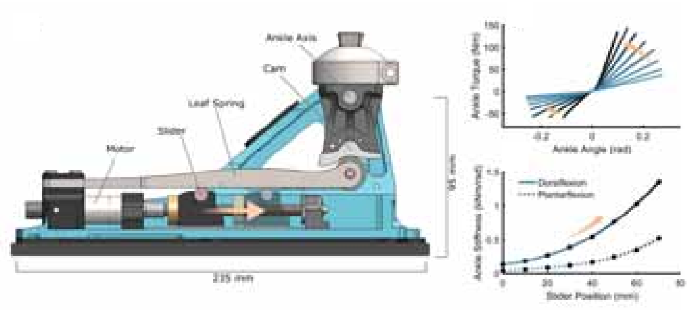
Introduction

- Modern prosthetic feet behave like springs, storing energy during mid-stance, which is returned at the end of stance to help propel the wearer forward
- Energy *storage* is a function of the foot's mechanics (stiffness) and the dynamics of the individual's gait; energy *return* is the stored energy minus elastic hysteresis
- Some prosthetics manufacturers have implied that increased energy storage and return is beneficial by advertising their energy-return as "high[1]", "dramatic[2]," or "superior[3];" the Renegade Foot is even described as having "up to 35% greater energy return[4]"
- In this study, we sought to determine if **energy storage and return is maximal at self-selected preferred stiffness**

Materials & Methods

Variable-Stiffness Prosthetic Ankle-Foot (VSPA-Foot)

- A titanium leaf spring is deflected by a cam mechanism when the ankle rotates, allowing the ankle to act like a rotational spring[1]
- The leaf spring is supported by a sliding support, which can be repositioned by a motor to increase or decrease stiffness



1. Preferred Stiffness

- Subjects used a **hand-held electronic dial** to change stiffness, and were instructed to select the stiffness that was "the most comfortable at this walking speed"
- After preferred stiffness was selected, the treadmill was stopped, stiffness was randomly changed, and the process was repeated for a total of five preferred stiffness values per subject

2. Biomechanics at and around the Preferred Stiffness

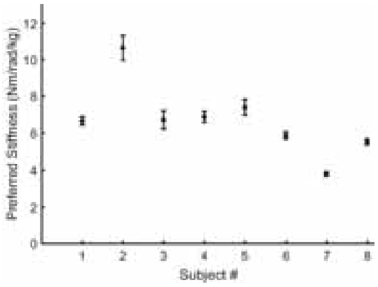
- Eight unilateral trans-tibial subjects walked with the prosthesis at five stiffness levels: **80%, 90%, 100%, 110%, and 120% of preferred stiffness**
- Ankle angle was recorded at 30 Hz by an onboard, 14 bit encoder. Angle was filtered (7.5 Hz, 4th order Butterworth) and up-sampled to 100 Hz (spline fit)
- Energy Storage was calculated as: $E = \frac{1}{2} k {\theta_p}^2$ where θ_p is the peak deflection in either plantarflexion or dorsiflexion, and k is known (experimentally tested) as a function of slider position

Subject	Age (yrs)	Height (m)	Weight(kg)	Time since amputation (yrs)	Residual Limb Length (cm)	Customary prosthesis	Amputation etiology
1	23	1.88	86.2	3	14	Össur *Vari-Flex XC*	Traumatic
2	41	1.52	76.2	4	15	Freedom Inn. *Senator*	Dysvascular
3	41	1.70	54.4	14	12	Össur *Elation*	Traumatic
4	46	1.85	86.0	26	24	College Park *Velocity*	Traumatic
5	33	1.75	72.5	13	15	College Park *Soleus*	Traumatic
6	24	1.65	61.2	1	14	Össur *Pro-Flex LP*	Traumatic
7	35	1.83	90.0	15	14	Ability Dyn. *Rush Foot*	Dysvascular
8	54	1.78	84.0	1	15	Endolite *Echelon*	Dysvascular

Results

1. Preferred Stiffness

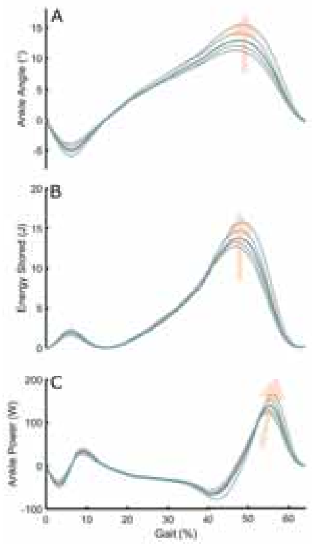
- Subjects were able to consistently select their preferred stiffness (Coefficient of Variation: 14%)
- Mean and standard errors are shown for each subject's preferred stiffness

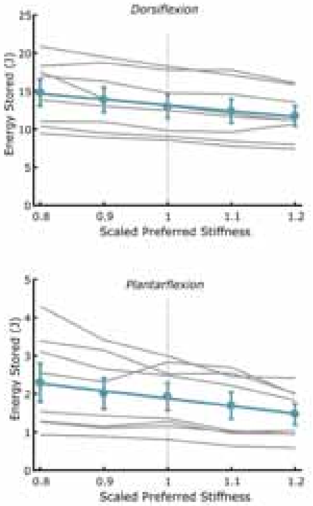


2. Energy Storage and Return at and around the Preferred Stiffness

The blue trace indicates the preferred stiffness. As stiffness **decreased** (denoted by the orange arrow):

A. Peak dorsiflexion and plantarflexion **increased**.
B. Energy storage and return **increased**
C. Prosthetic ankle power **increased**, and was slightly delayed





Energy Storage and Return varies by subject (gray traces), but is negatively correlated with stiffness near the preferred stiffness ($p < 0.001$)

Conclusion

- Around the preferred stiffness, energy stored and returned continued to increase as stiffness decreased
- *Peak energy storage did not occur at the most comfortable stiffness level*

Acknowledgments

The authors would like to thank Graci Finco for fitting the prosthesis, and Alejandro Azocar and Matthew Major for discussions regarding experimental design

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Type of Gait Alters Ankle Joint Mechanical Impedance

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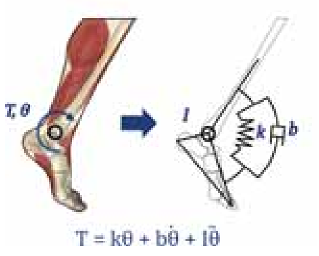
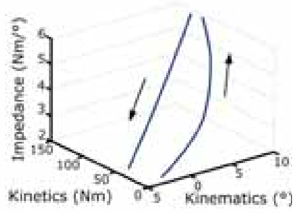
Introduction

Significance

- Walking and jogging differ in kinetics and kinematics
- Joint impedance plays an important role in the biomechanics of gait
- Unknown how ankle impedance differs between ambulatory tasks
- Facilitate the design of versatile biomimetic assistive technology



$T = k\theta + b\dot{\theta} + I\ddot{\theta}$

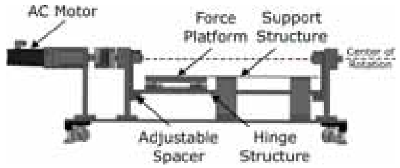


Purpose

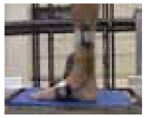
- Estimate ankle impedance during stance phase of jogging
- Evaluate differences in impedance between walking and jogging

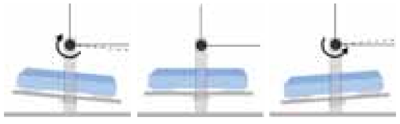
Methods

Frontal Plane View



Sagittal Plane View





2◦ Dorsiflexion

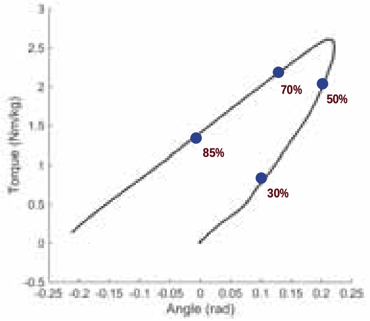
2◦ Plantarflexion

Experimental

- 5 able-bodied subjects
- Jog at 135 and 140 steps/min
- Perturbations at 30%, 50%, 70%, and 85%
- PF and DF perturbations occur with equal probability

Analytical

- Resolve GRF to equivalent torque at the ankle's center of rotation
- Multi-segment biomechanical model of the foot accounts for heel rise
- Least-squares system ID on a 2nd order parametric model estimates ankle impedance

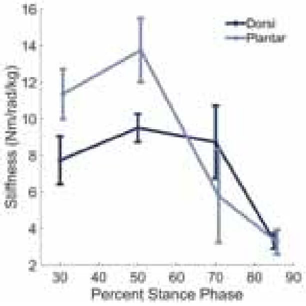


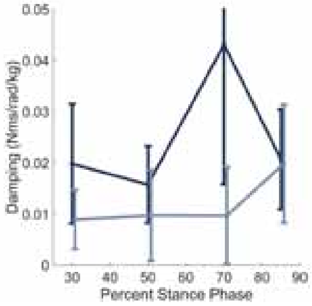
$$T = F_z\delta_x + F_x\delta_z$$

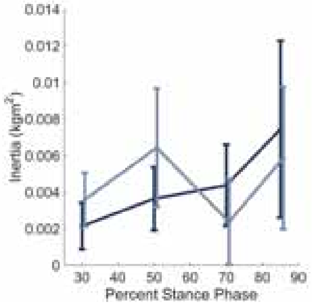
$$T_p = I_{tot}\ddot{\theta}_p + b_a\dot{\theta}_p + k_a\theta_p$$

Results

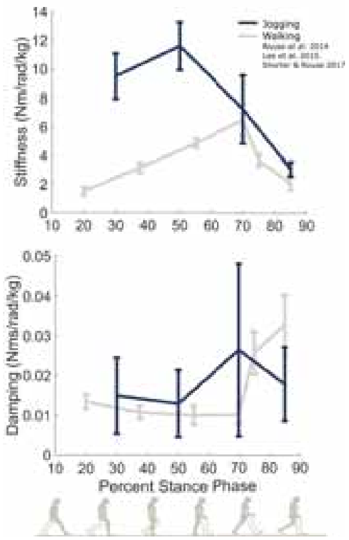
- Ankle stiffness increases throughout early-mid stance, and decreases during terminal stance phase
- Ankle viscosity differs across subjects as denoted by large inter-subject variability
- Inertia values similar to reported values of inertia of the foot in literature







Discussion



Impedance Across the Gait Cycle

- Stiffness corresponds with muscle activation, generated torque, and degree of dorsiflexion
- Trend towards increased damping prior to toe-off

Walking vs. Jogging

- Stiffness during jogging is increased during early –mid stance phase
  - › *Corresponds with increased muscle activation during jogging*
- Stiffness in terminal stance of jogging and walking follow similar trends
- Damping across the stance phase consistent between jogging and walking

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Mechanical Power and Work Profiles During Sprinting in Transfemoral Amputees

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INTRODUCTION

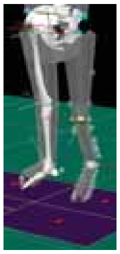
Running-specific prostheses (RSPs) can supplement movement via elastic energy storage and return.

Sprinters with unilateral transfemoral amputation using RSPs have impaired force production in the prosthetic limb compared to the sound limb [1].

It is currently unclear how the asymmetrical force production in unilateral transfemoral amputees influences the mechanical work profiles between the limbs.

METHODS

Sprinters with Unilateral Transfemoral Amputation (N = 10)
Body mass: 55.3 ± 10.3 kg
Height: 1.61 ± 0.11 meters



Same prosthetic knee and RSP for all sprinters:
3S80, hydraulic knee joint; Ottobock
RSP: Sprinter 1E90; Ottobock

Biomechanical Analyses during Maximal Sprinting
Power and work done by hip, knee, and below-knee structures [2]

PURPOSE: To quantify mechanical power/work during sprinting in unilateral transfemoral amputees

RESULTS/CONCLUSIONS

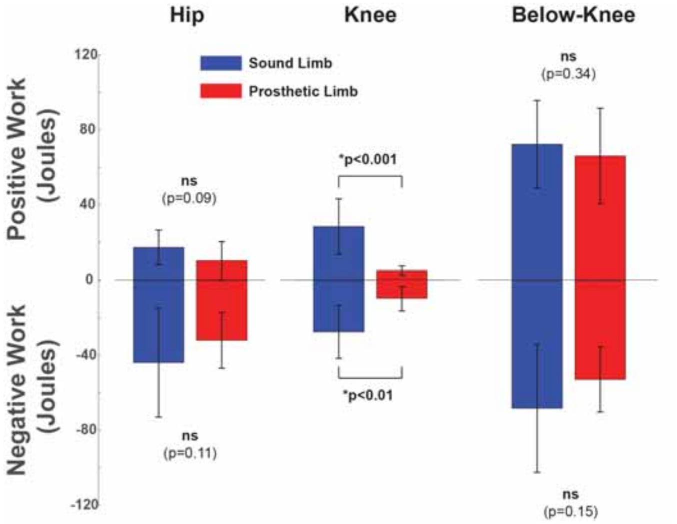


Figure 1: Stance Phase Mechanical Work (N=10).

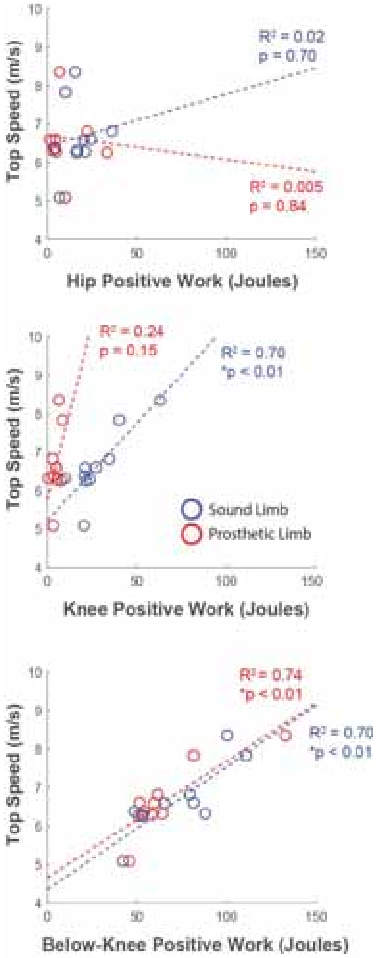
***The knee joint produced less work (positive and negative) in the prosthetic limb relative to the sound limb. No significant differences were found in the hip joint and below-knee structures between the sound and the prosthetic limbs.**

***Despite asymmetrical force production in unilateral transfemoral amputees [1], RSPs can produce nearly symmetrical mechanical work below the knee during sprinting.**

References:
[1] Makimoto et al. Journal of Applied Biomechanics 33, 406-409, 2018.
[2] Ray et al. Journal of NeuroEngineering and Rehabilitation 15, 6, 2018.

Figure 2: Relationship between positive work done by hip, knee, and below-knee structures and maximal sprinting speed in unilateral transfemoral amputees (N=10).

***Increase in positive work production from sound knee joint and below-knee structures (both prosthetic and sound limbs) are correlated with faster maximal speed.**



This work was supported by the Center for Research in Human Movement Variability of University of Nebraska at Omaha, NIH (P20GM109090).

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