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Log # BA180043

**TITLE:** Evaluating Mobility Interventions in the Real World

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**CONTRACTING ORGANIZATION:**  
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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>  Interventions for mobility disorders include many products and rehabilitation strategies, but there is little sound information about how different treatment options affect individuals' movement in their daily lives. We propose to develop new methods to assess the clinical effectiveness of these interventions using movement data from wearable sensors during everyday life. We hypothesize that frequently-repeated locomotion, such as walking the same paths daily near the home or in the workplace, are highly repeatable as in laboratory studies, but with greater ecological validity. We propose to compare the effects of different prostheses on these repeated movements using wearable sensor data such as foot movement and limb load. In the current reporting period, efforts at the University of Wisconsin focused on developing the sensor systems and data analysis methods. Efforts at subcontractor Walter Reed NMMC focused on protocol development and regulatory procedures, to begin study activities in year 2.					
<b>15. SUBJECT TERMS</b>  NONE LISTED					
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**1. INTRODUCTION:** *Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.*

Interventions for neuromusculoskeletal mobility disorders include many products and rehabilitation strategies, but there is little sound information about how different treatment options affect individuals' movement in their daily lives. In this project, we will evaluate mobility outcomes among individuals with a unilateral transtibial amputation, with particular emphasis on wearable sensors, to compare outcomes between daily-use and activity-specific prostheses in both short-term field testing (in-lab portion) and longer-term real-world locomotion testing (take-home portion). Incorporating both in- and out-of-the-lab measurements will provide a better understanding of the underlying environmental and behavioral influences on device- and activity-specific factors that collectively contribute to mobility outcomes. Such an understanding is especially important for Service Members with limb loss, who are generally high functioning, participate in a variety of activities, and often own/use multiple prosthetic devices. It is anticipated that data obtained in real-world environments will enhance ecological validity, and ultimately help drive future prescription practices for optimal functional performance, social/occupational integration, and quality of life.

**2. KEYWORDS:** *Provide a brief list of keywords (limit to 20 words).*

Limb loss; mobility; prosthesis; wearable sensor;

3. **ACCOMPLISHMENTS:** *The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency grants official whenever there are significant changes in the project or its direction.*

**What were the major goals of the project?**

*List the major goals of the project as stated in the approved SOW. If the application listed milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.*

Goal	Timeline (mo.)	Status
<b>Major Task 1:</b> IRB and HRPO Human Subjects Approval	1-6	IRB approved for UW. HRPO approved for UW. IRB/HRPO apps approved at WRNMMC
<b>Major Task 2:</b> Specify and acquire custom sensors	1-15	Sensors working. Continuous revision of packaging.
<b>Major Task 3:</b> Improve BD2SD and gait analysis from wearable data.	12-30	Improved motion reconstruction incl. alignment techniques. Ongoing.
<b>Major Task 4:</b> Test 10 Subjects using four prostheses.	12-30	Revised in October 2020. Delayed due to COVID-19. Planning to start Y3Q1.
<b>Major Task 4b:</b> Test 10 subjects using two orthotic solutions for foot-drop.	12-30	Revised in October 2020. Delayed due to COVID-19. Recruitment began 2021-06.
<b>Major Task 5:</b> Test 15 prosthesis users with daily-use, running-specific, and activity-specific prostheses.	15-36	Revised in October 2020. Delayed due to COVID-19. Starting in August 2021 (Y3Q1).

**What was accomplished under these goals?**

*For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results or key outcomes, including major findings, developments, or conclusions (both positive and negative); and/or 4) other achievements. Include a discussion of stated goals not met. Description shall include pertinent data and graphs in sufficient detail to explain any significant results achieved. A succinct description of the methodology used shall be provided. As the project progresses to completion, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.*

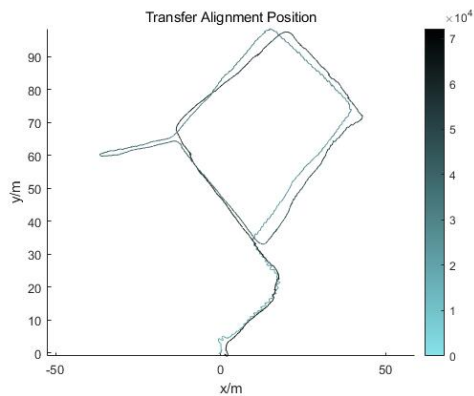
The major activities and associated accomplishments were:

**1. Objective: receive Human Subjects Approval.**

- a. All sites and branches of the study have received approval for Human Subjects testing.

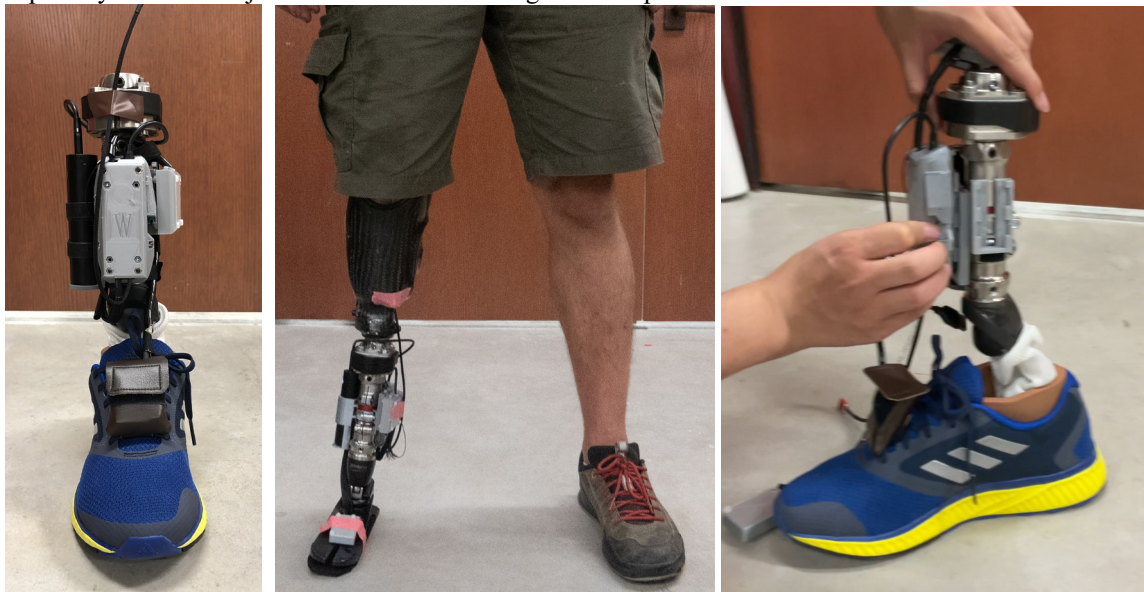
**2. Objective: Develop sensor systems and Analysis methods.**

- a. Goal: Finalize the software to log and synchronize data from the multiple sensors. Multiple IMUs, RTK-GPS and normal GPS, environmental sensors.
  - i. Result: Complete. Continuous revisions are being made for efficient operation, flexibility, compactness, etc..
  - ii. Many modifications have taken place to make the sampling robust and efficient (minimizing computational power and energy use).
- b. Incorporate the new information into the Kalman Filter used for determining user location.
  - i. Result: Kalman Filter for sensor fusion has been revised, with improvements continuing. Recent efforts have focused on cross-updating the compact and high-range but-drift-prone IMUs on most segments with the low-range but highly stable IMU on the shank (Figure shows an example reconstructed path). This approach is different from past transfer alignment techniques and requires modified mathematical techniques. Additional efforts have focused on fusion of GPS and IMU data and on detecting when GPS data is good.

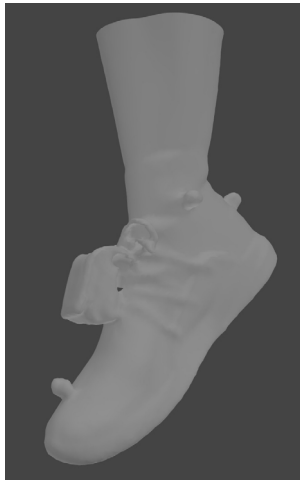


**c. Develop mounting hardware for prostheses and orthoses**

- i. Result: Several revisions of sensor mounts for a prosthetic pylon have been designed, with easy clip-in/clip-out capability to allow subjects to switch them among different prostheses.



- i. Result: Multiple variations of prosthesis mounts are under development to accommodate prostheses of different types such as blade-shaped prostheses or long residual limbs (mounting to socket instead of pylon). Example clip-in
- ii. Result: Some of the key outcomes we seek to study involve estimating ground clearance during walking, and to get this measurement we need to know how the sensor location relates to the geometry of the foot and shoe. We have tested several means of 3D-scanning a leg (prosthetic or orthotic – see Figure) to determine these locations accurately, and are finalizing the equipment and procedure needed to implement this step in all branches of the study. The solution will likely use a Structure Pro 3D scanner with follow-up in 3D meshing/solid modeling software.



### 3. Objective: Mechanical tests of prostheses.

- a. Mechanical testing of prostheses is important for describing the systems used in human subjects testing. UW staff are adapting the procedures in the 2010 AOPA Report (which specifies these tests) to the mechanical testing equipment available.
  - i. Status: This part of the project has been much delayed. We have finally been able to confirm a specific manufacturer (Freedom Innovations, Proteor branch); though their operations are still recovering from COVID. Mechanical testing will resume when the prosthetics tests at UW-Madison begin, likely Y3Q1.

### 4. Objective: Prosthetics and orthotics tests at UW-Madison

- a. UW-Madison has specified the experimental protocols for full multiple-week take-home testing of prostheses and orthoses.
  - i. Status: Freedom Innovations will supply prostheses for the project, consistent with earlier decisions on a preferred product line. We have consulted with a preliminary test subject about use of the sensor systems for prosthetics, and have continued refining them.
  - ii. Status: The Orthotics test (AFO vs. FES dorsiflexor stimulator) has begun recruitment. For the Orthotics test we are focusing on a population with drop-foot as a consequence of Multiple Sclerosis, as a readily available group in Madison. The study should continue throughout the Summer and Fall.
  - iii. Status: Data collection tools to manage the long-term, take-home studies (both Prosthetics and Orthotics, at both sites) are under development in REDCap HIPAA-compliant study software hosted at UW-Madison. For the Orthotics study this is complete and operational. It is currently being converted into a version for the Prosthetics study for use in the tests that will begin in August 2021.

**5. Objective: Tests of multiple customary prostheses at WRNMMC**

- a. Following the October 2020 revised protocol, WRNMMC is specified to run tests in which the same sensors are attached to multiple prostheses used by specific individuals, to track which is used for different activities and measure characteristics of those movements in detail.
  - i. Status: WRNMMC and UW teams will launch the first test subjects in August 2021 at WRNMMC.
  - ii. Status: REDCap conversion for prosthetics will include a form for logging prosthesis usage through a smartphone, to improve the accuracy and precision of prosthesis usage, activity, and event logs.

**What opportunities for training and professional development has the project provided?**

*If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. “Training” activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. “Professional development” activities result in increased knowledge or skill in one’s area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.*

**Training:**

Two graduate students – K. Heidi Fehr and Yisen Wang – had substantial one-on-one mentoring with Prof. Adamczyk on all the research methods as they developed the analysis and sensor systems. They also had interaction with the Prosthetics and Orthotics team at UW-Madison.

Another graduate student, Jennifer Bartloff, joined Ms. Fehr and Mr. Wang in refining the protocols for the Orthotics study and advancing it to the point of recruitment.

Another graduate student, Jingjun Liu, worked remotely on gait classification using the wearable sensors. He was not funded by this project, but worked on this related area.

One undergraduate student, Katherine Konieczka, has led the REDCap implementation and helped with 3D scanning and other logistical questions.

**Professional Development:**

Ms. Fehr and Mr. Wang both participated in the Dynamic Walking 2021 conference and have Abstracts accepted at the American Society of Biomechanics 2021 conference. Ms Fehr also has an Abstract in MHSRS 2021. These are opportunities to show their progress and receive feedback from other experts.

**How were the results disseminated to communities of interest?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe how the results were disseminated to communities of interest. Include any outreach activities that were undertaken to reach members of communities who are not usually aware of these project activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.*

Updated progress on Sensors and Analysis methods were put into the various conference Abstracts shown/to be shown in Summer 2021 (see previous box, and attachments).

Ms. Fehr is middle-author on a manuscript (currently in review) about a new way of using wearable sensor measurements to measure and potentially control DMAMA (dynamic mean ankle moment arm) in semi-active prostheses.

**What do you plan to do during the next reporting period to accomplish the goals?**

*If this is the final report, state "Nothing to Report."*

*Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.*

In Year 3 we plan the following steps:

UW-Madison:

- Enrollment of Orthosis users for 10-subject pilot test
- Enrollment of prosthesis users for 10-subject pilot test
- Mechanical testing of prostheses to correlate outcomes with properties.
- Ongoing improvement of Big Data to Small Data analysis methods.

Walter Reed NMMC:

- Execute 15-subject test of multiple prostheses in a month of daily-life usage.

**4. IMPACT:** Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

**What was the impact on the development of the principal discipline(s) of the project?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).*

The sensor system developed in Y1-2 will enable studies of prostheses and orthoses in Y3+ as specified in the plan. We are planning a paper on the sensor system itself (component choice, design, usage) that will inform others how to do long-term wearable recording studies similar to those we have planned. The techniques for analysis of biomechanics from wearable sensors, and the results of preliminary testing that are currently in review and in manuscript preparation, will inform the field about how to make such measurements and about the impact of specific prosthesis parameters (forefoot stiffness) across varied terrain.

**What was the impact on other disciplines?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.*

Nothing to report.

**What was the impact on technology transfer?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:*

- *transfer of results to entities in government or industry;*
- *instances where the research has led to the initiation of a start-up company; or*
- *adoption of new practices.*

**What was the impact on society beyond science and technology?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:*

- *improving public knowledge, attitudes, skills, and abilities;*
- *changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*

Nothing to report

- *improving social, economic, civic, or environmental conditions.*

5. **CHANGES/PROBLEMS:** *The PD/PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency grants official whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following additional information or state, "Nothing to Report," if applicable:*

**Changes in approach and reasons for change**

*Describe any changes in approach during the reporting period and reasons for these changes.*

The Orthotics study was focused on Multiple Sclerosis to reduce variability relative to the broad population of Orthosis users, and because these subjects are reasonably available at UW-Madison.

Formal changes were approved to change the WRNMMC protocol to focus on the multiple prostheses used by an individual, to include both biomechanics and use pattern information.

*Remember that significant changes in objectives and scope require prior approval of the agency.*

**Actual or anticipated problems or delays and actions or plans to resolve them**

*Describe problems or delays encountered during the reporting period and actions or plans to resolve them.*

COVID-19 disrupted the progress toward human subjects testing for a long time. Both sites were shut down, supply chains were disrupted, and everyone had to scramble trying to deal with it in many ways. All branches of the project are getting back up to speed, and at least two of three branches will be enrolling by the end of summer 2021.

Supplier for Europa+ Smart Pyramids has run out of stock and the item is on backorder. Lead time is currently unknown. We have two copies now (acquired for development and testing) and will deploy these for the WRNMMC portion of the study. UW portion could be delayed to acquire the rest.

**Changes that had a significant impact on expenditures**

*Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.*

All spending on human subjects and prosthetic/orthotic hardware was delayed. This will pick up as the studies are launched.

Spending at WRNMMC was delayed but will pick up with study enrollment.

**Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents**

*Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.*

**Significant changes in use or care of human subjects**

Human subjects testing/enrollment were delayed, but plans have not changed and risks/benefits have not changed.

**Significant changes in use or care of vertebrate animals**

Nothing to report.

**Significant changes in use of biohazards and/or select agents**

Nothing to report

6. **PRODUCTS:** *List any products resulting from the project during the reporting period. If there is nothing to report under a particular item, state “Nothing to Report.”*

- **Publications, conference papers, and presentations**

*Report only the major publication(s) resulting from the work under this award.*

**Journal publications.** *List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Identify for each publication: Author(s); title; journal; volume: year; page numbers; status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

No major publications in Y2.

We have a manuscript “in review” on analysis methods using wearable sensors in prosthetics.

Leestma JK, Fehr KF, Adamczyk PG (*In review*). Adapting semi-active prostheses to real-world movements: controlling dynamic mean ankle moment arm with a variable-stiffness foot on ramps and stairs. Submitted to *Sensors*. *Acknowledgement of federal support: yes.*

Ms Fehr is also working to complete a manuscript on an able-bodied data set that will underpin prosthesis control laws based on wearable sensor data (characterizing DMAMA across speeds, slopes and stairs in unimpaired persons).

Mr. Wang is planning a Tech Note about the sensor systems and their special use case in this project.

**Books or other non-periodical, one-time publications.** *Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (e.g., book, thesis or dissertation); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Nothing to report

**Other publications, conference papers and presentations.** *Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication as noted above. List presentations made during the last year (international, national, local societies, military meetings, etc.). Use an asterisk (\*) if presentation produced a manuscript.*

Conference presentations:

*These conference abstracts/posters covered an analysis using wearable sensors in prosthetics and able-bodied persons and an exploratory extension to convert these analyses into a biomimetic control law:*

Fehr KH, Kent JA, Leestma JK, Nakum J, Major MA, **Adamczyk PG** (2021). A biomimetic prosthetic ankle control law for a variable stiffness prosthetic foot using dynamic mean ankle moment arm. *Military Health Sciences Research Symposium 2021*, August 23-26, Orlando, FL, USA.

Fehr KH, Kent JA, Nakum J, Major MA, **Adamczyk PG** (2021). The effect of walking speed, slopes and stairs on dynamic mean ankle moment arm. *American Society of Biomechanics 2021*, Aug 12-15, Online meeting.

Fehr KH, Kent JA, Leestma JK, Nakum J, Major MA, **Adamczyk PG** (2021). Using dynamic mean ankle moment arm to generate a biomimetic prosthetic ankle control law. *Dynamic Walking 2021*, May 20, Online meeting.

*These posters covered our development of a sensor suite customized for studies of long-term real-world use of prostheses:*

Wang Y, Ojeda LV, **Adamczyk PG** (2021). Wearable Sensor Suite for Long-term Wearable Real-World Tracing. *American Society of Biomechanics 2021*, Aug 12-15, Online meeting.

Wang Y, Ojeda LV, **Adamczyk PG** (2021). Long-term Wearable Real-World Tracking using Wearable Sensors. *Dynamic Walking 2021*, May 20, Online meeting.

- **Website(s) or other Internet site(s)**

*List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified above in this section.*

Nothing to report.

- **Technologies or techniques**

*Identify technologies or techniques that resulted from the research activities. Describe the technologies or techniques were shared.*

Nothing to report in this project year.

**Inventions, patent applications, and/or licenses**

*Identify inventions, patent applications with date, and/or licenses that have resulted from the research. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.*

Nothing to report

- **Other Products**

*Identify any other reportable outcomes that were developed under this project. Reportable outcomes are defined as a research result that is or relates to a product, scientific advance, or research tool that makes a meaningful contribution toward the understanding, prevention, diagnosis, prognosis, treatment and /or rehabilitation of a disease, injury or condition, or to improve the quality of life. Examples include:*

- *data or databases;*

- *physical collections;*
- *audio or video products;*
- *software;*
- *models;*
- *educational aids or curricula;*
- *instruments or equipment;*
- *research material (e.g., Germplasm; cell lines, DNA probes, animal models);*
- *clinical interventions;*
- *new business creation; and*
- *other.*

Nothing to report.

## 7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

### What individuals have worked on the project?

Provide the following information for: (1) PDs/PIs; and (2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort). If information is unchanged from a previous submission, provide the name only and indicate “no change”.

<i>Name:</i>	<i>Peter Adamczyk</i>
<i>Project Role:</i>	<i>PI</i>
<i>Researcher Identifier (ORCID):</i>	<i>0000-0001-5374-7691</i>
<i>Nearest person month worked:</i>	<i>1</i>
<i>Contribution to Project:</i>	<i>Dr. Adamczyk worked to manage the sensor systems development, direct the biomechanical analysis with wearable sensors, negotiate the supply of prostheses and orthoses, and adjust the aims and objectives to recover from COVID.</i>
<i>Name:</i>	<i>Katherine Heidi Fehr</i>
<i>Project Role:</i>	<i>Graduate Student</i>
<i>Researcher Identifier (ORCID):</i>	<i>none</i>
<i>Nearest person month worked:</i>	<i>6</i>
<i>Contribution to Project:</i>	<i>Ms. Fehr worked to prepare biomechanical analysis of movement based on wearable sensor data, and to prepare detailed experimental protocols, manuals, subject materials, etc. for the testing.</i>
<i>Name:</i>	<i>Yisen Wang</i>
<i>Project Role:</i>	<i>Graduate Student</i>
<i>Researcher Identifier (ORCID):</i>	<i>none</i>
<i>Nearest person month worked:</i>	<i>6</i>
<i>Contribution to Project:</i>	<i>Mr. Wang worked to program the sensor suit and package it for prosthetic and orthotic applications. He has also worked on sensor fusion algorithms and Kalman filtering.</i>

*Name:* Jennifer Bartloff  
*Project Role:* Graduate Student  
*Researcher Identifier (ORCID):* none  
*Nearest person month worked:* 1  
*Contribution to Project:* Ms. Bartloff worked to prepare the Orthotics test, including specifying detailed recruitment criteria and protocols for persons with Multiple Sclerosis.

*Name:* Katherine Konieczka  
*Project Role:* Undergraduate Student  
*Researcher Identifier (ORCID):* none  
*Nearest person month worked:* 1  
*Contribution to Project:* Ms. Konieczka worked to set up REDCap survey tools to enable secure and HIPAA compliant online data collection, and to prepare for the Orthotics testing.

**Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.*

PI has acquired three other active grants, but these have not affected the availability of time to dedicate to this project.

Wearable Shear Wave Tensiometry for Tracking Tendon Load During Dynamic Movement

Capacity: Contact PI (Co-PI: D. Thelen)

Sponsor: NIH Phase II STT), R42AR07489

Dates: 2020-2022

DOD RESTORE: Multi-Axis Prosthesis Control Through an Osseointegrated Neural Interface

Capacity: PI

Sponsor: US Department of Defense, W81XWH-20-1-0884

DOD RESTORE: Objective Assessment of Functional Muscle-Tendon Behavior for Enhancing the Diagnosis and Treatment of Tendon Pathologies

Capacity: Co-Investigator (PI: D. Thelen)

Sponsor: US Department of Defense, W81XWH-21-2-0006

**What other organizations were involved as partners?**

*If there is nothing significant to report during this reporting period, state “Nothing to Report.”*

*Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.*

*Provide the following information for each partnership:*

Organization Name:

Location of Organization: (if foreign location list country)

Partner’s contribution to the project (identify one or more)

- *Financial support;*
- *In-kind support (e.g., partner makes software, computers, equipment, etc.,*

- *available to project staff);*
- *Facilities (e.g., project staff use the partner's facilities for project activities);*
- *Collaboration (e.g., partner's staff work with project staff on the project);*
- *Personnel exchanges (e.g., project staff and/or partner's staff use each other's facilities, work at each other's site); and*
- *Other.*

Organization Name: Navigation Solutions, LLC

Location of Organization: Ann Arbor, MI, USA

Partner's contribution to the project: Collaboration (partner makes the motion sensor systems used in this research).

Organization Name: Orthocare Innovations, LLC

Location of Organization: Edmonds, WA, USA

Partner's contribution to the project: Collaboration (partner makes the prosthetic pylon load sensor used in this research).

Organization Name: Walter Reed National Military Medical Center

Location of Organization: Bethesda, MD, USA

Partner's contribution to the project: Collaboration (partner will perform human subjects testing for part of this research).

## 8. SPECIAL REPORTING REQUIREMENTS

**COLLABORATIVE AWARDS:** *For collaborative awards, independent reports are required from BOTH the Initiating Principal Investigator (PI) and the Collaborating/Partnering PI. A duplicative report is acceptable; however, tasks shall be clearly marked with the responsible PI and research site. A report shall be submitted to <https://ers.amedd.army.mil> for each unique award.*

**QUAD CHARTS:** *If applicable, the Quad Chart (available on <https://www.usamraa.army.mil>) should be updated and submitted with attachments.*

- 9. APPENDICES:** *Attach all appendices that contain information that supplements, clarifies or supports the text. Examples include original copies of journal articles, reprints of manuscripts and abstracts, a curriculum vitae, patent applications, study questionnaires, and surveys, etc.*

Appendices attached:

- a) Abstract reprint: Fehr et al. *Dynamic Walking 2021*
- b) Abstract reprint: Fehr et al. *American Society of Biomechanics 2021*
- c) Abstract reprint: Fehr et al. *MHSRS 2021*
- d) Abstract reprint: Wang et al. *Dynamic Walking 2021*
- e) Abstract reprint: Wang et al. *American Society of Biomechanics 2021*

# Using dynamic mean ankle moment arm to generate a biomimetic prosthetic ankle control law

Katherine Heidi Fehr<sup>1\*</sup>, Jenny A. Kent<sup>2</sup>, Jennifer K. Leestma<sup>1,3</sup>, Jasmine Nakum<sup>1</sup>, Matthew J. Major<sup>2,4</sup>, and Peter Gabriel Adamczyk<sup>1</sup>

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## I. INTRODUCTION

Individuals actively regulate foot and ankle biomechanical properties—such as angular impedance [1]—when walking on inclines. This regulation presents challenges for lower limb prostheses, which aim to replace natural limb function with a synthetic alternative. In this work, we propose a prosthesis control law that varies the stiffness of a prosthetic forefoot keel to mimic the variations in dynamic mean ankle moment arm (DMAMA) [1] observed in unimpaired individuals. DMAMA is a summative measure that describes the ankle’s control of the location of force interaction with the ground in a single value that is sensitive to walking/running speed, ground slope, and ascent/descent in stairs [1], [2]. Having a single measure per stance makes DMAMA a useful target for semi-active prostheses that adjust only once per stride.

## II. METHODS

We used results from two studies, one including four adults with transtibial amputation (TTA) [2] and the other including ten unimpaired (UI) adults [3]. In both studies, participants traversed three different terrains at self-selected walking speeds: overground, a five-degree incline, and a five-degree decline. Participants with TTA used a pylon-embedded load cell, full-body suit of inertial measurement units, and a Variable Stiffness Foot (VSF) [4]. These individuals walked an indoor circuit three times, each with a different forefoot stiffness condition that was normalized across the participant’s total possible stiffness range—representing the Low stiffness as -0.5 (-50%), Medium as 0, and High as 0.5 (+50%). UI participants performed their trials in a motion capture laboratory using surface-embedded force plates and a 12-camera motion capture system.

To find the relationship between DMAMA, ground incline, and prosthetic forefoot stiffness, we computed a mixed multiple linear regression with incline, stiffness, and incline-times-stiffness interaction terms. To account for intersubject variability, we set the subjects as a random effect and ground incline and stiffness as fixed effects. For the UI data set, we fit a mixed linear least-squares regression, where the subjects were a random effect and ground incline was a fixed effect.

## III. RESULTS

In the TTA group, we found that as incline and stiffness increased, DMAMA shifted forward (Fig. 1b). The interaction coefficient’s negative sign demonstrates that the sensitivity of DMAMA to either fixed effect reduces at higher values of the other (Fig. 1b). In the UI group, we also found a significant shift forward in DMAMA as incline increased (Fig. 1a).

Combining the findings from both studies, we generated a control law (Fig. 1c) that suggests that to mimic an unimpaired human ankle, the prosthetic keel stiffness should be decreased when ascending a ramp and increased when descending a ramp. This law can be used in the design and control of future prostheses with adaptive forefoot stiffness. Using onboard sensors, the prosthetic foot could detect ground incline, or even estimate DMAMA continuously, and adjust the stiffness during swing phase.

## IV. REFERENCES

- [1] Adamczyk, *J. Biomech Eng.* 142, (2020)
- [2] Leestma, et al., *J. Biomech Eng.*, (In review)
- [3] Fehr, et al., 45th Meeting ASB 2021, (In review)
- [4] Glanzler, et al., *IEEE Trans. Neural Syst. Rehabil. Eng.* 26, (2018)

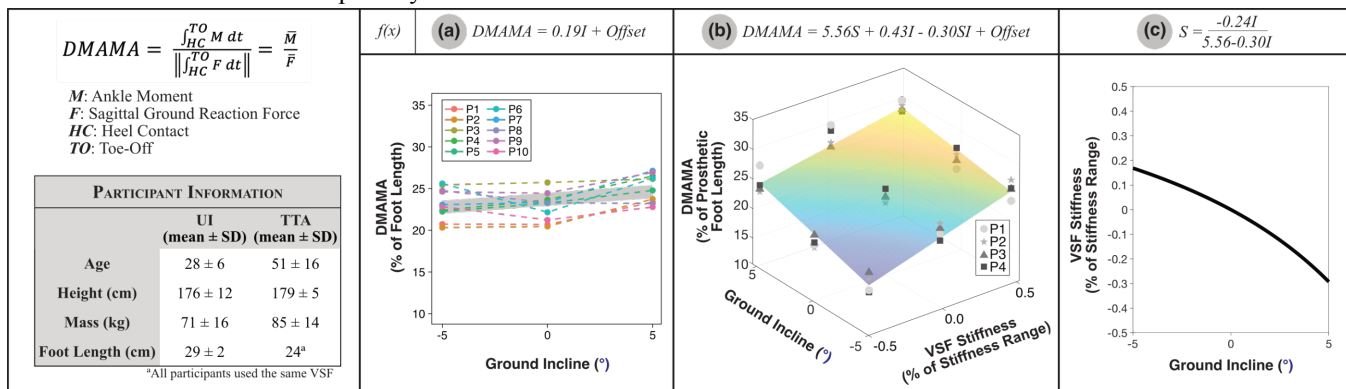


Fig. 1. Results from (a) UI participants,  $f(x)$  and corresponding thick grey line represents the sensitivity of DMAMA to degree of ground incline ( $I$ ), (b) TTA where  $f(x)$  and corresponding multicolored plane represents the multivariate regression with incline ( $I$ ), stiffness ( $S$ ), and incline-times-stiffness interaction terms, and (c) the bio-inspired control law where VSF stiffness ( $S$ ) is the suggested stiffness change (% individual stiffness range, with min: -50% and max: 50%) per degree of ground incline.

# THE EFFECT OF WALKING SPEED, SLOPES, AND STAIRS ON DYNAMIC MEAN ANKLE MOMENT ARM

Katherine Heidi Fehr<sup>1\*</sup>, Jenny A. Kent<sup>2</sup>, Jasmine Nakum<sup>1</sup>, Matthew J. Major<sup>2,3</sup>, and Peter Gabriel Adamczyk<sup>1</sup>

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## Introduction

Understanding the control mechanism of the human foot-ankle complex can inform the design of novel foot prostheses. To improve the adaptation of these designs to different activities such as ramp and stair descent, it is important to observe the way ankle control changes in a non-impaired human limb. In this study, we observe the changes in dynamic mean ankle moment arm (DMAMA) [1] when performing different activities. DMAMA describes the way the ankle controls the location of force interaction with the ground (moment arm). This summative measure accounts for temporal, spatial, and directional variations in the applied force in a single value. This makes DMAMA a useful target measure for semi-active prostheses that adjust only once per stride.

## Methods

Eight unimpaired adults (age: 30±6 years; mass: 65±13 kg; foot length: 28±2 cm; mean ± SD) provided written informed consent to participate in this study. Participants performed at least 8 trials of each of the 7 activities. Walking speeds were self-selected. Kinematics were collected using a 12-camera motion capture system and ground reaction forces using multiple force plates: 6 embedded in a level walkway, 2 in a 5° incline ramp, and a force plate stairway with 3 steps, the last step forming a part of the top platform.

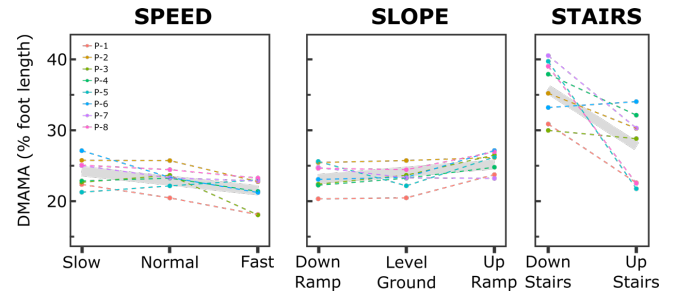
We used Visual3D (C-Motion, Inc.) to filter the force and kinematic data, determine foot contact with force plates, and calculate ankle moment and ground reaction force/moment. We used a custom MATLAB script to determine heel contact (HC) and toe-off (TO) and calculate DMAMA during stance phase according to Equation 1 where  $M$  is the ankle moment and  $F$  is the sagittal ground reaction force [1]. DMAMA values were subsequently normalized to participant foot length.

$$DMAMA = \frac{\int_{HC}^{TO} M dt}{\left\| \int_{HC}^{TO} F dt \right\|} = \frac{\bar{M}}{\bar{F}} \quad (1)$$

To assess the difference in DMAMA across different activities, we fit a linear mixed model (LMM) to the means of each subject's DMAMA for each category: speed, slope, and stairs. We included DMAMA as the dependent variable, the activities as the fixed effects and the participant as a random effect. We define sensitivity in table 1 as the regression coefficient from this LMM and each change in activity corresponds to an increment of one (e.g., for speed: slow (-1), normal (0), fast (1)). Critical  $\alpha$  was set to  $p < 0.05$ .

## Results and Discussion

As walking speed increased, DMAMA decreased as shown in figure 1 and table 1. This result matches previous work by Adamczyk [1], who also found that DMAMA tended to move towards the heel (decrease) as walking speed increased. Higher DMAMA at slower walking speeds may be due to an increased plantar flexor moment attempting to slow the body's progression [2]. We observed an even sharper decrease in DMAMA when participants ascended stairs versus descended them.



**Figure 1:** Trends in DMAMA across activities. The thick grey lines show the subject-independent data fit as a result of the linear mixed model. Colored markers connected by dashed lines represent each participant's average in the different categories.

Table 1. Subject-independent regression – LMM			
Fixed Effect	Sensitivity (DMAMA per increment)	p-value	R <sup>2</sup>
Walking Speed	-1.34	0.002	0.49
Slope	+1.01	0.010	0.60
Stairs	-8.00	0.003	0.46

Table 2. Mean DMAMA (% foot length) by Activity			
Activity	Mean ± SD	Activity	Mean ± SD
LG Walking:		Down Ramp (-5°)	23.6 ± 2.60
Slow	23.9 ± 2.85	Up Ramp (5°)	25.5 ± 2.20
Normal	23.3 ± 2.28	Up Stairs	27.8 ± 5.48
Fast	21.1 ± 2.54	Down Stairs	35.9 ± 4.99

As the ground incline changed from negative to positive, we observed a significant shift forward in DMAMA. This is consistent with prior work by Leestma et al. [3] who showed a similar increase in DMAMA with increasing ground slope in participants with amputation using an experimental foot-ankle prosthesis. While the sensitivities in table 1 may appear small, DMAMA moving 1-8% foot length per increment, it is important to note that typical DMAMA values fall within a relatively narrow numerical range [1].

## Significance

The results of this study can be used to design more biomimetic assistive devices such as prostheses, exoskeletons and orthoses. Using approaches such as varying prosthetic keel stiffness to tune DMAMA, semi-active prostheses can alter the biomechanics of a person's gait [3]. Target DMAMA values, such as the ones presented in this work, could be used to inform the control algorithms of novel prostheses, allowing them to adapt to different activities. DMAMA could also be used as a performance metric in fully robotic devices to evaluate and adjust their continuous ankle torque controllers. Having the ability to adapt to different speeds and terrains may improve the experience of prostheses users, e.g., by reducing maladaptive socket torques.

## Acknowledgments

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- [3] Leestma, et al., *J. Biomech Eng.*, (In review)

\*Submission was copy & pasted into online form

### **Abstract Title**

A biomimetic control law for a variable stiffness prosthetic foot using dynamic mean ankle moment arm.

### **Authors**

**Katherine Heidi Fehr**<sup>1\*</sup>, Jenny A. Kent<sup>2</sup>, Jennifer K. Leestma<sup>1,3</sup>, Jasmine Nakum<sup>1</sup>, Matthew J. Major<sup>2,4</sup>, and Peter Gabriel Adamczyk<sup>1</sup>

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### **Abstract**

#### **BACKGROUND.**

When walking on inclines, individuals without lower-limb impairments actively regulate foot and ankle biomechanical properties such as angular impedance [1]. This regulation presents challenges for lower limb prostheses, which aim to replace natural limb function with an artificial alternative. Ankle-foot prostheses fall into three categories: passive, semi-active, or fully robotic. Passive prosthetic feet have a single stiffness profile, and therefore cannot actively adapt to different ground inclines, while fully robotic prosthetic feet can continuously adapt their properties during ground contact. However, fully robotic prostheses can be heavy and cost-prohibitive. An alternative that combines benefits of passive and fully robotic devices are semi-active prostheses; these devices can modulate the foot's mechanical properties, such as stiffness or ankle angle, providing adaptation without actively powering body movement, reducing added weight and cost in comparison to fully robotic devices.

To inform the control of semi-active prostheses, we propose a prosthesis control law that varies the stiffness of a prosthetic forefoot keel to mimic the variations in dynamic mean ankle moment arm (DMAMA) [1] observed in unimpaired individuals. DMAMA is a summative measure that describes the ankle's control of the location of force interaction with the ground in a single value. This computationally simple measure is sensitive to walking/running speed, ground slope, and ascent/descent in stairs [1], [2] making it appropriate to control the biomechanical properties of semi-active prostheses based on locomotion mode. Having a single measure per stance makes DMAMA a useful target for semi-active prostheses that adjust only once per stride.

#### **METHODS.**

We used results from two separate studies, one included four participants with transtibial amputation [2] and the other included eight unimpaired participants. In both studies, participants completed three different tasks at self-selected walking speeds: overground, a five-degree incline, and five-degree decline. All participants provided written informed consent to participate in this study.

Participants with transtibial amputation (age: 51±16 years; mass: 85±14 kg; height: 179±5 cm; mean ± SD) used a Variable Stiffness Foot (VSF) [3]. These participants wore a full-body suit of inertial measurement units (IMUs), which we used to identify locomotion mode (walking, ramp ascent/descent). They also wore a pylon-embedded load cell to collect approximations of ground reaction force and moments on the side of their amputation [4]. These participants walked over level ground and slopes in an indoor circuit once for each of three forefoot stiffness conditions. The 'Low' stiffness was determined based on the participant's body mass, ensuring that the prosthetic keel deflection did not reach its physical limit (VSF minimum possible stiffness: 11 N/mm). The 'High' stiffness was set to the VSF's maximum possible

stiffness (32 N/mm). The ‘Medium’ stiffness was set as the mean of the participant’s low and high stiffnesses. In our results, stiffnesses were normalized across participants by representing the Low stiffness as -0.5 (-50%), Medium as 0, and High as 0.5 (+50%). This allows the stiffness range to span 100% of each individual’s stiffness range.

Unimpaired participants (age: 30±6 years; mass: 65±13 kg; height: 174±11 cm; mean ± SD) performed their trials in a motion capture laboratory. Ground reaction forces were collected using walking surface-embedded force plates. Kinematics were collected using a 12-camera motion capture system.

In both studies, DMAMA was calculated as the ratio of mean sagittal ankle moment to the mean sagittal ground reaction force during each stance phase [1]. For each subject, DMAMA was normalized to the participant’s foot length. To find the relationship between DMAMA, ground incline, and prosthetic forefoot stiffness, we computed a mixed multiple linear regression with incline, stiffness, and incline-times-stiffness interaction terms. To account for intersubject variability, we set the subjects as a random effect and ground incline and stiffness as fixed effects. For the unimpaired data set, we fit a mixed linear least-squares regression, where the subjects were a random effect and ground incline was a fixed effect. Critical alpha was set at 0.05. Calculations were performed using custom MATLAB scripts.

## RESULTS.

In the group of participants with amputation using the VSF, the multivariate regression revealed positive coefficients for sensitivity to incline (coefficient: 5.56 percent foot length per degree incline, CI: ±1.45) and prosthetic forefoot stiffness (coefficient: 0.43 percent foot length per percent individual stiffness range, CI: ±0.15), and a negative sensitivity to their interaction (coefficient: -0.30, CI: ±0.35) [2]. That is, as incline and stiffness increased, DMAMA shifted forward. The interaction coefficient’s negative sign signifies that the sensitivity of DMAMA to either fixed effect reduces at higher values of the other. In the unimpaired group, we found a significant shift forward in DMAMA as the ground incline changed from negative to positive (coefficient: 0.20 percent foot length per degree incline) [5].

Combining the findings from both studies, we generated a bio-inspired control law that can be used to control stiffness in the VSF. We equated the regression found in the unimpaired study to that found in the VSF study and solved for suggested percent stiffness change. This was found to be  $S = (-0.22 * I) / (5.56 - 0.3 * I)$ , where  $S$  is the suggested stiffness change (% individual stiffness range, with a minimum and maximum of -50% and 50%, respectively) and  $I$  is ground incline (degrees). This suggests that the prosthetic keel stiffness should be decreased when walking up a ramp and increased when walking down a ramp to mimic an unimpaired human ankle. Using this control law, the VSF is able to adapt to 38 degree declines and 7.5 degrees inclines. Since ground inclines in a built environment are typically within 5 degrees of level and the +7.5 degree limit is perceived as fairly steep by an unimpaired individual, the VSF with this control law can adapt to a substantial range of terrains encountered in daily movement.

Limitations of this work include the low number of participants with an amputation and that only a single VSF was used, preventing us from matching the VSF forefoot length to the length of the participant’s intact foot. Additionally, trials were only conducted at three different VSF stiffness settings, this may obscure nuances in the narrower parts of the stiffness range. Differences in the equipment used in the two studies also limit the extent to which we can draw comparisons. Future work will implement and test the efficacy of the proposed control law.

## CONCLUSIONS.

The control law found in this comparative study can be used in the design and control of future prostheses with adaptive forefoot stiffness. Using onboard sensors, the prosthetic foot could detect ground incline, or even estimate DMAMA continuously, and adjust the stiffness during swing phase. This real-time adaptation to ground incline using a semi-active device may improve biomechanics in comparison to passive prostheses.

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- [5] K. H. Fehr, J. A. Kent, J. Nakum, M. J. Major, and P. G. Adamczyk, “The effect of walking speed, slopes, and stairs on dynamic mean ankle moment arm,” presented at the 45th Meeting of the American Society of Biomechanics, Virtual, 2021.

### **Abstract Disclaimer**

This work was funded by DOD Awards W81XWH1920024 & W81XWH1710427. The views expressed in this abstract are those of the author and do not reflect the official policy of the Department of Army/Navy/Air Force, Department of Defense, or U.S. Government.

### **Learning Objectives**

- Explain the use of dynamic mean ankle moment arm (DMAMA) as target measure for semi-active prostheses.
- Describe the relationship between dynamic mean ankle moment arm (DMAMA) and ground slope.
- Understand the process of developing a biomimetic control law for variable stiffness prostheses.

# Long-Term Real-World Tracking using Wearable Sensors

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**Abstract**—This abstract introduces a wearable sensor system aimed for long-term real-world tracking, including hardware design, software architecture and sensor fusion algorithm. We also demonstrate the reconstruction results of shank movement using transfer alignment techniques.

## I. INTRODUCTION

Biomechanics research can acquire more informative results using walking trajectory data collected from real-world settings, facilitating a scientific comparison of mobility intervention. The main challenge for personal dead-reckoning (PDR) system are the heading error in indoors due to inevitable bias of angular rate gyroscope data and a trade-off between portability and accuracy. To address these problems on top of our previous method<sup>[1]</sup>, we propose a wearable sensor system containing several types of sensors aimed for weeks-long real-world tracking. In this abstract, we also demonstrate transfer alignment techniques for the reconstruction of shank movement from inertial measurement unit (IMU) data, which requires alignment to foot IMU movement for reliable reconstruction.

## II. METHOD

### A. Sensor System

Five types of sensors are integrated into our sensor suite: 1) a high-accuracy IMU for mitigating heading drift, 2) 4 low-cost IMUs, including a Bluetooth Low Energy IMU, for reconstructing foot and leg motion, 3) RTK-GPS module for providing centimeter-level localization in outdoor environments, 4) an instrumented prosthetic pylon (Europa+ smart pyramid<sup>[5]</sup>) for collecting force data, 5) environmental sensor (temperature, barometric pressure, humidity) for distinguishing indoor vs outdoor. The total system is small enough to install on a prosthetic pylon with similar diameter to the natural leg and weight around 350g.

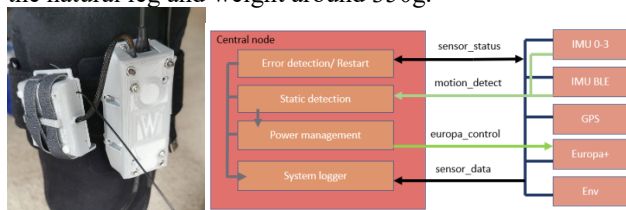


Fig1. a) sensor suite b) software architecture

The sensor system runs on a Raspberry Pi Zero W and utilizes Robot Operating System to manage and monitor all sensors. A central node coordinates data logging, error detection, synchronization and power management for other sensor nodes.

### B. Movement reconstruction

The main reconstruction task on the foot-mounted IMU is performed by an Error State Kalman Filter<sup>[2]</sup> using Zero Velocity Update (ZUPT)<sup>[3]</sup> constraints. Unlike foot-mounted IMUs, shank and knee IMUs cannot leverage the walking pattern during a gait cycle to reduce sensor drift and perform reconstruction reliably by themselves. However, we use the fact that these IMUs are moving together with the foot-mounted IMU to apply transfer alignment for heading angle. Position results generated by foot-mounted IMU are fed into a transfer alignment filter<sup>[4]</sup> as position observations to correct shank and thigh IMU data at every footfall. This process gradually aligns the shank and thigh IMUs with a global coordinate frame.

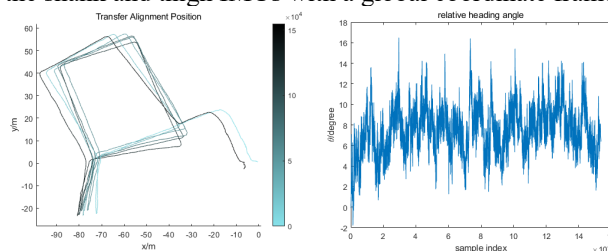


Fig2. A) transfer alignment results b) relative heading error

## III. RESULTS AND DISCUSSION

Fig. 2 demonstrates position reconstruction of a shank-mounted IMU during a 30-minute test on an intact subject, and convergence and bounded error of the shank's final heading with respect to a foot-mounted IMU. The results demonstrate a reliable reconstruction of heading and position, despite suboptimal attachment of the sensor system housing over pants and natural leg, which allows more shaking than the intended mounting on a prosthesis or ankle-foot orthosis.

The speed and accuracy of transfer alignment can be further improved by adding orientation correction when attached on a prosthetic foot, where a rigid body condition is satisfied between foot and shank IMU during swing phase.

The purpose of this method is to align the high accuracy IMU with the world frame and then let it function as a low-drift reference in indoor activities. These preliminary results demonstrate the effectiveness of transfer alignment in bringing multiple inertial sensors into heading alignment for multi-body reconstruction. These techniques will be applied to compare different types of prosthetic feet and orthoses.

## REFERENCES

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- [5] Europa+, Orthocare Innovations, LLC

# WEARABLE SENSOR SUITE FOR LONG-TERM REAL-WORLD TRACING

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email: \*peter.adamczyk@wisc.edu

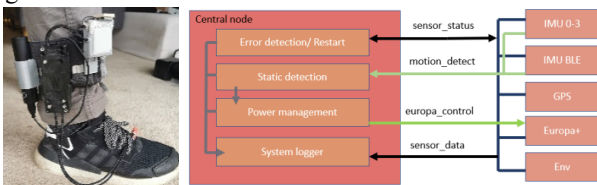
## Introduction

Biomechanics analysis may need abundant data from real world tracking, where more information can be extracted to enable scientific comparison of mobility interventions compared to pure lab testing. However, long-term tracking suffers from the trade-off of accuracy vs convenience as well as heading drift due to absence of GPS in indoor environments. As an attempt to resolve these problems, we are developing a sensor suite with a redundant high-accuracy IMU to mitigate long-term drift, three other low-cost IMUs and two Bluetooth devices for collecting motion and force data, as an extension to our previous method<sup>[1]</sup> with only a foot-mounted IMU. Here we describe the use of transfer alignment techniques to effectively reconstruct knee and shank IMU motions which by themselves alone are impossible to build accurately.

## Methods

**Hardware:** Our system incorporates 7 sensors with a total weight around 350 grams and similar diameter to the natural leg when attached on a prosthetic pylon. Various sources of data are collected to facilitate reliable reconstruction during long periods using sensor fusion techniques:

- 1) Five IMUs form the basis of sensor system. A low-cost cabled IMU is mounted on the instrumented foot and a Bluetooth Low Energy IMU on the other foot. The cabled IMU functions as the input of an Error State Kalman Filter for Pedestrian Dead Reckoning algorithm. Two more low-cost IMUs are attached to the shank and above the knee to reconstruct lower leg and upper leg motion. A high-accuracy low-drift IMU is installed together with the shank IMU, to maintain accurate heading during long-duration indoor motion.
- 2) Europa smart pyramid is an instrumented prosthetic pylon that monitors flexion and abduction bending moments and axial force via Bluetooth connection.
- 3) Environment sensors provide humidity, temperature and barometer data to distinguish indoor vs outdoor data and changes in height.
- 4) An RTK-GPS module provides centimeter-accuracy position measurements during outdoor movement to locate the system in the global frame.



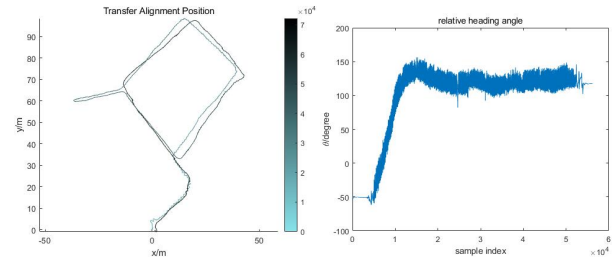
**Figure 1:** (a) sensor suite on leg (b) software architecture  
**Software:** The sensor system runs on a Raspberry Pi Zero W and utilizes Robot Operating System to manage and monitor all sensors. A central node coordinates the data logging, error detection, timestamp synchronization and power management for all sensor nodes.

**Movement Reconstruction:** The trajectory of each foot-mounted IMUs is reconstructed using an Error State Kalman Filter<sup>[2]</sup>,

which leverages the Zero Velocity Update (ZUPT)<sup>[3]</sup> assumption at every foot fall to reduce error in absence of GPS data.

The more challenging part is the reconstruction for the shank and thigh IMUs, where the ZUPT is not valid, making it difficult to bound the velocity and heading error. However, we have the knowledge that these IMUs move with foot-mounted IMU, with error around 0.1m in horizontal plane due to leg motion. Thus, we use position results from the foot-mounted IMU as observations for the shank and thigh Kalman filters at every footfall to perform transfer alignment<sup>[4]</sup>.

## Results and Discussion



**Figure 2:** (a) transfer alignment results (b) relative heading angle  
Fig. 2 demonstrates convergence and bounded error of the shank's final position and heading with respect to foot-mounted IMU during testing on an intact subject. The wiggling part at the beginning is an effect of orientation error before the transfer alignment converges. Once the initialization stage finishes, the result is smooth and has bounded relative heading error.

It is worth mentioning that the sensor system housing is attached on pants, which is not as strong as housing for rigid object like prosthesis and AFO. At every footfall, the shank IMU will endure significant shaking due to impact with the ground. However, even under this condition, the results still demonstrate a reliable reconstruction of heading and position.

In the special case of a prosthetic foot, there is a further rigid body relationship between the foot and shank IMUs during swing phase because the ankle joint angle is fixed. By applying orientation correction as an addition to position correction, the speed and accuracy of transfer alignment will be improved.

Reconstruction in indoor environments suffers most from heading error because of inevitable gyro drift. In both AFO and prosthesis cases, the previously aligned high-accuracy shank IMU can function as a low-drift reference to correct heading error in the foot-mounted IMU indoors.

The preliminary results shown here demonstrate the effectiveness of transfer alignment in bringing multiple inertial sensors into long-term heading alignment for multi-body reconstruction. These techniques will be applied to compare different types of prosthetic feet and orthoses in a controlled test.

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## References

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