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14. ABSTRACT

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.

15. SUBJECT TERMS

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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
Major Task 1: IRB and HRPO Human Subjects Approval	1-3	Complete at UW site In process at WRNMMC site.
Major Task 2: Test 10 Subjects using ESR vs AESR	3-12	Delayed. Revision to plan pending.
Major Task 3: Specify and acquire custom sensors	1-5	Complete.
Major Task 4: Improve BD2SD and gait analysis from wearable data.	1-18	Ongoing.
Major Task 5: Conduct repeated-measures study on prostheses.	15-36	Beginning Y2

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. UW IRB approval was obtained on 2019-09-03.
   b. HRPO approved the UW protocol on 2020-01-23.
   c. Subaward to WRNMMC is undergoing changes (change of SOW to be sought imminently). Protocol development is underway based on the UW information and the intended changes.
2. **Objective: Develop sensor systems.**
   a. Goal was for UW-Madison to work with Navigation Solutions, LLC (NSL) and Orthocare Innovations, LLC (OIL) to develop the custom sensor suite and software.
   b. UW worked with OIL to read data from Europa+ smart pyramids.
      i. Result: This effort succeeded in January 2020. The Europa+ streams data over Bluetooth LE to the Raspberry Pi Zero W logging system.
      ii. Improved effort (more efficient streaming) is under investigation through software changes
   c. UW worked with NSL to finalize all aspects of the sensor suite and data logger.
      i. Result: Sensors received in Q3 (by 2020-04-15). Individual copies are tested as they are prepared for use.
   d. UW staff developed the software to log and synchronize data from the multiple sensors.
      i. Result: The system is successful: all sensors working and recording data at full rate. Improvements to the logging software for efficiency are continuing.
      ii. Testing of the sensors will be undertaken by UW staff in Y2 Q1.
   e. Enable and use RTK GPS.
      i. RTK GPS logging is working, and data are interpretable.
   f. Develop mounting hardware for prostheses and orthoses
      i. Result: Multiple revisions have been made. Effort was interrupted by COVID-19 but has recently restarted with reopening of campus facilities. Ongoing efforts focus on mounting to prosthetic pylon and socket.
   g. Refine Kalman Filtering for determining the user's precise location.
      i. Result: Prior MATLAB code was converted into C++ for speed and efficiency. Testing is underway. UW staff have been making improvements and finding additional literature to incorporate.
3. **Objective: Prepare for mechanical tests of prostheses.**
   a. Mechanical testing of prostheses is important for describing the systems used in human subjects testing.
   b. UW staff are adapting the procedures in the 2010 AOPA Report (which specifies these tests) to the mechanical testing equipment available.
      i. Result: Sample prostheses were acquired and test equipment was partially prepared. Efforts to start in Y1 Q4 were disrupted by COVID-19. Efforts continued their alternative focus on developing biomechanical analysis. Mechanical testing efforts are expected to restart in earnest in Y2 Q1.
4. **Objective: Prepare for preliminary prosthetics and orthotics tests at UW-Madison**
   a. UW-Madison is specified to develop the experimental protocols that enable full multiple-week take-home testing of prostheses and orthoses.
   b. UW staff have specified the devices for the 10-subject preliminary study at UW.
      i. Result: Planning and execution interrupted by COVID-19 closure. Effort will restart to recruit initial subjects after team members test the sensors.

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, respectively. They also had interaction with the Prosthetics and Orthotics team at UW-Madison.
One undergraduate student, Jingjun Liu, assisted with programming the sensor suite and had one-on-one mentoring with Prof. Adamczyk and also with graduate student Yisen Wang.
Professional Development:
Ms. Fehr and Mr. Wang both participated in the Dynamic Walking 2020 conference, where they displayed their progress and received 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.

The project developed an analysis of ankle and knee mechanics based on combined wearable motion sensors and prosthetic pylon load sensors, which was presented in two posters during Y1 Q4 at Dynamic Walking 2020 virtual conference, 2020-05-14.

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 2 we plan the following steps:
UW-Madison:

- Testing sensors for robustness
- Begin 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:

- Obtain permission for a revised Statement of Work for the Walter Reed NMMC site
- Complete IRB and HRPO reviews for new protocol.
- Begin enrollment

4. **IMPACT:** D*escribe 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 will enable studies of prostheses and orthoses in Y2-3 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 being prepared in a manuscript, 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.*

Technical progress on the unified sensor system was fed back to the companies who supplied the components, Navigation Solutions, LLC and Orthocare Innovations, LLC.

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.

We are seeking a change in the Statement of Work for the Walter Reed NMMC site. The study we initially planned to "piggyback" on is essentially over, and clinical staff have expressed challenges to the original design and interest in an alternative design. We will submit a written proposed change in the near future.

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. Both sites were shut down and everyone had to scramble trying to deal with it in many ways.
UW-Madison reshuffled the timelines for work already scheduled – advanced sensor development, delayed human subjects testing.
UW-Madison is gradually reopening for human subjects testing. We have permission now, so plan to begin enrollment in Y2 Q1.
WRNMMC is preparing a revised protocol to improve the ability to enroll subjects and obtain data of interest of the clinical staff.

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.

Minor impact on expenditures at UW-Madison due to inability to do mechanical testing of prostheses. Human subjects testing was also delayed. But most progress continued, as sensor development and analysis development were not seriously interrupted.

Spending at WRNMMC was delayed but will pick up with Year 2 activities.

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*

No major publications in Y1. We have a manuscript "almost ready" on analysis methods using wearable sensors in prosthetics, to be submitted Y2 Q1.

publication; submitted, under review; other); acknowledgement of federal support (yes/no).

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:
Fehr KH, Leestma JK, Adamczyk PG (2020). Effects of Prosthetic Forefoot Stiffness on Ankle and Knee Mechanics on Level Ground, Ramps and Stairs. *Dynamic Walking 2020,* May 14, 2020. Online meeting due to COVID-19.
This poster covered our development of an analysis using wearable sensors in prosthetics.

Wang Y, Adamczyk PG (2020). Long-term Wearable Sensor Suite for Real-World Biomechanical Tracking in Prosthetics. Dynamic Walking 2020, May 14, Online meeting due to COVID-19.
This poster covered our development of a sensor suite customized for studies of long-term real-world use of prostheses.

- **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.

We worked with Navigation Solutions, LLC to develop a sensor suite designed specifically for the long-term tracking application in this project. The assembled computer code and logging system has been shared back with Navigation Solutions, LLC for potential future use in a consolidated product.
We worked with Orthocare Innovations, LLC to enable Bluetooth logging of signals from the Europa+ pylon load cell. We are in the process of returning a distributable code to them for potential use as a software development kit.

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".

Name: *Peter Adamczyk*
Project Role: *PI*
Researcher Identifier (ORCID): *0000-0001-5374-7691*
Nearest person month worked: *1*
Contribution to Project: *Dr. Adamczyk has worked to manage the sensor systems development, direct the biomechanical analysis with wearable sensors, negotiate the supply of prostheses and orthoses.*

Name: *Katherine Heidi Fehr*
Project Role: *Graduate Student*
Researcher Identifier (ORCID): *none*
Nearest person month worked: *5*
Contribution to Project: *Ms. Fehr has worked to prepare biomechanical analysis of movement based on wearable sensor data, and to prepare for mechanical testing of prostheses.*

Name: *Yisen Wang*
Project Role: *Graduate Student*
Researcher Identifier (ORCID): *none*
Nearest person month worked: *5*
Contribution to Project: *Mr. Wang has worked to program software for the unified sensor suite, including optimization to maximize battery life and robustness and to limit the computational load on the embedded logging computer.*

Name: *Jingjun Liu*
Project Role: *Undergraduate Student*
Researcher Identifier (ORCID): *none*
Nearest person month worked: *1*
Contribution to Project: *Mr. Liu has worked with Mr. Wang to program the data logging system for the new sensors.*

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.

No changes; some changes pending (new grants for other research).

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 2020
b) Abstract repring: Wang et al Dynamic Walking 2020

Relationship Between Dynamic Mean Ankle Moment Arm and Prosthetic Forefoot Stiffness on Level Ground, Ramps and Stairs

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***Abstract*— The goal of this research is to describe the biomechanical effect of forefoot stiffness in a foot prosthesis during different ambulatory tasks. This is accomplished by measuring the Dynamic Mean Moment Arm (DMAMA) of the prosthetic foot with data collected by a prosthesis-embedded load cell. Preliminary results suggest that both terrain (ramps and stairs) and prosthetic forefoot stiffness affects DMAMA.**

I. INTRODUCTION

Traditionally, the type and stiffness of a foot prosthesis is selected by a prosthetist based on the user's weight and activity level. However, a healthy ankle adapts and changes its biomechanical properties depending on its conditions and activities, such as going up and down stairs or walking on different terrains. Prosthetic feet with variable stiffness attempt to mimic this response [1].

In order to quantify the effects of the variable stiffness we calculated the Dynamic Mean Ankle Moment Arm (DMAMA) for different activities. The DMAMA metric is a summary of the net dynamic effect of a shift between hindfoot- and forefoot-dominated contact in running, walking and other activities [2]. As an example, DMAMA increases as a person transitions from walking to running as their gait becomes more forefoot dominant.

II. METHODS

Six subjects used a variable stiffness prosthetic foot [1] in three stiffness settings (Soft, Mid, and Stiff) and performed five ambulatory tasks. We collected data from a six-degree-of-freedom load cell (iPecs, RTC Electronics) that was mounted between the pylon and the socket of subjects' prosthesis and an inertial measurement unit (IMU) wearable suit (MVN Awinda, Xsens). The ambulatory tasks were level walking and ascending and descending ramps and stairs. Prior to the tasks we collected motion capture (Optitrack Prime 13, NaturalPoint, Inc.) and force plate (Bertec, Inc.) data for calibration purposes.

$$DMAMA: d = \frac{J}{I} = \frac{\int_{HS}^{TO} M dt}{|| \int_{HS}^{TO} \vec{F} dt ||} = \frac{\bar{M}}{\bar{F}} \quad (1)$$

We combined the forces and moments measured by the prosthesis-embedded load cell with leg kinematics measured from the IMU suit to calculate the three dimensional-moments about the knee and ankle. We used the IMU data to distinguish the ambulatory tasks from one another. By dividing the mean sagittal ankle moment ($\bar{M}$) by the mean sagittal ground reaction force ($\bar{F}$) we calculated the DMAMA across the different stiffness settings (1).

III. RESULTS & DISCUSSION

Preliminary results confirm prior findings that walking on slopes and ramps affects ankle moment with all prostheses. The summary measure DMAMA summarizes this effect over the whole stance period: greater DMAMA indicates more forefoot-dominated gait. The DMAMA metric appears to increase during ramp descent compared to ramp ascent. Similarly, DMAMA appears to increase during stair descent when compared to stair ascent. There is little difference between level ground walking and ramp ascent. Soft vs. Mid stiffness has little effect on DMAMA, but the Stiff setting shows an overall decrease in DMAMA.

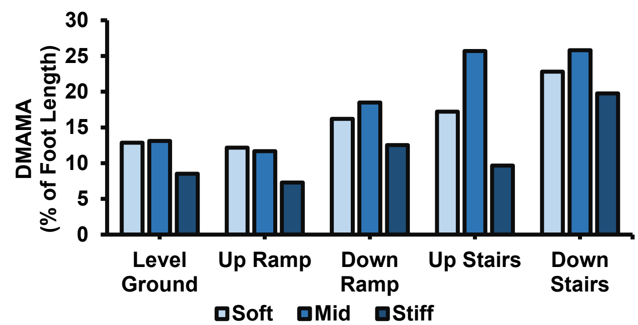

Fig. 1. DMAMA values across tasks and forefoot stiffness settings.

IV. CONCLUSIONS

We will present final results at the conference and discuss ways these field-based wearable analyses can be used to inspire the control of semi-active intelligent prostheses.

V. ACKNOWLEDGEMENTS

Supported by internal funds from the University of Wisconsin–Madison.

VI. REFERENCES

[1] E. M. Glanzer and P. G. Adamczyk, "Design and Validation of a Semi-Active Variable Stiffness Foot Prosthesis", IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 26, no. 12, pp. 2351-2359, Dec. 2018.

[2] P. G. Adamczyk, "Ankle control in walking and running: speed- and gait-related changes in Dynamic Mean Ankle Moment Arm (DMAMA)", J. Miomech. Eng., Dec 2019, doi: 10.1115/1.4045817

Long-term Wearable Sensor Suite for Real-World Biomechanical Tracking in Prosthetics

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***Abstract*—This work presents a suite of sensors configured to optimize long-term motion reconstruction and indoor/outdoor localization using wearable sensors. The system was designed to enable improved real-world biomechanical analysis in persons with amputation. We will present the design of the system, its data logging architecture, and hopefully the first recorded data sets.**

***Keywords*—wearable sensor, prosthetics, biomechanics**

I. Introduction

Real-world tracking is of great interest in biomechanics, but research to date has focused overwhelmingly on simple measures such as step counts or all-inclusive analyses based on big-data approaches. Neither of these methods yields sufficiently detailed analysis to enable decisions about biomechanical superiority of some interventions over others. Our team is developing a method that tracks a person's movement across all locations, indoors and out, and analyzes intervention-related changes only in the most frequently-repeated circumstances. Here we extend the previous method, based solely on foot-mounted movement sensors, to include a wider array of movement, biomechanical, and environmental sensors chosen to optimize this type of analysis. The goal is to enable sound scientific comparison of different interventions based solely on data from everyday life. The specific focus is on prosthetic foot-ankle systems with different classes of features.

II. Methods

A. Sensor Suite

The sensor system consists of one high-accuracy inertial measurement unit (IMU) mounted on the prosthetic shank; three wired low-power IMUs, on the prosthetic-side foot, shank and thigh; one Bluetooth low-power IMU on the intact-side foot; a real-time kinematic global positioning system (RTK-GPS) receiver; environmental sensors for air temperature, pressure and humidity; and a Bluetooth-enabled prosthetic pylon load cell. These data are sampled and synchronized by a Raspberry Pi Zero W (RPi) and logged to its integrated microSD card.

B. Data Logging Architecture

We use Robot Operating System (ROS) as the central coordinating software. ROS enables time-stamped synchronous logging of multiple sensors' data in a common file, while managing these sensors as independent program nodes within a Linux environment. By periodic communication with each sensor, error detection and power management based on subject's activity level are implemented. This architecture has relatively high computational overhead, but offers modularity, robustness to individual sensor failure and a standardized file format.

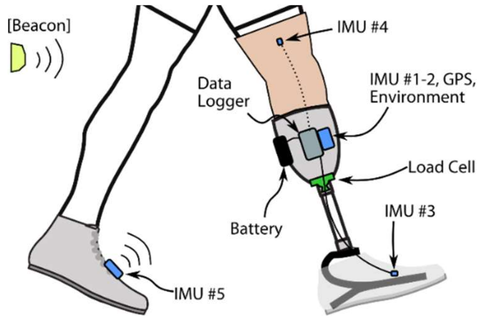

Fig 1: The sensor system will include 3-5 IMUs, GPS, environmental sensors, Bluetooth for location beacons, and a pylon load cell. These improved sensors will enable better movement reconstruction and gait analysis.

C. Reconstruction and Analysis

Movement reconstruction is done using Pedestrian Dead Reckoning (PDR) techniques [1] fused with RTK-GPS data using a Kalman Smoother [2]. Environmental sensors, GPS data and open-source maps are used to determine elevation changes and indoor/outdoor periods. Movement paths are clustered based on location, direction and overlap of multiple movement bouts to identify the most frequent paths. Biomechanical variables such as stride length, stride width and prosthetic socket load are characterized statistically for each cluster of frequent paths and compared across intervention conditions [2].

III. Results

We do not have any results yet, but we will show the sensor suite, debate its merits and demerits, and discuss any data we have recorded by the time of the conference.

References

[1] L. Ojeda and J. Borenstein, "Non-GPS Navigation for Security Personnel and First Responders," *The Journal of Navigation*, vol. 60, no. 03, pp. 391–407, Sep. 2007, doi: 10.1017/S0373463307004286.

[2] W. Wang and P. G. Adamczyk, "Analyzing Gait in the Real World Using Wearable Movement Sensors and Frequently Repeated Movement Paths," *Sensors*, vol. 19, no. 8, p. 1925, Jan. 2019, doi: 10.3390/s19081925.

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