AWARD NUMBER: W81XWH-21-2-0006

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

PRINCIPAL INVESTIGATOR: Dr Darryl Thelen, PhD

CONTRACTING ORGANIZATION: University of Wisconsin System, 1513 University Avenue, Madison, WI 53706

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Dr Darryl Thelen, PhD and Alex Reiter

E-Mail: dgthelen@wisc.edu and alex.j.reiter@wisc.edu

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14. ABSTRACT

The purpose of this study is to finalize development and field testing of a wearable kinetic system designed to objectively assess tendon health and function in individuals recovering from overuse tendon injuries. We will accomplish this by: (1) establishing baseline metrics of bilateral tendon kinetics during outdoor locomotor activities, (2) investigating functional adaptations in individuals exhibiting tendon pathology, and (3) evaluating the use of shear wave tensiometry to objectively identify tendon healing. We have nearly completed testing of uninjured participants and the initial results have been submitted as conference abstracts. Peer-review publications will be submitted once full data analysis is completed. Recruitment and testing of injured participants will be a major priority for this coming year.

15. SUBJECT TERMS

Tendon, tendinopathy, shear wave tensiometer, wearable devices, outdoor activity, rehabilitation, return-to-duty, symmetry, force, loading

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1. **INTRODUCTION:** *Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.*

   The purpose of this study is to finalize development and field testing of a wearable kinetic system designed to objectively assess tendon health and function in individuals recovering from overuse tendon injuries. We envision enabling clinicians the ability to precisely measure tendon behavior during operationally relevant activities such that they can monitor healing, guide rehabilitation, and quantitatively assess patients' capacity for safe return-to-duty. We will accomplish this by: (1) establishing baseline metrics of bilateral tendon kinetics during outdoor locomotor activities, (2) investigating functional adaptations in individuals exhibiting tendon pathology, and (3) evaluating the use of shear wave tensiometry to objectively identify tendon healing.

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

   Tendon, tendinopathy, shear wave tensiometer, wearable devices, outdoor activity, rehabilitation, return-to-duty, symmetry, force, loading

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.

   Specific Aim 1: Establish baseline metrics of bilateral tendon kinetics during outdoor locomotor activities in uninjured civilians.

   Specific Aim 2: Investigate functional adaptations in active duty Service members exhibiting tendon pathology.

   Specific Aim 3: Evaluate use of shear wave tensiometry to objectively identify tendon healing.

	Timeline	UW	NHRC	Progress (%)
Major Task 1: Prepare regulatory documents and research protocol	Months			
Write and submit CRADA	1-3	DT	AS/PS	100
Write and submit IRB protocol for civilian testing	1-2	DT/PA		100
Write and submit IRB protocol for injured/uninjured Active duty testing	1-2		AS/PS/JF	100
Submit amendments, adverse events and protocol deviations as needed	As needed	DT	AS/PS	100
Milestone Achieved: Local IRB approval at UW and NHRC	3			100
Milestone Achieved: CRADA approved	6			100
Major Task 2: Hiring and training of study staff				
Hire graduate student	1	DT/PA		50
Advertise for and interview postdoctoral fellow	7-9	DT/PA	AS/PS/JF	100
Advertise for and interview research engineer	7-9	DT/PA	AS/PS/JF	100
Hire and onboard postdoctoral fellow	13	DT/PA		100
Hire and onboard research engineer	13		AS/PS/JF	100
Train postdoctoral fellow	13-15	DT/PA		100
Train research engineer	13-15		AS/PS/JF	100
Milestone Achieved: Graduate student hired	1			50
Milestone Achieved: Postdoctoral fellow hired and trained	15			100
Milestone Achieved: Research engineer hired and trained	15			100
Major Task 3: Aim 1 – Testing of uninjured participants				
Identify outdoor locomotor course	1-3	DT/PA		100
Recruit and test uninjured civilian participants	3-12	DT/PA		90
Milestone Achieved: Validation testing complete	12			90
Major Task 4: Aims 2 & 3 – Testing of participants with tendinopathy				
Subtask 1: Establish testing protocol and prepare for recruitment				100
Identify 0.5-mile outdoor testing course	13-15		AS/PS/JF	100
Talk with local civilian and active duty physical therapists to aid in subject recruitment of injured participants	13-15		AS/JF	100
Subtask 2: Subject recruitment and testing				0
Recruit active duty participants with clinical tendinopathy diagnosis	16-39		AS/PS/JF	50
Confirm tendinopathy with questionnaire, Doppler ultrasound, and medical chart review	16-39		JF	0

Test participants with tendon injury, before and after completion of rehabilitation	16-42		AS/PS	0
Milestone Achieved: Testing protocol fully developed and implemented	15			100
Milestone Achieved: Partnering physical therapists identified	15			100
Milestone Achieved: Injured participant testing complete	42			0
Major Task 5: Data analysis, dissemination and reporting of results				
Subtask 1: Disseminate results				0
Milestone Achieved: Normative testing submitted for conference presentation	12			50
Milestone Achieved: Normative testing submitted for peer-reviewed publication	18			0
Milestone Achieved: Injured vs uninjured comparison submitted for conference presentation	30			0
Milestone Achieved: Injured vs uninjured comparison submitted for peer-reviewed publication	42			0
Milestone Achieved: Relationship between tendon structure and mechanical function submitted for conference presentation	42			0
Milestone Achieved: Relationship between tendon structure and mechanical function submitted for peer-reviewed presentation	48			0
Subtask 2: Prepare and provide quarterly and annual reports to DoD	Quarterly	DT/AS	AS/PS	50

Projected Quarterly Enrollment

	Year 1				Year 2				Year 3				Year 4				Total
Target Enrollment Uninjured Normative Data (per quarter)	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	
UW (projected)	-	8	8	8	-	-	-	-	-	-	-	-	-	-	-	-	24
UW (actual)	-	0	0	0	0	4	0	18									22
NHRC (projected)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NHRC (actual)	-	-	-	-	-	-	-	-									-
Target Enrollment (cumulative-projected)	**-**	**8**	**16**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
Target Enrollment (cumulative-actual)	**-**	**0**	**0**	**0**	**0**	**4**	**4**	**18**									**22**

	Year 1				Year 2				Year 3				Year 4				Total
Target Enrollment Outdoor Injured Testing (per quarter)	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	
UW (projected)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UW (actual)	-	-	-	-	-	-	-	-									-
NHRC (projected)	-	-	-	-	-	4	8	12	16	20	24	28	32	-	-	-	32
NHRC (actual)	-	-	-	-	-	0	0	0									0
Target Enrollment (cumulative-projected)	**-**	**-**	**-**	**-**	**-**	**4**	**8**	**12**	**16**	**20**	**24**	**28**	**32**	**32**	**32**	**32**	**32**
Target Enrollment (cumulative-actual)	**-**	**-**	**-**	**-**	**-**	**0**	**0**	**0**									**0**

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.

Major Task 1: Previously completed. We have submitted IRB renewals and amendments as necessary.

Major Task 2: We were not able to recruit a graduate student this past year but will attempt again with the current incoming cohort of graduate students at UW this fall. However, our postdoc with the assistance of a part-time research staff member have been able to nearly complete the testing of the uninjured participants. We anticipate being complete with testing during the next quarter. Any newly hired graduate student will take the lead role of data processing, analysis, and dissemination at UW. We have identified and trained the necessary staff personnel at NHRC to assist with testing.

Major Task 3: We had a very successful year recruiting and testing uninjured participants. To date, 22/24 participants have been tested with 6-8 more scheduled for the next quarter.

Major Task 4: We have been in contact with seven military clinics in the San Diego area but have been unsuccessful at recruiting injured participants. The Navy-based clinics have expressed to us that they are seeing very few tendinopathy patients compared to 3-4 years ago. They theorize this is due to the physical readiness test (PRT) now only happening once per year, with a running component no longer required. As an alternate option, we have connected with the two SMART clinics at Camp Pendleton, CA, approximately 1-1.5 hours North of San Diego. These clinics have a much higher prevalence of tendinopathy cases. We have identified an additional course there and have begun recruiting. We anticipate testing to begin in the coming quarters.

Major Task 5: We have started processing and analyzing the data for the uninjured population. Two abstracts have been related to these data to the Military Health System Research Symposium and the American Society of Biomechanics Annual Conference. See appendices for full abstracts including methods and results of a small subset of the data analyzed to date.

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.

Alex Reiter, the hired postdoctoral research associate at UW, has received extensive training and professional development because of working on this project. Under the guidance and mentorship of the key personnel on this project as well as working with other members of the lab, Alex gained experience in human subject research, tensiometry, motion capture, wearable technology, and ultrasound imaging. He has also attended several conferences to present results and broaden his professional network.

Elizabeth Schmida, a research staff member at UW, has subsequently been mentored by Alex Reiter. Through her work on the project at UW, Elizabeth has increased her proficiency in wearable sensor data analysis and ultrasound imaging.

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.

Nothing to report.

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.

Major Task 1: Submit IRB renewals and amendments as necessary.

Major Task 2: We will attempt to recruit and train a graduate student at UW during this next academic year.

Major Task 3: We will complete testing on the remaining uninjured participants during the next quarter. This will finish data collections for Aim 1 of the project.

Major Task 4: We will begin and complete testing of injured participants during the next year.

Major Task 5: We will submit additional conference abstracts for the normative uninjured participants this coming winter. Peer-reviewed publications will be submitted throughout the year as data analysis is completed. We plan to submit conference abstracts for the injured versus uninjured comparison next spring as progress is made on Major Task 4.

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 completion of the integrated wearable system has provided the field with a novel system that can collect joint-level kinematics, tissue-level kinetics, and highly accurate location data simultaneously. This new system will enable important research questions, such as those in this study, to be answered that previously have not been possible. Our initial results on uninjured participants submitted to conferences this past year have already improved our understanding of patellar tendon loading in an ecological setting not previously known. See appendices for full abstracts including methods and results of a small subset of the data analyzed to date.

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.*

The project has shown the capacity of the wearable system to collect joint-level kinematics, tissue-level kinetics, and highly accurate location data simultaneously, with a particular emphasis on patellar tendon loading. This project has shown the maturity of the technology that will aid in future commercialization efforts. In addition, a non-provisional patent application was submitted for the wearable system calibration device by the UW team.

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

Nothing to report.

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

Nothing to report.

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.

Major Task 2-3: We were not able to recruit a graduate student this past year but will attempt again with the current incoming cohort of graduate students at UW this fall. However, our postdoc with the assistance of a part-time research staff member have been able to nearly complete the testing of the uninjured participants. We anticipate being complete with testing during the next quarter. Any newly hired graduate student will take the lead role of data processing, analysis, and dissemination at UW.

Major Task 4: We have been in contact with seven military clinics in the San Diego area but have been unsuccessful at recruiting injured participants. The Navy-based clinics have expressed to us that they are seeing very few tendinopathy patients compared to 3-4 years ago. They theorize this is due to the physical readiness test (PRT) now only happening once per year, with a running component no longer required. As an alternate option, we have connected with the two SMART clinics at Camp Pendleton, CA, approximately 1-1.5 hours North of San Diego. These clinics have a much higher prevalence of tendinopathy cases. We have identified an additional course there and have begun recruiting. We anticipate testing to begin in the coming quarters.

Major Task 5: We have been delayed in submitting uninjured participant results to peer-reviewed publications. Now that testing is nearly complete, the priority at UW can shift toward dissemination of results for this next year.

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.

Nothing to report.

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

Nothing to report.

Significant changes in use or care of vertebrate animals

Not applicable.

Significant changes in use of biohazards and/or select agents

Not applicable.

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).*

  Nothing to report.

  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.*

1. Reiter AJ, Schmitz DG, Harper SE, Ma Y, Adamczyk PG, Thelen DG: Estimating relative patellar tendon loading with wearable technology while navigating various outdoor terrains. Military Health System Research Symposium, Kissimmee, FL, 2023.

2. Reiter AJ, Schmitz DG, Harper SE, Ma Y, Adamczyk PG, Thelen DG: Wearable estimates of patellar tendon loading while navigating outdoor terrains. American Society of Biomechanics Conference, Knoxville, TN, 2023.

- **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.

- **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.

  Reiter AJ, Thelen DG, Adamczyk PG: Calibration tool for tissue tension sensor. Non-provisional patent application submitted.

- **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".

Example:

Name:	*Mary Smith*
Project Role:	*Graduate Student*
Researcher Identifier (e.g. ORCID ID):	*1234567*
Nearest person month worked:	*5*
Contribution to Project:	*Ms. Smith has performed work in the area of combined error-control and constrained coding.*
Funding Support:	*The Ford Foundation (Complete only if the funding support is provided from other than this award.)*

Name:	Darryl Thelen
Project Role:	PD/PI
Nearest person month worked:	1
Contribution to Project:	Dr. Thelen oversaw the scientific direction and administrative requirements of the overall project, and day-to-day oversight of the portions of the project at UW. He also contributed to data interpretation of the preliminary uninjured normative database results.
Name:	Pinata Sessoms
Project Role:	Co-PD/PI
Nearest person month worked:	1
Contribution to Project:	Dr. Sessoms contributed to the scientific direction of the project.
Name:	Amy Silder
Project Role:	Co-PI
Nearest person month worked:	6
Contribution to Project:	Dr. Silder managed the administration requirements and provided the day-to-day oversight of the portions of the project at NHRC. She led the recruitment efforts at NHRC.
Name:	John Fraser
Project Role:	Co-I
Nearest person month worked:	1
Contribution to Project:	Dr. Fraser contributed to the scientific direction of the project.
Name:	Peter Adamczyk
Project Role:	Co-I
Nearest person month worked:	1
Contribution to Project:	Dr. Adamczyk has directed the development and deployment of the wearable systems. He also contributed to the scientific direction of the project and data interpretation of the preliminary uninjured normative database results.
Name:	Alex Reiter
Project Role:	Postdoctoral Research Associate
Nearest person month worked:	12
Contribution to Project:	Dr. Reiter led all data collection activities at UW. He processed the preliminary uninjured normative database results and prepared both conference abstracts for submission.

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.

Nothing to report.

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.*

Nothing to report.

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://ebrap.org/eBRAP/public/index.htm*** *for each unique award.*

QUAD CHARTS: *If applicable, the Quad Chart (available on https://www.usamraa.army.mil/Pages/Resources.aspx) 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.*

Appendix-1: Abstract submitted to the Miltary Health System Research Sympsium

Title: Estimating Relative Patellar Tendon Loading with Wearable Technology while Navigating Various Outdoor Terrains

Authors: Alex J. Reiter, PhD[1], Dylan G. Schmitz[1], Sara E. Harper[1], Yiteng Ma[1], Peter G. Adamczyk, PhD[1], and Darryl G. Thelen, PhD[1]
[1]University of Wisconsin-Madison, Madison, WI

Introduction

Musculoskeletal injuries (MSKIs) in training and deployed environments are one of the leading health problems in the military, resulting in detrimental effects to both individual and unit readiness. Nearly 800,000 injuries are reported annually representing an injury rate of 628 per 1000 person-years [1-2]. Among these reported injuries, 22% were classified as injuries of the knee and lower extremity [1]. Minimizing the risk of injury and expediting recovery following injury are of utmost importance to maximize readiness and retention on duty over the long term.

Assessments of lower limb tissue loading can be used as indicators of musculoskeletal injury risk or as rehabilitation criteria for determining recovery and the ability to return-to-duty. Wearable sensors are becoming increasingly popular to assess lower extremity loading in real-world environments. However, conventional wearables (e.g., inertial measurements units or instrumented insoles) can only provide indirect measures of the internal loading of the tissue of interest. There is a need for wearable technologies that can directly assess tissue loading during military-relevant tasks, such as load carriage on variable terrains, to understand injury risk or recovery.

Shear wave tensiometers [3] are non-invasive sensors capable of directly assessing changes in muscle-tendon loading during activity. They measure the speed of shear waves induced in biological tissues to estimate force. Prior studies have used wearable tensiometry to assess Achilles tendon loading while walking on level, inclined, and declined pavement [4]. This purpose of this study was to estimate relative loading changes in the patellar tendon (PT), a commonly injured tissue in service members, while navigating an outdoor course with multiple terrain types. Quantifying relative changes in PT loading directly with a wearable sensor during outdoor navigation opens the door to assessing performance and injury risk, tracking recovery, and defining return-to-duty criteria during training or deployment.

Methods

With the approval of the University of Wisconsin Institutional Review Board, three healthy, young adults (2F/1M, 23.0 ± 1.6 years) have been tested in this on-going study. Shear wave tensiometers were placed bilaterally over the PT of each participant. The tensiometers consisted of an electrodynamic tapper device to induce shear waves in the PT. Wave propagation was captured by two miniature accelerometers embedded in silicone separated by a known distance (8 mm) placed downstream from the tapper. Signal generation and data acquisition hardware were contained in a small electronics box (~4”x4”x4”) which was secured to participants with a running-style backpack. Synchronously, location data were acquired by a global positioning system (GPS) antenna included the electronics box. After donning the tensiometers and pack, participants walked at a self-selected pace along an approximately 1600m outdoor course consisting of *level pavement*, *uphill pavement*, *downhill pavement*, *level packed dirt*, and *level grass*.

The shear wave speed was computed by dividing the known distance by the wave travel time between the accelerometers. A Kalman filter was used to improve the quality and reliability of the computed wave speeds [5]. Wave speed data were segmented into strides, and the corresponding GPS data were used to match strides with course location and incline. *Level pavement*, *level packed dirt*, and *level grass* were portions of the course corresponding to a level paved sidewalk, dirt path, and grass courtyard, respectively. Inclines were binned in 2° increments (i.e., 3° to 5° → +4° bin, -3° to -5° → -4° bin); *uphill pavement* and *downhill pavement* were the +4° incline bin and -4° decline bin, respectively. To assess relative changes in PT wave speed (i.e., loading) across the various terrains, wave speeds were normalized to the median peak wave speed during *level pavement* for each participant. One-dimensional statistical parametric mapping repeated measures analysis of variance was used to identified regions of the gait cycle where the various terrains were significantly different ($p < 0.05$). A repeated measures analysis of variance was used to compare normalized peak wave speed between the various terrains, with Dunnett's post hoc test to compare each condition to *level pavement* ($p < 0.05$).

Results

Normalized wave speed showed significant differences among some of the five terrain conditions for the 0-27% ($p < 0.001$), 38-40% ($p = 0.049$), 43-52% ($p = 0.005$), and 96-100% ($p = 0.025$) portions of the gait cycle. The *level pavement*, *level packed dirt*, and *level grass* were visibly similar throughout the gait cycle, whereas the *uphill pavemen*t reached ~25% higher normalized wave speeds during the 0-27% portion of the gait cycle compared to the three level terrains, and the *downhill pavement* reached values ~50% higher during the same period.

Normalized peak wave speed showed significant differences among some of the five terrain conditions ($p = 0.008$). *Level packed dirt* (95CI = [0.94, 1.03], $p = 0.918$) and *level grass* (95CI = [0.93, 1.07], $p = 0.999$) were similar to *level pavement* (95CI = [0.98, 1.01]), but *uphill pavement* (95CI = [1.14, 1.32], $p = 0.004$) and *downhill pavement* (95CI = [1.21, 1.86], $p = 0.022$) were significantly higher than *level pavement* with *downhill pavement* having the largest increase.

Conclusions

This study demonstrates the feasibility for a wearable system to monitor relative PT loading changes while navigating an outdoor course across various terrains. While loading throughout the gait cycle on *level pavement*, *level packed dirt*, and *level grass* were similar, loading during early stance and peak loading values were significantly increased on *uphill pavement* and even more so on *downhill pavement*. These results support prior observations in studies of knee extensor muscle forces and work during uphill and downhill walking. In past tests of walking on +/-6° indoor ramps, participants generated higher mean forces compared to level walking in the four quadriceps femoris muscles which load the PT; the larger forces occurred on the -6° ramp [6]. These results were mirrored in the absolute knee joint work [7]. Importantly, the knee plays different roles depending on the incline, absorbing relatively larger amounts of energy during downhill walking, and generating relatively smaller amounts of energy during uphill walking. In future studies, understanding these roles will be critical for identifying risk of injury or recovery using loading metrics; the manner of PT loading may be as important as the magnitude of loading.

Unsurprisingly, walking on *level grass* and *level packed dirt* showed similar peak loading and profiles throughout gait compared to *level pavement*. Interestingly, the larger variability during peak loading in grass compared to pavement may suggest that the uneven grass surface causes ankle perturbations which trigger compensatory knee muscle forces to maintain balance. Future work may reveal important distinctions in loading variability while navigating more severe uneven terrains, such as wooded areas, not fully captured by peak loading alone.

These results motivate the use of wearable tensiometry to evaluate PT loading outside a military treatment facility or laboratory setting. Future work will calibrate the relative loading metrics presented here to an absolute measure of PT loading. When combined with wearable kinematic data to characterize joint work, these measures may enable objective assessments of injury risk and recovery during realistic training or deployed environments.

References

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Disclaimers

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Learning Objectives:

1. Describe how wearable tensiometry can be implemented to assess patellar tendon loading in real-world environments.
2. Analyze the relationship between relative patellar tendon loading across various terrains.
3. Discuss potential applications of wearable tensiometry to assess musculoskeletal injury risk or recovery.

Appendix-2: Abstract submitted to the American Society of Biomechanics Conference

WEARABLE ESTIMATES OF PATELLAR TENDON LOADING WHILE NAVIGATING OUTDOOR TERRAINS

Alex J. Reiter[1]*, Dylan G. Schmitz[1], Sara E. Harper[2], Yiteng Ma[1], Peter G. Adamczyk[1], Darryl G. Thelen[1]
[1]Department of Mechanical Engineering, [2]Department of Biomedical Engineering, University of Wisconsin–Madison, Madison, WI
*alex.j.reiter@wisc.edu

Introduction: Wearable sensors are becoming increasingly popular to assess movement biomechanics in real-world environments. However, conventional wearables (e.g., inertial measurements units or instrumented insoles) can only provide indirect measures of the internal loading of the tissue of interest. Shear wave tensiometers [1] are non-invasive sensors capable of directly assessing changes in muscle-tendon loading. Prior studies have used wearable tensiometry to assess Achilles tendon loading while walking outdoors [2]. The purpose of this study was to estimate relative loading changes in the patellar tendon (PT) while navigating an outdoor course with multiple terrain types. Quantifying relative changes in PT loading directly with a wearable sensor opens the door to assessing performance and injury risk, tracking recovery, and defining return-to-activity or sport criteria in real-world environments.

Methods: With the approval of the University of Wisconsin Institutional Review Board, three healthy, young adults (2F/1M, 23.0 ± 1.6 years) have been tested in this on-going study. Shear wave tensiometers were placed bilaterally over the PT of each participant ($n = 6$). Signal generation and data acquisition were managed by a Raspberry Pi 4B and Measurement Computing Corps MCC172 HATs [3] secured to a running-style backpack worn by the participant. Synchronously, location data were acquired by a GPS antenna. After donning the equipment, participants walked at a self-selected pace along an approx. 1600m outdoor course consisting of *level pavement*, *uphill pavement*, *downhill pavement*, *level packed dirt*, and *level grass*. Wave speed data were segmented into strides, and the corresponding GPS data were used to match strides with course location and incline. Inclines were binned in 2° increments (i.e., 3° to 5° → +4° bin, -3° to -5° → -4° bin); *uphill pavement* and *downhill pavement* were the +4° incline bin and -4° decline bin, respectively. Wave speeds were normalized to the median peak wave speed during *level pavement* for each participant. Statistical parametric mapping was used to identify regions of the gait cycle where the various conditions were different ($p < 0.05$). Repeated measures analysis of variance with Dunnett's test was used to compare normalized peak wave speed of each condition to *level pavement* ($p < 0.05$).

Results & Discussion: Normalized wave speed showed significant differences among a subset of the five terrain conditions for the 0-27% ($p < 0.001$), 38-40% ($p = 0.049$), 43-52% ($p = 0.005$), and 96-100% ($p = 0.025$) portions of the gait cycle (Fig. 1). The *uphill pavement* reached ~25% higher values during the 0-27% portion of the gait cycle compared to the three level terrains, and the *downhill pavement* reached values ~50% higher during the same period. Normalized peak wave speed was significantly dependent on the terrain condition ($p = 0.008$). *Level packed dirt* (95CI = [0.94, 1.03], $p = 0.918$) and *level grass* (95CI = [0.93, 1.07], $p = 0.999$) were similar to *level pavement* (95CI = [0.98, 1.01]), but *uphill pavement* (95CI = [1.14, 1.32], $p = 0.004$) and *downhill pavement* (95CI = [1.21, 1.86], $p = 0.022$) were significantly higher than *level pavement*. *Downhill pavement* induced the largest PT wave speeds, which were 55% larger than the *level pavement*.

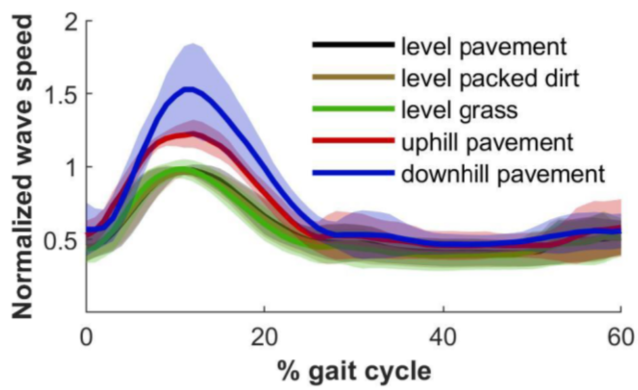

Figure 1: Normalized patellar tendon wave speed for approx. stance phase of gait to highlight the largest differences during early stance. (mean ± SD)

Walking on *level grass* and *level packed dirt* showed similar peak loading and profiles throughout gait compared to *level pavement*. Interestingly, the larger variability during peak loading in grass compared to pavement may suggest that the uneven grass surface causes ankle perturbations which trigger compensatory knee muscle forces to maintain balance. Future work may reveal important distinctions in loading variability while navigating more severe uneven terrains not fully captured by peak loading alone.

It is exciting to note that these wearable measures of loading are comparable to laboratory-based assessments. For example, in past tests of walking on +/-6° indoor ramps, participants also generated the larger forces on the declined (-6°) ramp condition [4]. Going forward, it is feasible to couple tensiometry metrics with IMUs to estimate joint power and work in real-world environments [3], as has been done in the laboratory [5]. Such metrics could prove crucial for identifying injury risk or recovery.

Significance: This study demonstrates the feasibility for a wearable system to monitor metrics of PT loading while navigating an outdoor course across various terrains. Future work will calibrate the relative loading metrics presented here to an absolute measure of PT loading. When combined with wearable kinematic data to characterize joint work and power, these measures may enable objective assessments of performance, injury risk, and recovery during real-world activity.

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