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CONTRACTING ORGANIZATION: The University of Texas, Austin, TX

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14. ABSTRACT Falling is a common problem for lower limb amputees, which can lead to reduced physical and emotional health. The overall aims of this project are to: 1) establish a baseline fall detection algorithm derived from simulated falls in a laboratory setting, and 2) utilize and refine the initial laboratory-based algorithm to provide detection of fall events during activities of daily living in real-world environments. To achieve these aims we will perform two human subject experiments. The first experiment will use 30 non-amputee and 5 lower limb amputee individuals to simulate falls in a laboratory setting while wearing the sensor. However, due to the COVID-19 pandemic, we were delayed in starting our data collection. However, in January 2021 we were given approval to start data collection and we have completed the data collection. We then performed our second experiment where we recruited 20 lower limb amputees to wear the sensor in the real-world. The data collection has been completed and we are currently refining our fall detection algorithm. An abstract describing our Aim 2 work was submitted and accepted for presentation at the 2023 annual meeting of the <i>American Society of Biomechanics</i> (August 8-11).		

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1. Introduction

Falling is a common problem for lower limb amputees, which can lead to reduced physical and emotional health. The overall aims of this project are to: 1) establish a baseline fall detection algorithm derived from simulated falls in a laboratory setting, and 2) utilize and refine the initial laboratory-based algorithm to provide detection of fall events during activities of daily living in real-world environments. The proposed research has two aims: 1) establish a baseline fall detection algorithm derived from simulated falls in a laboratory setting, and 2) utilize and refine the initial laboratory-based algorithm to provide detection of fall events during activities of daily living in pragmatic, real-world environments. To achieve these aims we will perform two human subject experiments. The first experiment will use 30 non-amputee and 5 lower limb amputee individuals to simulate falls in a laboratory setting while wearing the sensor. The sensor will record the motion of the body while falling so that we can create an algorithm to detect a fall in comparison to normal daily activities. The second experiment will recruit 20 lower limb amputees to wear the sensor in the real-world. Amputees will use the sensor for two 5-hour periods. During that time the sensor will record their motion and detect when a fall occurs. Participants will also report about any fall events that were not detected so that the algorithm can be improved. The outcomes from this two-year project will be new information for clinicians to better understand the number of falls that occur for lower limb amputees. This work represents an initial pilot study to collect data for the fall detection algorithm and lead to future studies where large numbers of amputees will be supplied with the sensors in order to better quantify falling in the larger amputee community and other communities that are at high risk for falling.

2. Keywords

Biomechanics, amputation, balance, fall detection, sensors, algorithms

3. Accomplishments

What were the major goals of the project?

Specific Aim 1: Establish a baseline fall detection algorithm derived from simulated falls in a laboratory setting.	Timeline (months)	Status
Major Task 1.1: Human subject experiment (n=35)	1-7	
Milestone 1.1.1: Obtain approval from the governing Institutional Review Boards.	2	Complete
Milestone 1.1.2: Complete enrollment of all participants and collect experimental data.	5	Complete
Major Task 1.2: Analyze Human Subject Data	5-8	
Milestone 1.2.1: Perform machine learning analysis of falling data from healthy subjects to determine the initial fall detection algorithm.	1	Complete
Milestone 1.2.2: Perform hypothesis tests to evaluate the effectiveness of the falling algorithm.	1	Complete
Milestone 1.2.3: Implement the algorithm in the IMU sensor.	0.5	Currently in Progress)
Milestone 1.2.4: Complete writing of manuscript and conference abstract describing initial algorithm development and results.	2	Two Abstracts Completed, Manuscript Submitted

Specific Aim 2: Utilize and refine the initial laboratory-based algorithm to provide detection of fall events during activities of daily living in pragmatic, real-world environments.	Timeline (months)	
Major Task 2.1: Human subject experiment (n=20)	6-21	
Milestone 2.1.1: Obtain approval from the governing Institutional Review Boards.	2	Complete
Milestone 2.1.2: Complete enrollment of all participants and collect experimental data.	15	Complete
Major Task 2.2: Analyze Human Subject Data	21-24	
Milestone 2.2.1: Perform machine learning analysis on complete dataset to determine final algorithm with all data.	2	In Progress
Milestone 2.2.2: Perform hypothesis tests to evaluate the effectiveness of the falling algorithm in the real-world.	3	In Progress
Milestone 2.2.3: Complete writing of manuscript and conference abstracts describing the algorithm development, validation and results.	3	One Abstract Complete, Manuscript in Progress

What was accomplished under these goals?

In Year 3, we received approval for our revised Statement of Work that modified Aim 2 to fit up to 20 individuals with a lower limb amputation with an IMU sensor and data logger over two separate 5-hour periods. We successfully completed this data collection from 20 subjects and are currently refining our fall detection algorithms as proposed.

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

This project has provided professional development opportunities for graduate students Lindsey Lewallen and Mojtaba Mohasel through technical writing and presenting their work at scientific conferences.

How were the results disseminated to communities of interest?

The results of our Year 1 activities were accepted and presented at the annual meeting of the *American Society of Biomechanics* in August, 2021. A research poster describing this work was also presented at the UT Austin Department of Mechanical Engineering Graduate Student Research Poster Session. A manuscript describing this work has been submitted. The results of our Year 2 activities were accepted and presented at the *North American Congress on Biomechanics* in August, 2022. A portion of the results of Year 3 will be presented at the annual meeting of the *American Society of Biomechanics* with a poster titled “Development of an Automated Framework for a TinyML-Based Fall Detection System” The conference abstract is attached in the Appendix.

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

We are currently refining our fall detection algorithms as proposed. First, we will focus on updating the Convolutional Neural Network (CNN) for the fall detector using the Laboratory data (Aim 1) and the new Real-World Data (Aim 2). In this work we will determine the feasibility of using Laboratory-based data to detect Real-World events. Then we will seek to personalization the CNN using participants who participated in both Laboratory and Real-World data collections. In addition, we will seek to optimize the Classical Machine Learning (ML) and Deep Learning (DL) models for the microprocessor hardware used by developing a new Automated Machine Learning (AutoML) pipeline to optimize ML and DL models for small processor and memory applications without post-pruning of the data. This will allow us to collect richer datasets in the future. We will be presenting a

portion of this work at the annual meeting of the *American Society of Biomechanics* with a poster titled “Development of an Automated Framework for a TinyML-Based Fall Detection System” on August 8-11, 2023 (see attached abstract in the Appendix).

4. Impact

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

Nothing to Report at this time as the project is still ongoing.

What was the impact on other disciplines?

Nothing to Report.

What was the impact on technology transfer?

Nothing to Report.

What was the impact on society beyond science and technology?

Nothing to Report.

5. Changes/Problems

Nothing to Report.

6. Products

Publications, conference papers, and presentations

Lewallen, L.K., Pew, C.A., Wurdeman, S.R., and Neptune, R.R. (2021). Detection of different fall types in healthy young adults. *45th Annual Meeting of the American Society of Biomechanics*, August 10-13, Atlanta, GA.

Mohasel, M., Lewallen, L.K., Pew, C., Neptune, R.R. (2022). A machine learning scheme to identify falling for lower limb amputees. *North American Congress on Biomechanics*, August 21-25, Ottawa, ON, Canada.

Lewallen, L.K., Pew, C.A., Wurdeman, S.R., and Neptune, R.R. (2022). Detection of different fall types in healthy young adults. *Department of Mechanical Engineering Graduate Student Research Poster Session*, March 4, Austin, TX.

Molina, L.K., Pew, C.A., Wurdeman, S.R., and Neptune, R.R. (2023). The influence of machine learning configurations on the detection of fall types in individuals with lower-limb amputations. *IEEE Sensors* (submitted Nov 30, 2022).

Mohasel, M., Molina, L.K., Wurdeman, S.R., Neptune, R.R. and Pew, C.A. (2023). A machine learning scheme to identify falling for lower limb amputees, *IEEE Sensors* (in preparation).

Mohasel, M., Molina, L.K., Wurdeman, S.R., Neptune, R.R., and Pew, C.A. (2023). Development of an automated framework for a TinyML-based fall detection system. 47th Annual Meeting of the American Society of Biomechanics, August 8-11, Knoxville, TN.

Website(s) or other Internet site(s)

Nothing to Report.

Technologies or techniques

Nothing to Report.

Inventions, patent applications, and/or licenses

Nothing to Report.

Other Products

Nothing to Report.

7. Participants & Other Collaborating Organizations

What individuals have worked on the project?

Name:	Richard R. Neptune
Project Role:	PI
Researcher Identifier:	NIH eRA Commons ID: rneptune
Nearest person month worked:	1
Contribution to Project:	Dr. Neptune helped put together the IRB application for approval from both UT Austin and HRPO. He also supervised the graduate student work on the project.
Name:	Lindsey Lewallen
Project Role:	Graduate Student
Researcher Identifier:	N/A
Nearest person month worked:	6
Contribution to Project:	Ms. Lewallen helped put together the two IRB applications and has been working with the machine learning algorithms to be used in the project.
Name:	Corey Pew
Project Role:	Collaborator
Researcher Identifier:	N/A
Nearest person month worked:	1
Contribution to Project:	Dr. Pew has helped to refine the machine learning algorithms to work in real-time.

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

None to Report.

What other organizations were involved as partners?

- **Organization Name:** Hanger Clinic
- **Location of Organization:** Austin, TX
 - **Partner's contribution to the project:** Collaboration, help with subject recruitment.
- **Organization Name:** Montana State University,
- **Location of Organization:** Bozeman, MT
 - **Partner's contribution to the project:** Collaboration, help with algorithm development.

8. Special Reporting Requirements

Collaborative Awards: Not applicable

Quad Charts: Attached in Appendix.

9. Appendices

Development of an Automated Framework for a TinyML-Based Fall Detection System

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Introduction

Falls pose a significant risk of injury and even mortality for individuals with lower limb amputations [1]. Although fall detection devices can objectively track fall incidence, they often have limited memory and low power. Therefore, many previous studies have relied on simple machine learning (ML) algorithms, which can suffer from high false alarms and low detection rates [2]. In contrast, deep learning (DL) models have the potential to reduce false alarms by automatically learning features from input data using neural networks. However, designing a TinyML [3] model architecture (i.e., to be run on low-power, small footprint devices) that achieves a high detection rate relies on multiple interdependent variables, making manual configuration challenging. This study aims to automate both ML and DL workflows and optimize their performance, thereby enabling the development of an efficient TinyML system.

Methods

Data were collected from 35 individuals, 30 intact controls (model training) and 5 lower limb amputees (model testing). Two inertial measurement unit sensors [4] placed on the anterior of each shank measured acceleration and angular velocity in the x, y, and z directions. Participants navigated a laboratory course that involved a range of activities of daily living (ADL) and controlled falling movements.

Data was highly imbalanced, with 98.3% ADL versus 1.7% falls, requiring appropriate methods and metrics (F-score) for training and model comparison. RUSBoost [5] and Easy Ensemble [6] are designed for imbalanced data and represent ML models. For DL, a one-dimensional Convolutional Neural Network (CNN) has shown high accuracy on time series data [2]. CNNs extract features from input data with convolutional layers, allowing parallel processing and faster inference time compared to similar deep models. The final model was designed to be implemented on an ESP32 processor with onboard memory of 512 KB. Automation utilized a weighted sum approach [7] with F-beta score and the number of inference operations as objectives, and memory capacity as a constraint.

ML classifier data was segmented into windows of 15 consecutive samples based on hardware restrictions. Optimal performance of models considered several hyperparameters including the number of estimators, maximum depth of trees, minimum sample leaves, minimum number of samples required to split a node, the cost-complexity parameter (ccp_alpha), sampling strategy, and window size. A Bayesian optimization method [8] and 10-fold cross-validation techniques were employed to tune the hyperparameters and determine the optimal combination that yielded the highest F-beta score while minimizing the number of inference operations.

CNN data was segmented into fixed windows of 100 consecutive samples, representing the duration of a fall or ADL. A weighting method by percent of sample count was utilized to handle the class imbalance [9]. Hyperparameters including the number of convolutional, pooling, and dropout layers, as well as their order, filter size, number of fully connected layers, and number of neurons were fine-tuned using Bayesian optimization. The developed neural architecture search approach simultaneously

scales all dimensions of the network (width, depth, and resolution) and constructs architectures that use memory below 512 KB.

Results and Discussion

Table 1: Comparison of developed models. Best performance bolded.

Model	RUSboost		EasyEnsemble		CNN	
	Fall	ADL	Fall	ADL	Fall	ADL
Recall	91%	79%	81%	93%	97%	98%
Precision	6%	100%	15%	100%	43%	100%
F-score	87%		95%		98%	
Run-time	18 KB		27KB		228 KB	

The CNN model outperformed in all metrics except run time size (Table 1). The RUSboost model ranked second in fall detection with a 91% recall, but with a high false alarms rate (6% precision). The EasyEnsemble model lowered the false alarm rate but at the expense of misclassifying fall incidence (81% recall). The success of the CNN model can be attributed to three factors: 1) CNN employs time domain features to distinguish between falls and ADLs, whereas the raw data was directly used in the other models as generating features for traditional ML models was not feasible in real time due to the hardware constraint of our ESP32, 2) availability of 7 million samples for training favors deep models more, and 3) the weighting method utilized for CNN is effective for high imbalance ratios.

Significance

This study presents a novel automated framework that uses multi-objective optimization to train ML and DL models. It facilitates the deployment of these models on hardware with limited resources, which is ideal for settings where resources are constrained. The framework also addresses the persistent challenge of class imbalance in fall detection studies.

Prior research [2] developed a CNN architecture for TinyML, achieving a 96% recall rate without class imbalance, indicating our present work meets or exceeds previous methods. Building upon this work, the proposed automated framework can export TinyML with high detection rates without requiring tedious manual model tuning. Our CNN model can provide clinicians with accurate and objective information about patient falls, enabling them to develop appropriate interventions and prosthetic prescriptions to improve patient care and safety.

Acknowledgements

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