Proceedings of the 2025 Design of Medical Devices Conference
DMD2025
April 28-30, 2025, Minneapolis, MN, USA

DMD2025-1XXX

FOOD-WASTE DERIVED TRIBOELECTRIC SENSORS FOR BIOMECHANICAL MONITORING OF FRAILTY STATUS AND FALL RISK IN OLDER ADULTS

Md Salauddin, Ph.D.
University of Illinois Urbana-Champaign
Urbana, IL

Prakhar Gupta
University of Illinois Urbana-Champaign
Urbana, IL

Yang Fu
University of Illinois Urbana-Champaign
Urbana, IL

Manuel Hernandez, Ph.D.
University of Illinois Urbana-Champaign
Urbana, IL

Yi-Cheng Wang, Ph.D.
University of Illinois Urbana-Champaign
Urbana, IL

ABSTRACT

Value-added products that could be made from food waste include triboelectric (nano-)generators, which rely on contact electrification and electrostatic induction to convert ambient mechanical energy into electricity. Compared to the other two leading mechanical-energy harvesting approaches, respectively based on piezoelectricity and electromagnetism, triboelectric devices can more effectively harvest ambient mechanical energy at low frequencies (< 5 Hz): the range into which most such energy, including that from human motion, falls. This suggests that triboelectric devices could be more suitable than their piezoelectric and electromagnetic counterparts for both biomechanical energy harvesting and biomechanical monitoring. In addition, previous research concluded that triboelectric energy-harvesting devices have half the negative environmental impact of piezoelectric ones. Nevertheless, triboelectric technology is in its infancy, and more research is needed to 1) improve its performance and 2) devise real-world applications for it. The present study seeks to validate a wearable triboelectric sensor in real-world scenarios used to evaluate fall risk and frailty in older adults: standing, walking, and walking while talking. Using standing balance and gait characteristics from novel wearable sensors it will seek to detect changes in fall risk or frailty status using more environmentally friendly devices.

Keywords: wearable devices, frailty, fall risk, aging

1. INTRODUCTION

Food waste is a massive and critical problem. More than 80 billion pounds of food worth $161 billion are wasted annually in the United States,[1] and most of it is sent to landfill, potentially causing a range of downstream environmental problems. Such waste can occur both before and after consumers purchase food. In the former case, valorization of food waste via engineering approaches is commonly used to address it, while in the latter, the focus has been on long-term education programs and policy changes. Therefore, exploring new opportunities for utilizing products derived from food waste is vital.

Mechanical energy from the ambient environment can potentially be used to power wearable devices and other small electronic items such as the sensors and actuators used in the Internet of Things (IoT). Unlike other forms of renewable energy that can be limited by weather and/or location (e.g., solar/geothermal), mechanical energy – from ocean waves, wind, moving vehicles, human motion, and many other sources – is ubiquitous and abundant, even indoors. Successful mechanical-energy harvesting could therefore revolutionize long-term healthcare monitoring, as current devices require large, heavy power units and/or frequent charging or battery changes. Also, the importance of biomechanical monitoring can hardly be overemphasized, as it is commonly used in the contexts of musculoskeletal disorders, Alzheimer's disease, and other conditions that collectively cost the U.S. economy more than $1 trillion annually.[2] Mechanical-energy harvesting could also reduce the replacement costs and negative environmental impacts of using vast numbers of batteries in the more than 26 billion devices that comprise the IoT.

Value-added products that could be made from food waste include triboelectric (nano-)generators, which rely on contact electrification and electrostatic induction to convert ambient mechanical energy into electricity. Compared to the other two leading approaches to mechanical-energy harvesting, which are respectively based on piezoelectricity and electromagnetism, triboelectric devices can more effectively harvest ambient mechanical energy at low frequencies (< 5 Hz [3,4]): the range of most such energy, including that from human motion. This suggests that triboelectric devices could be more suitable than their piezoelectric and electromagnetic counterparts for both biomechanical-energy harvesting and biomechanical monitoring. In addition, previous research concluded that triboelectric energy-harvesting devices have half the negative environmental impact of piezoelectric ones. [4] Nevertheless, triboelectric technology is in its infancy, and more research is needed to 1) improve its performance and 2) devise real-world applications for it.

Annually, an estimated 36 million falls occur each year among adults over 65 years of age.[5] Of those affected, 8 million are injured and an estimated 3 million adults sustain injuries that require emergency care and may precipitate frailty. Falls may also be fatal; on average, 32,000 deaths a year are attributed to falls in the U.S. alone, and worldwide they are the second most common cause of unintentional death.[5] Furthermore, the U.S. saw a 30% increase in fall-related deaths for older adults between 2009 and 2018, and in the coming years, these numbers are expected to grow, as the number of Americans 65 years of age and older continues to increase. Economic costs associated with falls in older adults amount to $50 billion for non-fatal fall-related injuries and $754 million in fall-related fatalities.[6] Thus, early detection of adults at higher risk for falls would benefit from earlier interventions aimed at maintaining functional capacity across people's lifespan and minimizing the risk of injurious falls. Thus, energy-harvesting triboelectric sensors may have considerable utility as part of a smart home for monitoring changes in fall risk and frailty that may negatively impact independence. The work presented below outlines prototype development and proof-of-concept testing.

2. MATERIALS AND METHODS

Many of the high-performance triboelectric devices invented to date involve complex and/or expensive manufacturing processes such as ion injection and plasma treatment, or expensive functional materials: substantial barriers to their wide adoption and application. Recently, however, it was demonstrated that by doping polymers with carbon-based materials using a simple, inexpensive blending approach, devices' triboelectric output performance could be increased more than tenfold compared to undoped ones, due to increases in the relative permeability of the triboelectric layers. In addition, as 25-30% by weight of fruit and vegetable products – notably including peels – is wasted during processing, using fruit peel to synthesize the carbon-based materials mentioned above could sharply lower the cost of fabricating triboelectric devices. [7] Thus, the proposed work uses carbonized fruit peels to make flexible and stretchable films for the fabrication of triboelectric devices.

2.1 Triboelectric Sensor

The proposed truncated-pyramid structured wearable sensor is made of four distinct layers. The first, a layer of conductive fabric, is initially attached to the second: a carbonized orange peel (COP) and polydimethylsiloxane (PDMS) layer. In the resulting two-layer structure, the fabric serves as the top electrode, and the COP/PDMS layer functions as the positive triboelectric contact material. The third layer, comprising truncated pyramids of PDMS, is next attached to the fourth, of conductive polymer (composed of COP and PDMS), with the pyramid-structured PDMS layer functioning as the triboelectrically negative material and the conductive polymer as the bottom electrode. Finally, the two pairs of layers, as shown in Figure 1, are encapsulated in PDMS.

The initial prototype considered a single triboelectric sensor location at the heel, so as to monitor heel strike events during walking, as seen in Figure 2.

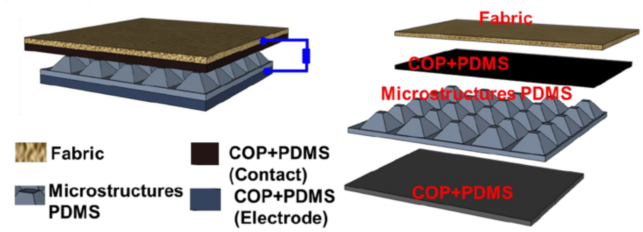

FIGURE 1: OVERVIEW OF THE CARBONIZED ORANGE PEEL TRIBOELECTRIC SENSOR

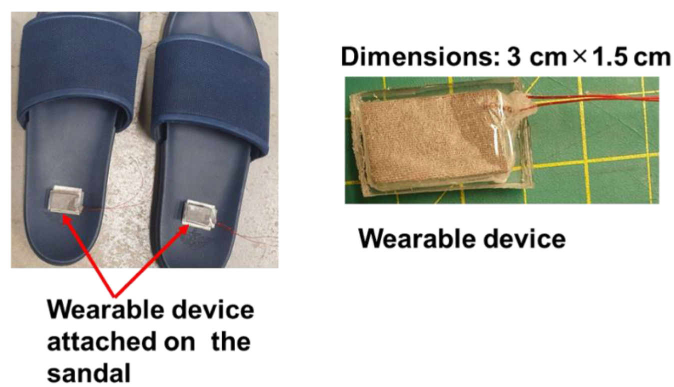

FIGURE 2: PROTOTYPE OF THE CARBONIZED ORANGE PEEL TRIBOELECTRIC SENSOR

2.2 Biomechanical Monitoring System Design

In addition to the sensor, a data capture and wireless transmission module was designed to provide interconnectivity with a mobile device for storing and monitoring of biomechanical characteristics. A custom analog circuit consisting of a simple Unity gain op-amp, with a DC offset of VDD/2 and a low-pass filter was initially considered (see Fig. 3). This was intended to "stabilize" the output of the TENG, utilizing the unity-gain op-amp to behave as a current buffer. The DC offset of VDD/2 was added since the ESP32-C2 ADC can only sample values in [0, VDD]. An additional scaling resistor was considered to ensure that V_{esp} was within this range. Additionally, we intended to add a low pass filter to filter out all frequency components beyond 32Hz. However, this in-house solution was abandoned, and replaced with a TI ADS8689, due to its improvement on noise in the ADC and better ability to handle a high swing in input voltage (~20 V). The TI ADC offered a high-performance solution that works for high input variances and has already been tested for accuracy. A schematic of this updated circuit is provided on Figure 4.

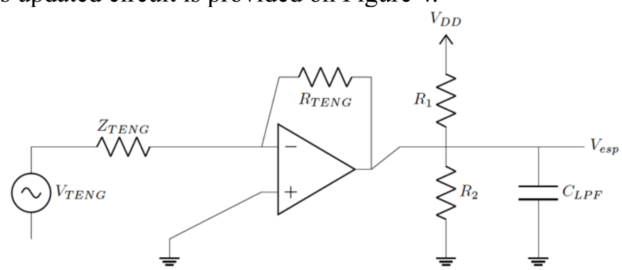

FIGURE 3: INITIAL CIRCUIT SCHEMATIC OF BIOMECHANICAL MONITORING SYSTEM

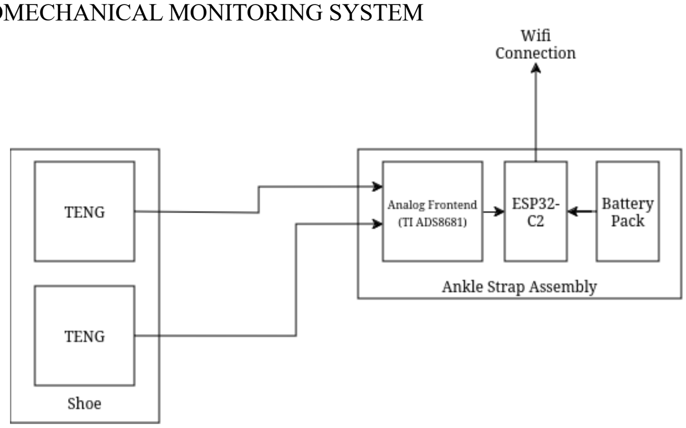

FIGURE 4: CIRCUIT SCHEMATIC OF BIOMECHANICAL MONITORING SYSTEM

2.3 Fall and Frailty Prediction Framework

Using 2 minutes of treadmill walking data from each of 52 healthy adults (20-78 years of age) with and without a history of falls within the past year we evaluated how well we could classify fallers from non-fallers using wearable sensor data. The features of those data included stance time and cadence, among other measures. In the interest of maximizing the number of samples available for classification evaluation, all 2-minute treadmill walking data recordings were segmented into 10-second epochs. For every epoch generated, the means and standard deviations of every gait parameter were calculated and used for classification. This means that 1,025 samples from non-fallers and 257 samples from fallers were used in this analysis. A binary classifier using LightGBM was evaluated in terms of both accuracy and F1-score. Fall-risk model performance was evaluated with a group-stratified k-fold (k=5) cross-validation approach using Python libraries (Numpy, Pandas, Optuna, Matplotlib) so as to minimize information leakage between training and testing.

3. RESULTS AND DISCUSSION

The triboelectric sensor was evaluated using different loads and frequencies of load application. Figure 4 illustrates that the output voltage increases with the weight ratio of COP to PDMS, ranging from 9% to 17%, which enhances the conductivity of the electrode. As shown in Figure 5, the generated voltage remains nearly constant as the frequency increases from 1 Hz to 5 Hz. These results highlight the potential of the COP-based electrodes as a low-cost, environmentally friendly alternative to expensive commercial metal electrodes, making it suitable for next-generation metal-free harvesting devices, flexible sensors, electronics, and human-machine interactive systems.

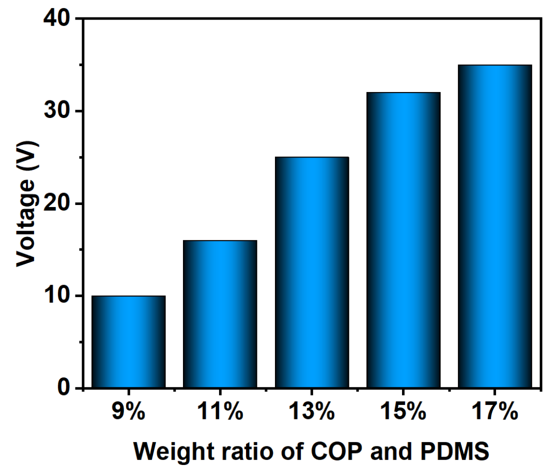

FIGURE 5: VARIATIONS IN THE TRIBOELECTRIC NANOGENERATOR (TENG) VOLTAGE FOR PDMS WITH DIFFERENT CARBONIZED ORANGE PEEL (COP) WEIGHT RATIOS AT A FREQUENCY OF 2 HZ AND A FORCE OF 10 N

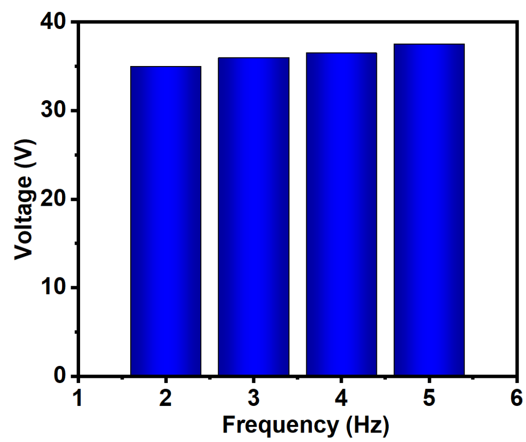

FIGURE 6: OUTPUT PERFORMANCES OF TENG VOLTAGE WITH 17% CARBONIZED ORANGE PEEL (COP) AND PDMS MADE ELECTRODE AS A DIFFERENT FREQUENCY

The fall prediction framework we derived from wearable sensor data achieved an accuracy of 0.64 and an F1-score of 0.65 for individual 10-second segments. Using this benchmark for performance, our future work will evaluate whether transfer learning can be applied to a database of triboelectric sensor data as a means of evaluating the proposed fall-prediction framework.

Prior work has demonstrated the feasibility of using gait-derived metrics from wearable sensors to predict falls.[8–10]

Further, prior work has changes due to neurological conditions, such as multiple sclerosis or Parkinson's disease,[11–13] that are associated with increased frailty.[14] Future work should be focused on evaluating the feasibility of using triboelectric sensor derived features for frailty prediction.

4. CONCLUSION

Overall, this proof-of-concept study demonstrates how a food-waste derived triboelectric sensor could be used in a future smart home. Future work will focus on miniaturization of the system and decreasing its energy demands. Ensuring that the system remains as light as possible and compatible with user selected footwear are priorities, as both are likely to impact system adoption by older adults.

ACKNOWLEDGEMENTS

This work was supported by the USDA-NIFA Hatch grants program (ILLU-698-994).

REFERENCES

[1] Buzby, J. C., Farah-Wells, H., and Hyman, J., 2014, "The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States," USDA-ERS Economic Information Bulletin, (121).

[2] Norins, L. C., 2019, "Predicted Economic Damage from a Quick, Simple Alzheimer's Disease Cure," Med Hypotheses, **133**, p. 109398.

[3] Zi, Y., Guo, H., Wen, Z., Yeh, M.-H., Hu, C., and Wang, Z. L., 2016, "Harvesting Low-Frequency (< 5 Hz) Irregular Mechanical Energy: A Possible Killer Application of Triboelectric Nanogenerator," ACS Nano, **10**(4), pp. 4797–4805.

[4] Ahmed, A., Hassan, I., Helal, A. S., Sencadas, V., Radhi, A., Jeong, C. K., and El-Kady, M. F., 2020, "Triboelectric Nanogenerator versus Piezoelectric Generator at Low Frequency (< 4 Hz): A Quantitative Comparison," iScience, **23**(7).

[5] for Disease Control, C., and Prevention, "Deaths from Older Adult Falls."

[6] for Disease Control, C., and Prevention, "Cost of Older Adult Falls."

[7] Kumar, H., Bhardwaj, K., Sharma, R., Nepovimova, E., Kuča, K., Dhanjal, D. S., Verma, R., Bhardwaj, P., Sharma, S., and Kumar, D., 2020, "Fruit and Vegetable Peels: Utilization of High Value Horticultural Waste in Novel Industrial Applications," Molecules, **25**(12), p. 2812.

[8] Howcroft, J., Kofman, J., and Lemaire, E. D., 2017, "Prospective Fall-Risk Prediction Models for Older Adults Based on Wearable Sensors," IEEE Transactions on Neural Systems and Rehabilitation Engineering. https://doi.org/10.1109/TNSRE.2017.2687100.

[9] Montesinos, L., Castaldo, R., and Pecchia, L., 2018, "Wearable Inertial Sensors for Fall Risk Assessment and Prediction in Older Adults: A Systematic Review and Meta-Analysis," IEEE Transactions on Neural Systems and Rehabilitation Engineering. https://doi.org/10.1109/TNSRE.2017.2771383.

[10] Buisseret, F., Catinus, L., Grenard, R., Jojczyk, L., Fievez, D., Barvaux, V., and Dierick, F., 2020, "Timed up and Go and Six-Minute Walking Tests with Wearable Inertial Sensor: One Step Further for the Prediction of the Risk of Fall in Elderly Nursing Home People," Sensors, **20**(11), p. 3207.

[11] Kaur, R., Motl, R. W., Sowers, R., and Hernandez, M. E., 2022, "A Vision-Based Framework for Predicting Multiple Sclerosis and Parkinson's Disease Gait Dysfunctions-A Deep Learning Approach," IEEE J Biomed Health Inform.

[12] Kaur, R., Chen, Z., Motl, R., Hernandez, M. E., and Sowers, R., 2020, "Predicting Multiple Sclerosis from Gait Dynamics Using an Instrumented Treadmill – A Machine Learning Approach," IEEE Trans Biomed Eng. https://doi.org/10.1109/TBME.2020.3048142.

[13] Kaur, R., Levy, J., Motl, R. W., Sowers, R., and Hernandez, M. E., 2023, "Deep Learning for Multiple Sclerosis Differentiation Using Multi-Stride Dynamics in Gait," IEEE Trans Biomed Eng.

[14] Motl, R. W., Chaparro, G., Hernandez, M. E., Balto, J. M., and Sandroff, B. M., 2018, "Physical Function in Older Adults with Multiple Sclerosis: An Application of the Short Physical Performance Battery," Journal of Geriatric Physical Therapy, **41**(3). https://doi.org/10.1519/JPT.0000000000000115.