Comparison and Analysis of Adversarial Machine Learning Techniques on MNIST

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***Abstract*—This study presents the development of electricity-generating footwear that captures mechanical energy from footsteps using integrated piezoelectric sensors and rectifier diodes within the shoe sole. Each step compresses the sensors, generating a small, continuous electrical current. Silicon-based cushioning pads are used to enhance comfort and optimize force distribution on the sensors, improving energy conversion. The AC output is rectified to DC for storage or direct use.**

The project involves design, fabrication, testing, and evaluation phases, with prototypes tested for efficiency. The generated energy can power low-energy devices, offering a potential alternative to traditional charging methods. This research demonstrates the feasibility of piezoelectric footwear as a sustainable energy solution, contributing to advancements in renewable energy and innovative applications of piezoelectric technology.

***Index Terms*—Electricity-generating footwear, piezoelectric sensors, sustainable energy, mechanical energy conversion, energy harvesting, wearable technology.**

I. Introduction

In a world marked by increasing energy demands and the pressing need to reduce our carbon footprint, the pursuit of innovative and sustainable energy sources has become crucial. This project focuses on the development of electricity-generating footwear as a source of renewable energy.

A. Background and Motivation

Conventional energy generation primarily relies on finite fossil fuel resources, presenting significant environmental and geopolitical challenges [1]. The adverse impacts of these methods—climate change, pollution, and resource depletion—underscore the urgency of seeking alternative energy solutions. Moreover, the demand for portable and decentralized power sources is growing, particularly for remote or off-grid locations and for powering wearable electronic devices.

Electricity generation from human footsteps offers a promising avenue for supplemental sustainable energy [2]. Human locomotion, a fundamental aspect of daily life, presents an untapped reservoir of mechanical energy. Efficiently harnessing this energy could provide a valuable source of renewable power, contributing to the global shift towards clean and sustainable energy technologies and reducing reliance on fossil fuels in niche applications.

B. Importance of Sustainable Energy Sources

Sustainable energy sources, which produce power without depleting finite resources or causing harmful environmental effects, are crucial for an environmentally responsible future. Beyond mitigating climate change, these sources promote energy security, reduce pollution, and foster economic stability. Sustainable energy technologies alleviate environmental strain and empower communities, businesses, and individuals to control their energy needs [3].

C. Overview of Electricity Generation from Footsteps

Electricity generation from footsteps is based on the principle of piezoelectricity, where piezoelectric materials convert mechanical stress into electrical energy. When subjected to pressure or deformation, these materials generate a voltage potential, making them ideal for harvesting energy from motion. By integrating piezoelectric sensors into footwear soles, mechanical energy from each step can be captured, creating a renewable power source suitable for powering low-energy devices.

D. Objectives and Scope

The primary objective is to explore, design, fabricate, and evaluate the feasibility and practicality of electricity-generating footwear. We aim to demonstrate that human motion can efficiently generate electricity without compromising footwear comfort and functionality. Additionally, we will investigate potential applications of the generated electricity, including energy storage and powering low-energy devices

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such as mobile phones, flashlights, or lighting up a sidewalk in a park.

This project's scope includes selecting appropriate materials, integrating piezoelectric sensors and rectifier diodes, conducting tests and data collection, and utilizing the generated electricity practically. By the project's conclusion, we aim to validate this technology's viability and contribute to the growing body of knowledge in renewable energy and wearable technology. Our endeavor represents a small but significant step towards a more sustainable and energy-responsible future, focusing on niche applications where this technology can make a meaningful impact.

II. Literature Review

Ahmad et al. [4] investigated the biomechanics of walking to develop a customized plate that optimizes energy harvesting. By strategically placing piezoelectric discs at the heel and ball regions of the foot, the design targets areas of greatest impact during each step. This placement ensures efficient conversion of mechanical force into electrical energy, capturing energy from the natural gait of the wearer and enhancing the overall efficiency of the electricity-generating footwear. This approach significantly contributes to the practicality and effectiveness of sustainable energy solutions.

Boby et al. [5] demonstrated that utilizing a dual-layer configuration of piezoelectric materials significantly amplifies the generated voltage, nearly doubling the output compared to a single-layer setup. To efficiently store this electrical energy, a Lithium-Polymer (LiPo) battery was employed. This configuration not only enhances energy harvesting performance but also ensures that surplus electricity is effectively captured and stored for later use. This method exemplifies a commitment to maximizing energy efficiency and sustainability through the power of footsteps.

Laumann et al. [6] highlighted the versatile applications of piezoelectric technology beyond electricity-generating footwear. The technology can be applied in flooring systems, road surfaces, and railway tracks to capture mechanical energy generated by vehicular or pedestrian traffic. This broader application signifies the adaptability of piezoelectric materials for sustainable power generation, potentially revolutionizing how electricity is generated from everyday activities.

Rocha et al. [7] examined the use of PZT (lead zirconate titanate) and PVDF (polyvinylidene fluoride) as cost-effective materials for energy harvesters. PZT ceramics are particularly advantageous due to their high mechanical-electric coupling factors, higher power output, and easier integration with force amplification frames. Additionally, foot pressure measurements can indicate diseases and abnormalities, as foot pressure varies with health status, age, and activities.

Zhao et al. [8] focused on designing footwear primarily for mobile phone charging. The system includes piezoelectric sensors for energy conversion, voltage boosters to amplify the generated voltage, a voltage regulator for stable output, a PIC microcontroller for control and monitoring, a battery for energy storage, an LCD display for real-time information, an LDR (Light-Dependent Resistor) for ambient light sensing, and a dedicated socket for mobile device charging. This comprehensive setup highlights the multifunctionality and practicality of the footwear, enabling not only energy harvesting but also convenient mobile device charging on the go.

III. Methodology

A. Materials

- **Piezoelectric Sensors**: Lead zirconate titanate (PZT) crystals were selected for their superior piezoelectric properties. These sensors generate an electric charge under mechanical stress, with high sensitivity ensuring maximum energy conversion efficiency.
- **Rectifier Diodes**: Schottky diodes were used for their low forward voltage drop and rapid response to AC input, minimizing energy loss during rectification and enhancing overall system efficiency.
- **Rechargeable Battery**: A 3.7V LiPo battery, chosen for its high discharge rate and energy density, stores the generated energy. Its rechargeable nature promotes sustainability and long-term usability.
- **LED (Light Emitting Diode)**: An LED integrated into the circuit serves as a practical demonstration of the system's functionality, providing illumination and indicating the operation of the electricity-generating footwear.

B. Design of Prototype

The prototype utilizes the piezoelectric effect [9] to convert footstep pressure into electrical energy. To enhance voltage generation, two PZT (Lead Zirconate Titanate) crystals were configured in a dual-layer stack, with one stack positioned at the heel and the other at the ball of the shoe sole. A full-wave rectifier circuit, constructed using four diodes in a bridge configuration, was employed to rectify the output from the piezoelectric sensors. The connections between the piezoelectric sensors and the rectifier circuit are illustrated in Figure 1. The rectified voltage is stored in a Lithium Polymer (LiPo) battery charging module, with an LED connected in parallel to the battery to provide a visual indication of power generation. All components were secured in place using adhesive. The embedded piezoelectric material generates voltage through the following processes:

1) Piezoelectric Effect:

- **Electron Displacement**: Piezoelectric materials exhibit a charge imbalance between anions and cations. Mechanical stress causes atom displacement within the crystal lattice, resulting in charge separation. [10]
- **Anion-Cation Asymmetry**: The difference in electronegativity between anions and cations creates a dipole moment, signifying spatially separated charges within the material.
- **Polarization**: Mechanical stress amplifies charge separation in piezoelectric materials like quartz, increasing the dipole moment and leading to polarization.

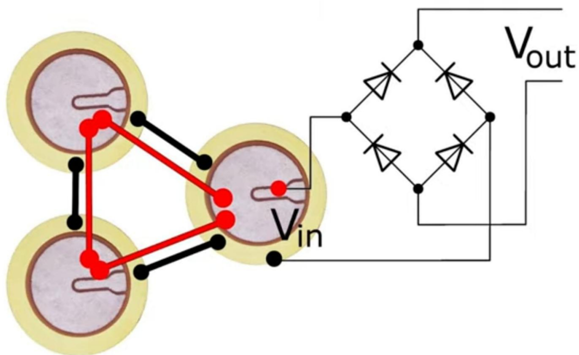

Fig. 1. Schematic Circuit Diagram

- **Voltage Generation**: The cumulative charge separations generate a measurable voltage potential, converting mechanical energy into electrical energy suitable for various applications.

2) Features of Piezoelectric Sensors:

- **Temperature Resilience**: Piezoelectric materials remain stable up to 150°C, with performance changes between 150°C-250°C, and rapid degradation above 250°C. This resilience is crucial for sensor operation in varied environments. [11] Mean Time Between Failure (MTBF) analysis for typical industrial sensors predicts a life of 12 years.
- **Dynamic Sensitivity**: These sensors are highly sensitive to dynamic pressure changes across a range of frequencies and levels, making them valuable for applications involving rapid and varied pressure fluctuations. The output is linear over a wide range, typically 0.7 KPa to 70 MPa (0.1 to 10000 psi) with an accuracy of about 1%.
- **Limitations in Measuring Static Pressure**: Piezoelectric sensors are less effective for static pressure measurements, as their output signal decreases over time under constant or slowly changing pressure.
- **High Sensitivity**: Despite limitations with static pressure, piezoelectric sensors excel in detecting small pressure variations, making them ideal for electricity generation from small and variable movements. A useful output can be generated with as little as 0.1% deformation.

In summary, the piezoelectric effect enables the efficient conversion of footstep pressure into electrical energy, integral to the functionality of electricity-generating footwear. The distinctive features of piezoelectric sensors also extend their utility to a wide range of applications beyond energy harvesting.

IV. Testing and Data Analysis

A. Procedure for Testing and Data Collection

To ensure accurate evaluation, a comprehensive testing procedure was implemented:

Curve	Voltage vs Velocity	Duration vs Voltage	Power vs Voltage	Steps vs Voltage
Linear fit	0.9472	0.8653	0.9507	0.9406
Polynomial fit	0.9045	0.821	0.8059	0.8158
Exponential fit	0.7252	0.7730	0.8096	0.8056

TABLE I
PERFORMANCE METRICS OF DIFFERENT CURVE FITTING METHODS

- **Participant Selection**: A pool of 25 participants was selected, representing various age groups and physical characteristics.
- **Data Collection**: Each participant's height and stride length were measured using a typical measuring tape. Weight was measured using a standard weighing scale. Voltage generated by each participant was calculated and analyzed concerning their physical characteristics. Velocity was calculated as $\frac{\text{stride length} \times \text{number of steps}}{\text{time}}$.
- **Testing Protocol**: Participants wore the electricity-generating footwear and walked a predetermined number of steps that were varied linearly. Participants walked on a smooth pathway. Uniform testing conditions were maintained by measuring the number of steps and time taken for each trial.

B. Data Analysis

Each of the features of the collected data was plotted individually against the target variable *voltage*. R-squared values were calculated for each curve, as shown in Table I and the linear curve was determined to be the best-fitting curve for each metric. Each metric's value was plotted, as shown in Figures 2, 3, 4 and 5. We can see that the graphs display a clearly linear trend.

Figure 2 demonstrates a clearly linear linear relationship between the voltage generated and the velocity of the walk.

As with velocity, voltage generated also appears to be linearly related to the duration as seen in Figure 3.

The power generated was calculated using the measured features, and displays a linear relationship with the voltage as seen in Figure 4.

The relationship between the voltage generated and the measured number of steps was best represented my a linear fit, as seen in Figure 5.

On performing multiple linear regression utilising all features, we obtain a measure of the voltage generated in (1). A graphical representation is shown in Figure 6.

$$\begin{aligned} \text{Voltage} = {} & 4.0337 \cdot \text{Velocity} + 0.0101 \cdot \text{Power} \\ & + 1.4801 \cdot \text{Duration} + 1.9282 \cdot \text{Steps} \\ & - 1.6706 \end{aligned} \tag{1}$$

V. Applications

- **Power Supply for Soldiers:** Electricity generation footwear offers a portable, renewable power source that minimizes battery dependency, enabling soldiers to charge essential electronic devices like GPS units, radios, and night vision goggles while on the move. This

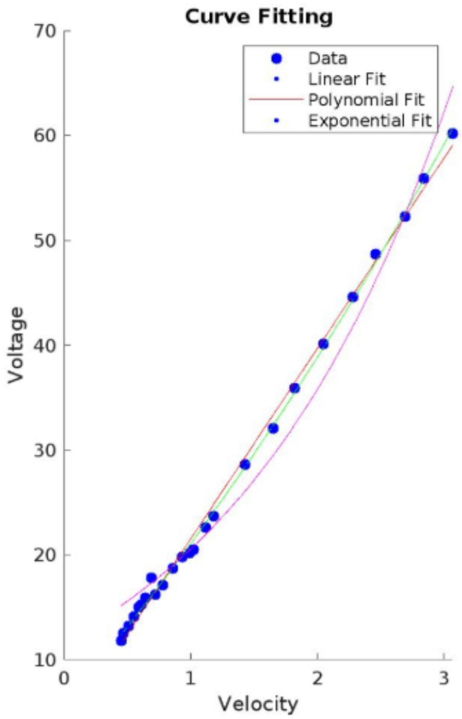

Fig. 2. Voltage vs Velocity

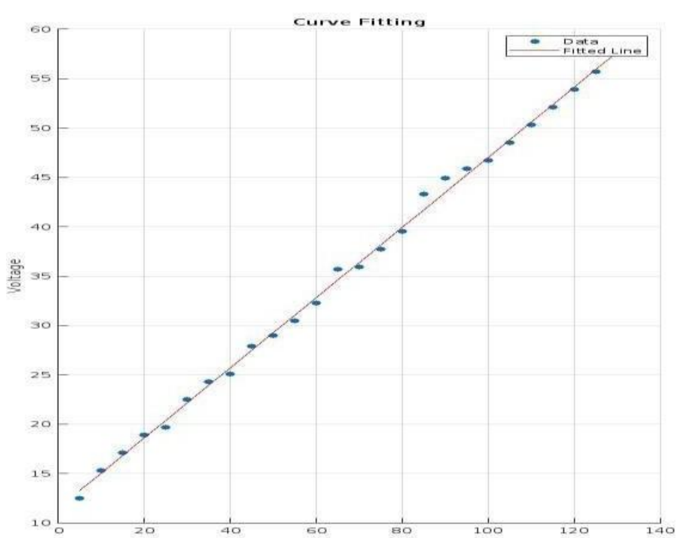

Fig. 3. Voltage vs Duration

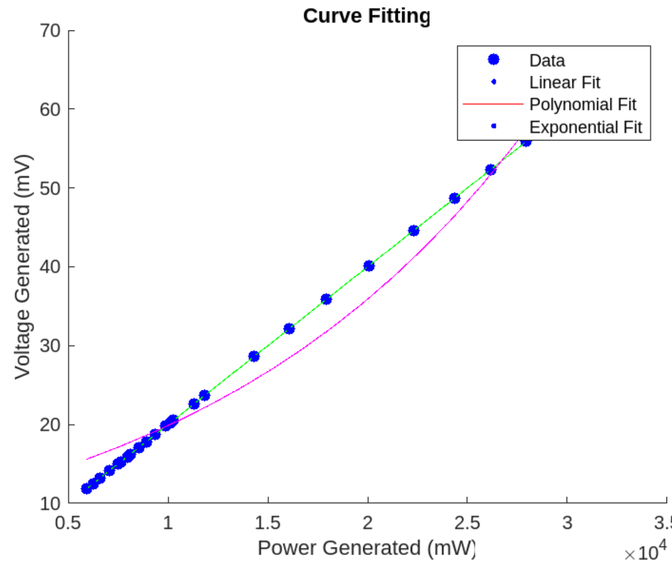

Fig. 4. Voltage vs Power

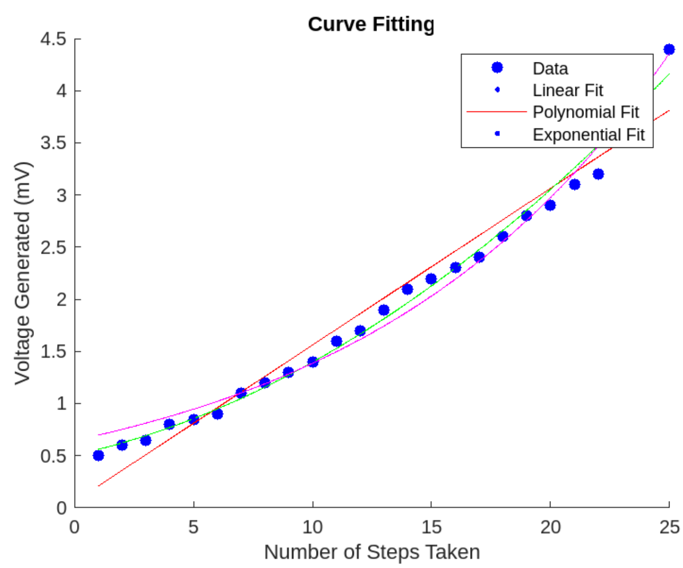

Fig. 5. Voltage vs Number of steps

innovation reduces the need for extra batteries, thereby enhancing mobility and endurance, and allowing for extended operational periods without resupply, ultimately improving mission efficiency and effectiveness.

- **Urban Energy Harvesting**: The potential of electricity-generating footwear presents a significant opportunity for urban energy harvesting. High-footfall areas, such as city streets and public transportation hubs, could greatly benefit from the integration of this technology. Municipalities and urban planners should consider incorporating energy-harvesting pavements and walkways into urban infrastructure. This approach could effectively capture the energy of millions of daily footsteps, potentially powering streetlights, and traffic signals, and even contributing to

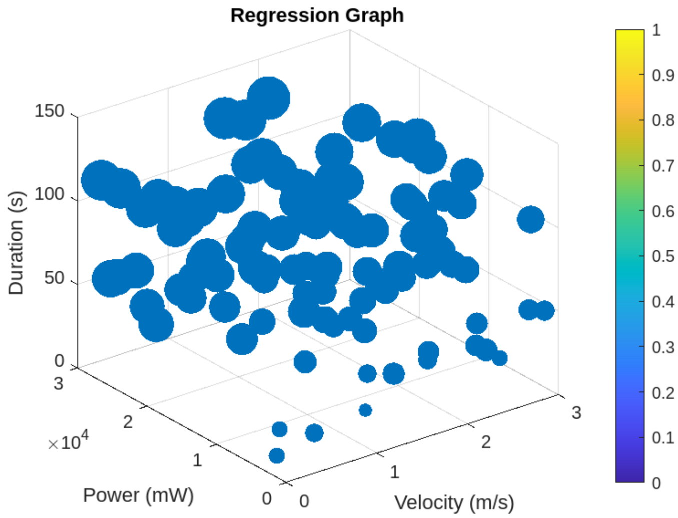

Fig. 6. Multiple feature representation

the electrical grid. [12]

- **Wearable Technology**: The integration of electricity-generating technology into wearable devices represents a promising emerging field. Collaborations with wearable tech companies are recommended to develop energy-efficient gadgets such as fitness trackers, smartwatches, and augmented reality glasses. These devices could harness the energy generated by the user's movement, thereby reducing the need for frequent recharging and enhancing user convenience. [13]
- **Outdoor Recreation**: For outdoor enthusiasts, electricity-generating footwear offers notable benefits. Hikers, backpackers, and campers could use the energy harvested during their activities to recharge essential devices like GPS units, flashlights, and emergency communication tools. Outdoor industry manufacturers should explore partnerships to integrate this technology into their products, providing added functionality for users in remote and demanding environments.
- **Healthcare and Assistive Devices**: Electric-generating footwear could be adapted to support patients with mobility challenges in the healthcare sector. The energy produced from assisted walking could power medical monitoring devices or assistive exoskeletons, thereby enhancing the quality of life for individuals with limited mobility and providing practical solutions for daily living. [14]
- **Smart Textiles:** Integration of electricity generation footwear with smart textiles enables the powering of embedded sensors and health monitoring systems, allowing for real-time tracking of physiological data such as heart rate, temperature, and movement. Additionally, these footwear solutions facilitate energy harvesting for Internet of Things (IoT) devices embedded in clothing, supporting seamless communication and data transfer for smart clothing applications.
- **Educational Tools:** Electricity generation footwear can be employed in educational settings to teach students about renewable energy, biomechanics, and energy conversion principles through hands-on experiments and interactive demonstrations . Additionally, these devices can be used as practical examples in STEM (Science, Technology, Engineering, and Mathematics) projects, motivating students to innovate and develop their own energy-harvesting solutions, thereby enhancing creativity and problem-solving skills.

VI. Challenges

- **Electric Shock Risk**: Improper insulation or exposure to moisture can lead to electric shock, especially since footwear is often subjected to various environmental conditions.
- **Durability:** The constant pressure and movement involved in walking or running can wear down the piezoelectric sensors and the associated circuitry, leading to malfunction or failure.
- **Component Failure:** Components such as piezoelectric sensors and LiPo batteries are susceptible to failure due to overuse, physical damage, or environmental factors.

VII. Future Scope

- **Safety**: subsequent development will incorporate high-grade insulation materials and ensure that all components are housed in waterproof enclosures. This can prevent moisture ingress, reducing the risk of electric shock.
- **Optimizing Energy Conversion:** Future research will prioritize enhancing the efficiency of energy conversion in electricity-generating footwear. Investigations into advanced piezoelectric materials, refined sensor designs, and optimized circuitry can significantly improve the energy yield per step, leading to more effective energy harvesting.
- **Durability and Longevity:** A critical area for future research is the durability and longevity of electricity-generating footwear. Evaluating performance under diverse environmental conditions and extended usage is essential for ensuring practical, long-term adoption. Studies focusing on wear resistance, material fatigue, and overall robustness will be conducted. [15]
- **Customization and Comfort:** To enhance user experience, future research should explore customization options tailored to individual preferences and biomechanics. Potential improvements from adjustable settings for energy output and designs that accommodate various walking styles, thereby maximizing comfort and satisfaction can be investigated. [4]
- **Scalability and Manufacturing:** Advancing the scalability and efficiency of manufacturing processes is vital for making electricity-generating footwear more accessible and cost-effective. Research will address mass production techniques, material sourcing, and supply chain optimization to facilitate broader adoption and reduce costs.

- **Environmental Impact Assessment:** Future studies should incorporate comprehensive life cycle assessments (LCAs) to evaluate the environmental impact of electricity-generating footwear. This includes analyzing the energy and resources required for production, usage, and end-of-life disposal or recycling, ensuring the technology's sustainability. [16]

  These recommendations and future research directions highlight the transformative potential of electricity-generating footwear across various applications, from sustainable urban infrastructure to personalized wearable devices. Continued innovation and exploration in this field will be crucial for realizing its full potential.

VIII. Conclusion

This project explores the potential of electricity-generating footwear, leveraging human motion to produce sustainable energy. Through experimentation and analysis, we have drawn several significant conclusions:

- The velocity of the moving individual significantly affects the voltage generation.
- The number of steps taken and total duration of movement also affect the voltage generation.
- Voltage varied linearly with all measured factors.

Our investigation of the potential impact of electricity generating footwear reveals:

- **Efficient Energy Conversion**: Our research has validated the feasibility of generating electricity from footsteps using piezoelectric sensors and rectifier diodes. The dual-layer design, with sensors strategically positioned at the heel and ball of the foot, significantly increased voltage output, demonstrating the effectiveness of this approach.
- **Sustainability and Environmental Impact**: The development of electricity-generating footwear offers substantial promise in advancing sustainable energy solutions. This technology supports efforts to reduce carbon emissions and decrease reliance on non-renewable energy sources.
- **Wearable Technology Applications**: Integrating this technology into footwear presents practical benefits for powering wearable electronic devices. It reduces the frequency of recharging and enhances user convenience. The generated electricity was effectively stored in a LiPo battery, proving its potential to power low-energy devices.
- **Urban Infrastructure Potential**: Our findings suggest that this technology could extend to urban infrastructure applications. Smart pavements and walkways powered by this footwear could provide energy for streetlights and other urban amenities, contributing to more sustainable city environments.

In summary, this project not only achieved its core goals but also highlights numerous potential applications in sustainable energy and wearable technology. Our findings contribute to the quest for alternative energy sources and the advancement of eco-friendly, user-centric innovations. In an era prioritizing sustainability and energy efficiency, electricity-generating footwear represents a tangible and impactful solution, offering a promising path toward a greener future.

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