ENGINEER - Vol. LVIII, No. 01, pp. [27-37], 2025

DOI: https://doi.org/10.4038/engineer.v58i1.7675

# Improving Road Safety of Bicycles through Vibration Based Energy Generation

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**Abstract:** The world is currently prioritizing sustainable energy concepts, recognizing the significance of electric power in modern living and technological advancement. Amidst a recent fuel crisis in Sri Lanka, bicycles have gained popularity as transportation vehicles and globally renowned sporting equipment, contributing significantly to eco-friendly mobility in urban and suburban areas. In this research context, it focuses on harnessing piezoelectric energy from bicycle vibrations to enhance eco-friendly mobility and bicycle safety in Sri Lanka. It addresses as a solution to environmental concerns related to disposable batteries, promoting the use of rechargeable batteries, and offering a sustainable alternative to traditional bicycle lighting systems.

**Keywords:** Sustainable, Energy, Piezoelectric, Harnessing

## 1. Introduction

In the current era of prioritizing sustainable energy, the focus is on harnessing electricity for modern living and technological advancement while minimizing environmental impact. Piezoelectric energy harvesting is a promising technology that converts wasted kinetic energy from vibrations into usable electricity. Recently, bicycles have gained popularity in Sri Lanka due to a fuel crisis, contributing to eco-friendly mobility. However, the vibrations generated by the rolling motion of bicycle wheels on rough roads lead to rider discomfort and muscle pains. This research proposes a novel approach to harvest energy from these vibrations and use pedalling to generate continuous power. This energy can enhance bicycle safety by powering lights, navigation systems, and electronic devices, aligning with the global sustainability shift and the demand for safer, more comfortable cycling.

## 2. Aims and Objectives

Bicycles, often seen as precursors to automobiles, serve as highly versatile and efficient short-range modes of transportation worldwide, even in diverse regions like Sri Lanka. The paramount concern for cyclist safety has prompted many countries to implement comprehensive regulations governing bicycle use. These regulations extend to lighting, specifying requirements for active and passive lighting systems, including the types of lights, reflectors, placement, and colour schemes. Compliance with these regulations, as depicted in Figure 1, is critical to ensuring cyclists' visibility to both fellow road users and pedestrians, thereby enhancing overall safety.

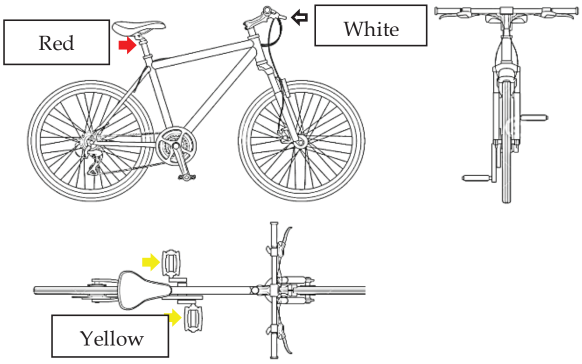


**Figure 1 - Typical View of a Bicycle Highlighted with Minimum of Illumination**

The core objective of this research project is the development of a precisely tailored energy harvesting module designed to power bicycle lighting systems. Key project objectives include the creation of ergonomic conceptual designs for this specialized energy harvesting device and a detailed evaluation of its structural integrity and performance through Finite Element Analysis. It underscores the commitment to ensuring cyclists' safety and comfort while simultaneously harnessing the energy generated during their rides to power vital lighting systems, improving the overall quality of the cycling experience.

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## 3. Literature Review

Today, there are lots of designs of bicycle that are developed mainly considering aerodynamic aspects to minimize aerodynamic drag when riding a bicycle. But basic components of a bicycle like, two wheels, saddle, pedals, handlebar etc. still exist. As typically experience, on riding a bicycle in a road, vibrations from the road are transferring to the human body at different locations. Much research has been proven that it is mainly via five contact points as shown in Figure 2. Though there are cushioning effects from tires and shock absorbers (if available), considerable number of vibrations are yet transferring to human body.

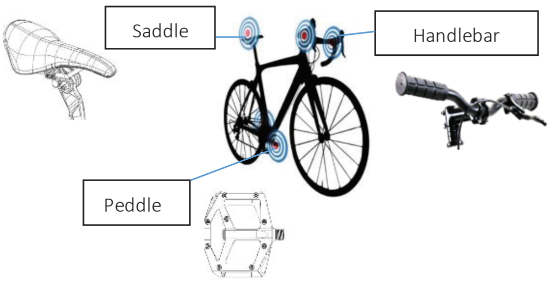



**Figure 2 - Five Contact Points of a Bicycle with Human Body when Riding a Bicycle**

As shown in Figure 2, saddle is often called a bicycle seat, is one of comfort zone essential in riding a bicycle for longer range. Several layers of cushions are used to achieve the required amount of comfortability. Pedals are a part of a bicycle that the rider pushes with their foot to propel the vehicle forward. The entire force required to drive bicycle wheels are exerted on pedals.

Improving traffic safety for bicyclists is a focal point in the road traffic safety as well, with the prominent movement for bicycle usage in roads by now. Even many causalities have happened due to slowing or stopping, turning, overtaking, and going ahead proving illumination is essential to prevent many cyclist causalities. So, this issue can be addressed by implementing proper active and passive illumination on bicycles.

Generally, the dynamo system generates some amounts of electrical energy essential for feeding lights. But the amount of energy liberated from a dynamo is not sufficient and limited with its size as cyclist needs to deliver a considerable amount of additional mechanical energy input to the system to generate electrical power as required. Since dynamo power generation has considerable limitations and external battery packs still require frequent replacements and add up additional weight on the bicycle, several approaches based on cycling movements, vibrations and heating can be addressed to harvest considerable amount of energy wasted in the bicycle itself. In the early days, bicycles were integrated with a dynamo to generate electricity as essential to power up lights in any dark environment. But it has become mostly obsolete by now and has been replaced by different technologies of other renewable energies.

### 3.1 Availability and Applications

There are many energy harnessing concepts readily developing for bicycles as shown in Figure 3 to generate electrical energy as required for the bicycle itself.

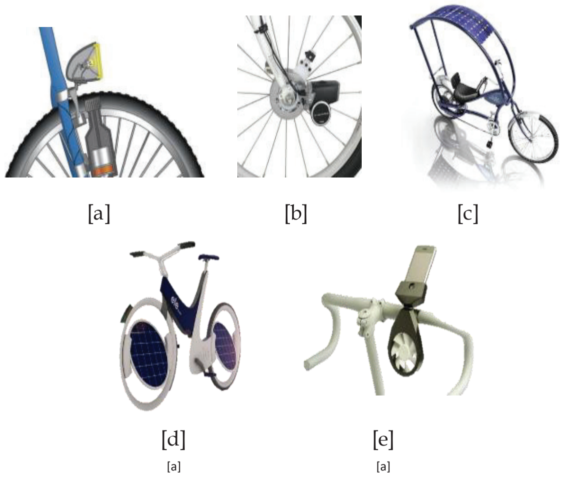



**Figure 3 - Different Types of Energy Modules for Bicycles [a] Classical Dynamo[b] Enhanced Design of a Dynamo [c] Bicycle with Solar Roof [d] Bicycle with Solar Wheel [e] Wind Energy Module**

Figures 3[a] and 3[b] represent a dynamo which is based of electromagnetic induction, Figure 3[c] represents two conceptual models of gathering energy via solar radiation and Figure 3[d] represents an energy module that extracts wind energy while riding a bicycle. So, it always exists the requirement of electrical energy for bicycles as for other automobiles and to integrate comfortability to the rider.

### 3.2 Energy Harnessing Techniques

The study of literature identified several concepts of energy harnessing at different applications. Design and Analysis of Kinetic Energy Recovery System in Bicycles was published in the National Conference on Advances in Mechanical Engineering FORGE'15 which elaborated the system KERS (Kinetic Energy Recovery System) which is a type of regenerative braking energy harnessing method. As shown in Figure 4, this system, akin to regenerative braking, employs a flywheel integrated into the bicycle's chain drive to capture sudden kinetic energy loss during braking. Positioned midway within the bicycle frame, the flywheel operates via a separate driving chain mechanism while riding. Activation of the clutch system upon brake application releases the flywheel to rotate, subsequently generating energy via a dynamo system for storage and various bicycle applications according to the investigation by Aedla et al., (2015).

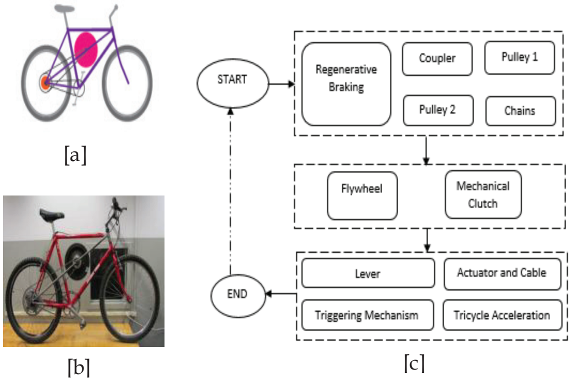



**Figure 4 - Design of a Kinetic Energy Recovery System for a Bicycle [a] KERS Model [b] Maxwell von Stein's Flywheel Bicycle [c] System Architecture of the Model (Aedla, et al., 2015)**

In the study, a vital comparison is made on the energy storage system on what mechanism to adopt in the design, a coiled spring, or a flywheel. This research was mainly carried out to find out how much pedalling power can be saved by having a KERS bicycle. The results from study showed that around 30% of the energy delivered can be recovered. But it was identified, friction as the major distraction for the design where clutch engagement and disengagement process to continue is mandatory.

A review article of "Bicycle kinetic energy recovery system by using flywheel" which was published in International Journal of Research in Engineering and Innovation also states that KERS powered bicycles will reduce up to some extent of energy which is wasted during braking and energy used to lift or accelerate the bike again. Here the moment of inertia of the flywheel adds up a difficulty at the start-up of the bicycle due to higher torque requirement. There exists a safety concern as well with the high speed rotation of flywheel in the developed design. Moreover, the materials used for designing of flywheels and shafts are also a matter of the research.

According to the results from the research, it generates a reasonable level of energy and energy storage mechanism so that the displacement of the energy harvesting input end and the mover core meet the design requirements as well to adopt in the medical industry. Accommodating this principle of energy harnessing in bicycle pedal would generate many difficulties due to permanent magnets and the coil. Because the attraction and repulsion forces from permanent magnets can induce additional work on the rider during pedalling as the crank angle changes. So, bicycle pedals must be made of iron or iron alloys to withstand the rider's pedalling force. Also, special attention is required to prevent electric current short circuit in the system if it is adopted with a bicycle pedal.

Another approach is detailed in the study titled "Design & Implementation of Energy Harvesting System using Piezoelectric Sensors," published in IEEE in June 2017. In this study, the energy generation technologies that use piezoelectric materials as uninterrupted power supplies are identified as one of the most practical solutions of low-power wireless sensor networks. The piezoelectric generator collects mechanical energy from the environment and transforms it into electricity to supply to microelectronic devices. Thus, these alternative energy sources can reduce the consumption of batteries, thereby reducing environmental pollution. Piezoelectric materials can work in the bending, compression, and shear modes, which are named as d31, d33, and d15 modes, respectively.

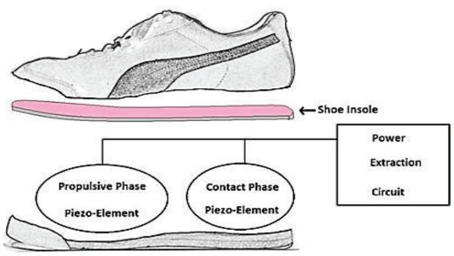



**Figure 5 - Schematic Assembly of Energy Generating Shoe (Dewangan and Dubey, 2017)**

As shown in Figure 5 extracted from the publication Design & Implementation of Energy Harvesting System using Piezoelectric Sensors, the introduced technique is based upon piezoelectric components where deformations produced by different means are directly converted to electrical charge via piezoelectric effect. Then the electrical energy can be regulated or stored for further use. As per the results from the research, it states that the output obtained at piezoelectric crystal is very small (in the range of 3-5 mV), so that it is fed to an amplifier for proper amplification. After amplification, the signal strength was observed in the range of 5-7 Volts (V). Thereafter this amplified signal can be given to either the load or to a storage device such as a rechargeable battery.

### 3.3 PZT Theoretical Background

Piezoelectric transducers (PZTs) are pivotal for energy harvesting in various settings, including roads, trails, and parking lots, as highlighted in "Piezo-Gen - An Approach to Generate Electricity from Vibrations" (Garimella et al., 2015). By converting kinetic energy from vehicle vibrations and gravity into electrical energy, PZTs offer self-generating advantages with no external power requirement. However, limitations such as instability in stable conditions and the need for continuous vibrations exist. PZTs operate in compression (d33) and flexure (d31) configurations, with d33 preferred for vibration energy production.

In contrast, Martín-Sosa and Chaves (2021) explore pedalling force in clinical rehabilitation. Monitoring pedalling forces aids in optimizing bicycle adjustments for maximum effective force application, crucial for minimizing injury risk during therapy sessions. Interestingly, excess mechanical power on pedals could potentially be harnessed to generate electrical energy on the bicycle itself. Employing force nomenclature and strain gauges, the study measure forces along three axes: tangential force (FT), radial force (FR), and lateral-medial force (FLM). FT produces a useful moment to rotate the crank, while FR and FLM do not. The cyclic nature of pedalling force, resembling a sinusoidal curve with one cycle per pedal revolution, suggests a promising opportunity for energy harvesting as shown in Figure 6.

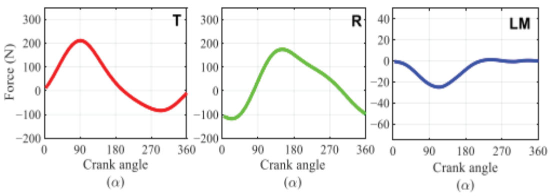



**Figure 6 - Mean Pedaling Forces Time Evolution Applied to the Pedal. Red: Tangential Force (T) Green: Radial Force (R) Blue: Lateral-Medial Force (LM) (Martín-Sosa, Alvarado eta al., 2021)**

Harnessing energy from pedalling force could offer sustainable power for various bicycle functionalities. This synergy between clinical rehabilitation practices and energy harvesting technology underscores the potential for enhancing both cycling performance and sustainability.

## 4. Methodology

The research focuses on mitigating wasted energy in bicycles, primarily originating from the vibrations absorbed through the bicycle's five contact points with the road. A groundbreaking method is proposed to efficiently harness these vibrations. At the heart of this approach lies a specially engineered bicycle pedal designed to transform both the cyclic movements of the rider's foot and the road vibrations into usable electricity. The research begins by conducting experiments to determine the pedal force using actual participants under typical external conditions, employing a load cell apparatus. Real-time data collection is facilitated through an IoT (Internet of Things) setup, playing a pivotal role in the research methodology.

Following the determination of pedal force, a conceptual design is crafted and continuously refined through iterative exploration using finite element analysis. An essential objective of this design is to minimize the transmission of pedal force from the bicycle pedal to the rider's body. A prototype of the final model is then developed using 3D printing and subjected to various pedal force scenarios. Additionally, a piezoelectric transducer model is created using COMSOL 5.4 Multiphysics software to validate the design. In summary, as depicted in Figure 7, the methodology encompasses understanding pedal force, developing an efficient energy harvesting module, and validating its performance through simulation. This comprehensive approach culminates in a pioneering method to harness the otherwise wasted energy from bicycle vibrations.

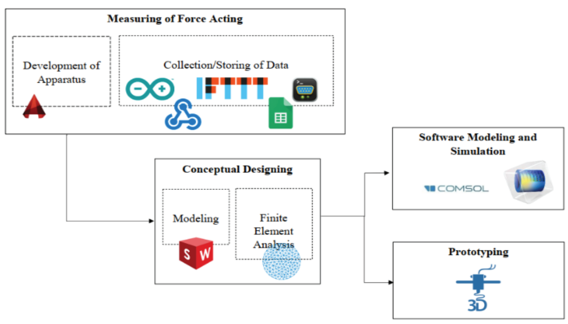



**Figure 7 -Project Methodology Block Diagram**

## 5. Experimental Analysis

The research identifies variations in pedal force exerted by cyclists, considering both the inherent force variations and additional force fluctuations caused by road vibrations. The study quantifies the combined effects of these forces on the bicycle pedal, a crucial point of contact during cycling.

### 5.1 Construction of Load Cell Scale Apparatus

To enhance accuracy, load cells are typically used in sets of four, employing the Whinstone Bridge (WB) principle to offer both positive and negative strain resistance to the circuit. An apparatus incorporating four load cells is created and mounted onto the bicycle pedal, so that riders exert their pedalling force atop this apparatus, as illustrated in Figure 8[a].

### 5.2 Wiring, Programming and Arduino Implementation

The apparatus design, as shown in Figure 8[b], considers the rotation of bicycle pedals, making wired connections impractical. An IoT solution with the DOIT ESP32 DEVKIT V1 Board enables wireless data transmission. Load cells produce analogue output converted to digital via the HX711 module. Rigorous testing in Proteus Software ensured reliability. Programming in Arduino IDE and data transmission through IFTTT to Google spreadsheets provide a comprehensive wireless solution.

### 5.3 Assembling and Testing

Assembly of the load cell scale on the bicycle pedal, depicted in Figure 8[c], is executed along with the integration of the designed circuitry and a power bank. Calibration is important and is accomplished using known masses for setup, followed by thorough testing to validate its accuracy.

### 5.4 Analysing of Pedal Force

The analysis of rider pedal force involved a series of experiments conducted under controlled conditions with the participation of 20 subjects. The first experiment was conducted under a specific condition, where the bicycle was pedalled under a "no load" condition. This condition entailed cycling the bicycle stationary on a bicycle repair stand. The experimental parameters and conditions are detailed in Table 1, ensuring consistency and clarity in the study's design and execution.

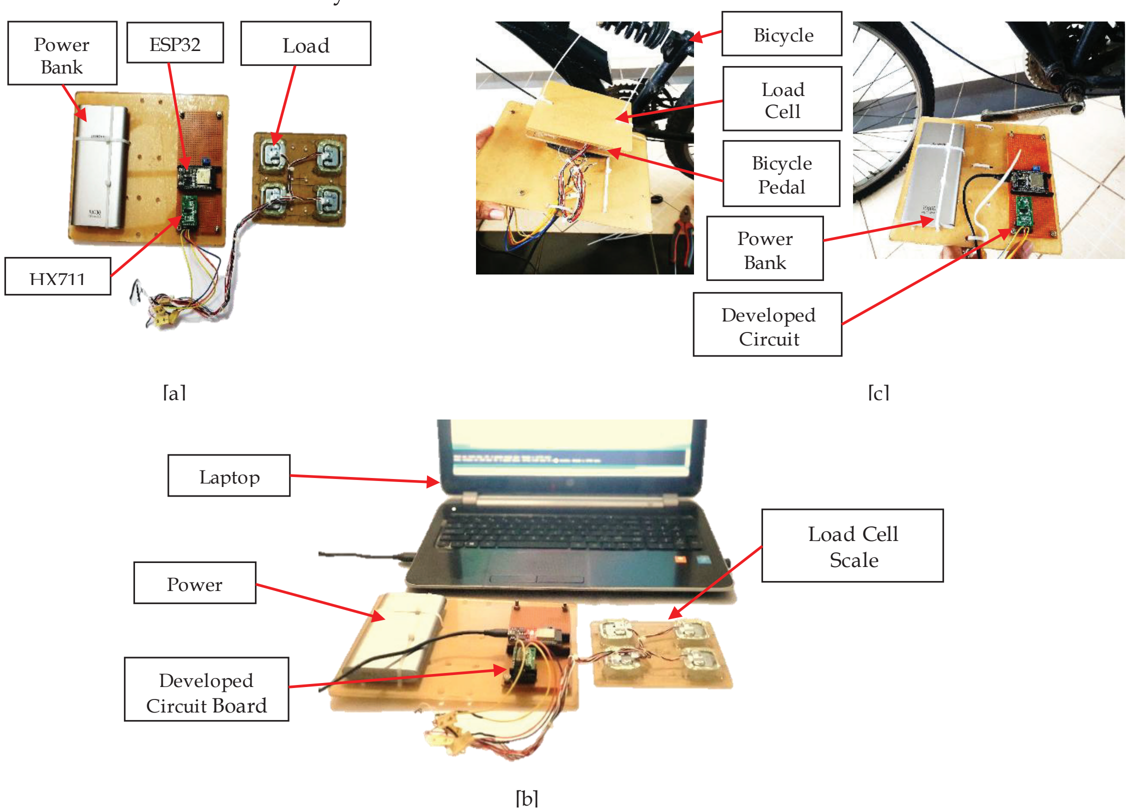



**Figure 8 - Developed Load Cell Scale Apparatus and its Testing Assembly [a] Load Cell Scale [b] Hardware and Software Implementation of the Apparatus, DOIT ESP32 DEVKIT V1 Board Programming [c] Assembling of the Setup**

Table 1 - Experiment 1 Conditions

| Participants | Male (10) | Female (10) |
|---|---|---|
| Average Weight | 62.6 kg | 54.7 kg |
| Maintained RPM | 60 rpm | |
| Vehicle Movement | Stationary | |

In accordance with the conditions outlined in Table 1, the resulting data was graphically represented as "Force Vs Time" in Figure 9, facilitating visual analysis and interpretation.

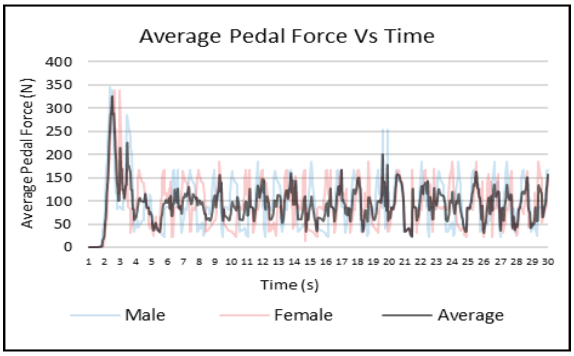



**Figure 9 - Experiment 01 Pedal Force Variation with Time**

The second experiment involved cycling under normal road conditions, where the bicycle was subjected to the typical forces such as drag, friction, and aerodynamic drag, along with reactions and vibrations. The experimental conditions are maintained as previous. Figure 10 illustrates the force variation with time, with a focus on the initial 30 seconds of the journey. This experiment aimed to capture real-world cycling conditions and their impact on pedal force.

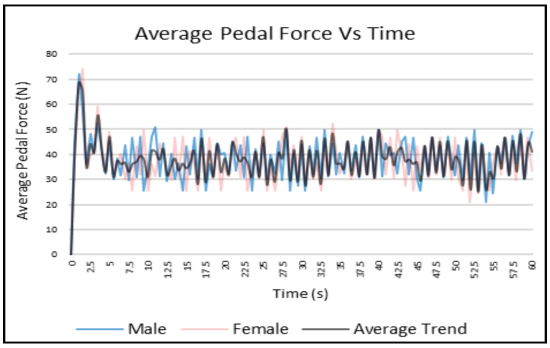
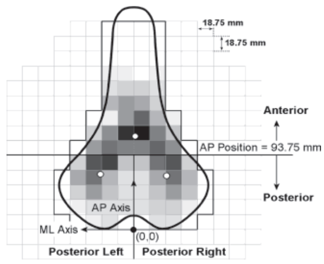



**Figure 10 - Experiment 02 Pedal force variation with time**

As evident in both Figure 9 (no load condition) and Figure 10 (real cycling condition), it is apparent that the force exerted by the rider substantially increases. Notably, the patterns of the force curves differ significantly. The curve in the no-load condition appears much smoother than the one in the normal load condition. This discrepancy can be attributed to the vibrations absorbed from the road surface irregularities. These vibrations continue to transmit to the human body, presenting an opportunity for energy harvesting. The stark contrast in the force curves underscores the potential to capture and convert this energy into a valuable resource.

## 6. Conceptual Designing and Finite Element Analysis

The conceptual design phase is an initial step in the design process. By comprehending the dynamic forces acting on the pedal, it becomes possible to craft a mechanism capable of generating energy while cycling. Conceptual designs for the pedal and essential components were developed. In alignment with findings by Potter and Sauver (2008), Figure 11 [a] illustrate pressure variations on the bicycle saddle during cycling. This variability in pressure, which occurs at different locations due to the rider's cycling pattern and crank angle, offers the potential to absorb not only the forces exerted during cycling but also vibrations from the road, presenting a multifaceted design adaptation as illustrated in Figure 11 [b]. Citing the paper, their work provides valuable recommendations for the installation of piezoelectric materials.




[a]


[b]

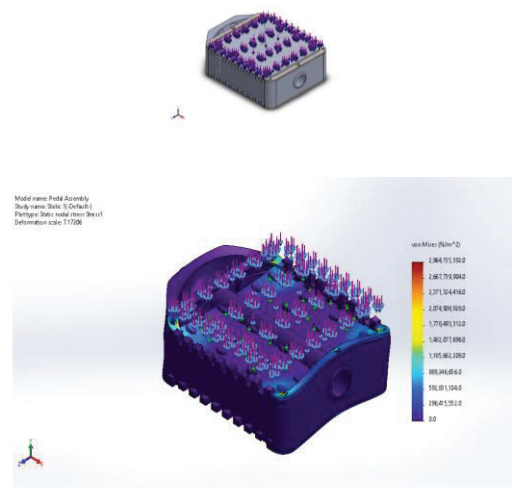
**Figure 11 [a] - Bicycle Saddle Pressure Variation [b] Conceptual Saddle Design**

The conceptual design presented for saddle is important as it is one of the critical contact points; it is important to recognize that vibrations from the road continue to impact the rider. In light of this, a design approach that factors in the behaviour of piezoelectric transducers and their applications emerges. A layer of piezoelectric material can be strategically applied beneath the cushion layers of the saddle, offering a promising avenue for energy harvesting. Pedals serve as pivotal components for transferring forces, enabling cyclists to drive the bicycle. These forces manifest in a sinusoidal pattern on the pedal during cycling. To ensure a secure foothold, pedal design necessitates adequate friction and grip. A grip layer has been incorporated into the conceptual design, addressing these key factors. The design was designed using SolidWorks software, as depicted in Figure 12, considering the critical role pedals play in the cycling process.

The development of conceptual designs is rooted in the identification of key locations and contact points on the bicycle where vibrations are notably prominent and transmit to the rider's body. Various conceptual designs were explored, with primary focus on rider comfort. It became evident that developing an energy-harvesting concept at the saddle of the bicycle is less practical. The bicycle saddle is a critical element for rider comfort, and it experiences relatively minor force variations due to its existing cushioning. In contrast, the bicycle pedal, responsible for transmitting all riding forces, cannot be soft. Vibrations from this location still affect the rider, making the pedal the preferred choice for further development in the project. Finite Element Analysis (FEA) was performed based on the maximum observed experimental force of 400N by setting the pedal hole as a rotating boundary around the central pedal axis. The mesh used in the analysis is optimized with tetrahedral elements and converged with a sag of 0.1 mm.

**Table 2 - Stress Analysis**

| Name | Type | Min | Max |
|---|---|---|---|
| Stress1 | VON: Von Mises Stress | 0.0N/m^2 Node: 45260 | Range : 2.9 GN/m^2 Node: 2056 1.6GPa @ node 1257 |



**Pedal Assembly-Static 1-Stress-Stress1**

## 7. Software Modelling of Piezoelectric Energy Module and Implementation

The modelling of the piezoelectric discs in COMSOL 5.4 Multiphysics was conducted using the averaged dimensions obtained from the samples. During this process, the direct configuration is characterized by the crystalline material's piezoelectric effect, which polarizes when subjected to mechanical deformation, generating a potential difference. In contrast, the inverse configuration involves the material undergoing elastic deformation when exposed to electrical current. The material properties of the selected transducer were essential for the modelling.

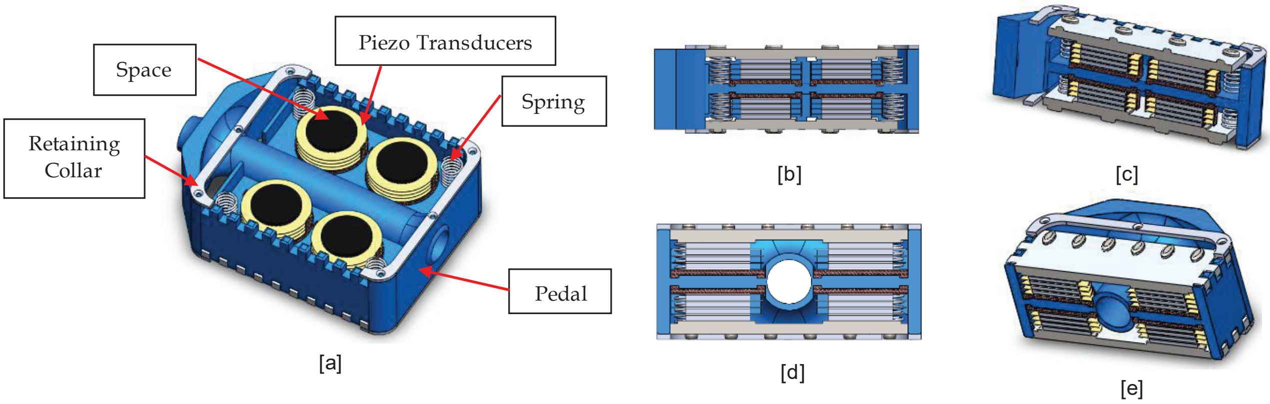



**Figure 12 - Pedal Design Sectional Views [a] Without Pedal Outer Cover [b],[c] Front Plane Sectional View [d],[e] Right Plane Sectional View**

Piezo transducers were modelled and simulated under stationery and time-varying loads to assess voltage generation. Stationary load studies are aimed at determining harnessable voltage ranges, while time-varying load simulations analysed behaviour under real-world conditions. Data, including force-time variations, were input into COMSOL 5.4 Multiphysics. Plots in Figure 13 depicted force-time relationships. This comprehensive process provides insights into harnessing energy from piezoelectric transducers under diverse loading conditions, crucial for project advancement.

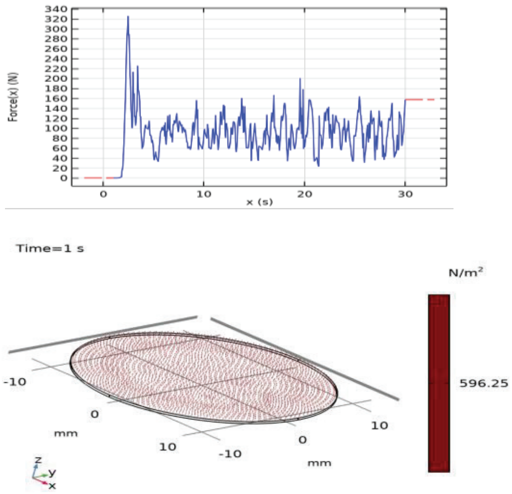
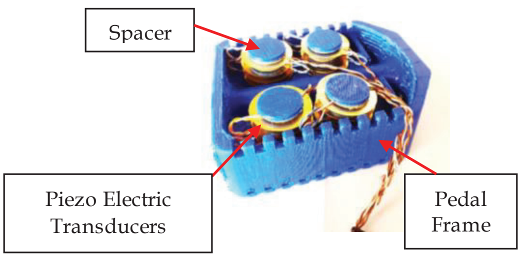


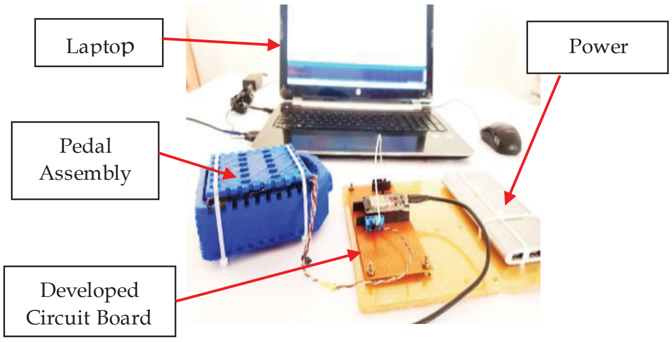

**Figure 13 - Force Application on developed MEMS Model – Variable Loading**

## 8. Rapid Prototyping and Implementation

Piezoelectric energy modules were precisely developed with Lead Zirconate Titanate (PZT-4) Piezo sensors of diameter 25mm, thickness 3mm and strategically integrated into the pedal design, arranged in a parallel configuration to optimize energy generation. This hardware implementation, illustrated in Figure 14, was essential for bringing the concept to life and testing its functionality in real-world conditions. The same IoT setup was helpful in data collection, crucial for continuous monitoring during bicycle operation. Piezoelectric cells, responsive to applied force, were seamlessly integrated into this system, enabling analogue voltage variations to be captured and transmitted wirelessly. Rigorous testing and verification, including program functionality and electrical connections, were conducted using Proteus Software to ensure reliability. Programming the DOIT ESP32 DEVKIT V1 Board as depicted in Figure 14 and this wireless solution not only accommodated the pedal's rotational motion during bicycle operation but also aligned with the project's real-time monitoring objectives for energy harvesting. This meticulous hardware implementation lays the groundwork for




[a]

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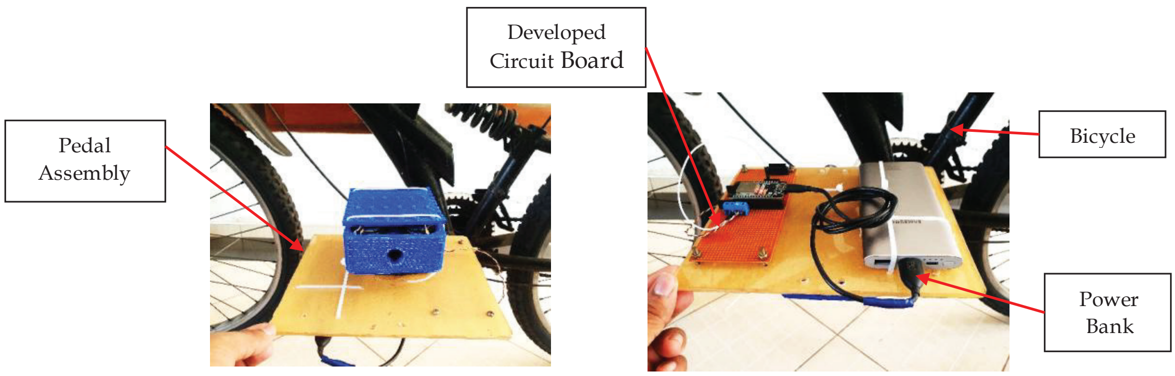



[c]

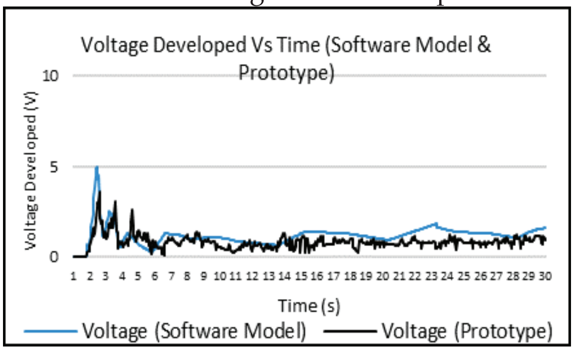
**Figure 14 [a] - Hardware Implementation [b] Software Implementation of the Setup, DOIT ESP32 DEVKIT V1 Board Programming [c] Mounting and Testing of Pedal Prototype**

subsequent testing and validation stages, where the energy-harnessing capabilities of the system will be rigorously examined.

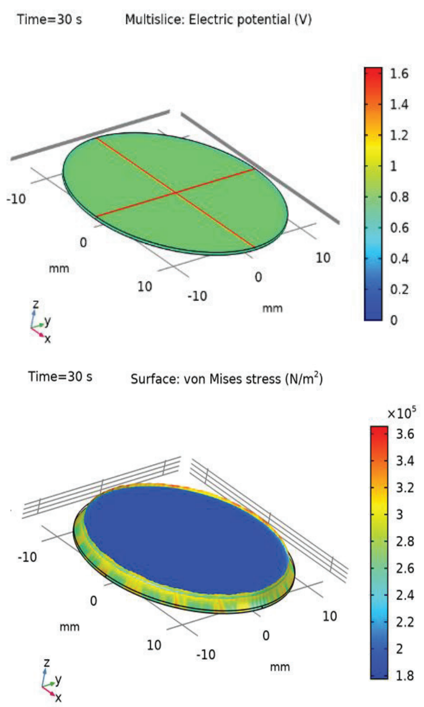
## 9. Results and Discussion

The research investigates the performance of a piezoelectric transducer using a combination of software simulations and physical prototype testing.

Finite element analysis shows that the maximum stress, occurring at the edges of the structure (1.6 GPa), is less than the yield strength of the selected material, carbon steel (2.1 GPa). Therefore, the designed model is finalized. In the simulations, various loads are applied to the transducer, including constant and variable loading scenarios. Experimental




[a]




[b]

**Figure 15 [a] -Voltage Developed – Software Model vs Prototype [b] Electric Potential Plot –Variable Loading & Stress Simulation at 30$^{th}$ s**

data reveals that pedal force varies between approximately 30N to 330N. Under constant loading, the simulation demonstrates a voltage variation of up to 2V compared to the transducer's baseline, showcasing its potential as an energy source. However, real-world conditions involve cyclic pedal loading and road vibrations, resulting in a variable load simulation. The results from the variable load simulation indicate voltage development in response to force variation. There is an initial peak of 3.8V, attributed to overcoming inertia, and an average voltage of 1.175V during the cyclic pedal force application at 60rpm (as shown in Figure 15[b]). Experimental data collected from the prototype, tested under similar conditions as the simulation, shows voltage variation between 0.845V and 3.63V, with fluctuations reflecting the cyclic movement of the pedal, as depicted in Figure 15 [a]. Notably, there is no distinct pattern or rhythm in the voltage generation, which may be due to unexpected road surface vibrations. When comparing the prototype's performance to the software simulations, it becomes evident that the prototype generates slightly lower voltages. This deviation can be attributed to energy losses during real-world implementation and the inability to maintain precise conditions as in the software models. Despite these variances, the voltage generation from the prototype remains within the expected range, affirming the feasibility of the study.

In summary, the research study offers valuable insights into the potential of voltage generation using piezoelectric transducers on bicycle pedals. This study lays the foundation for future enhancements that could integrate piezoelectric energy harvesting with existing power sources in bicycles, contributing to sustainable and eco-friendly transportation solutions.

## 10. Conclusions and Further Developments

Bicycles are widely recognized as a popular mode of eco-friendly transportation. But, ensuring bicycle safety is paramount, and an effective illumination system plays a pivotal role in achieving this. However, the vibrations generated by the rolling motion of bicycle wheels on uneven road surfaces pose a significant challenge. To harness the energy produced by vibrations, the feasibility of piezoelectric energy harvesting technology is explored. By utilizing piezoelectric transducers within the bicycle pedal, the system can harness the energy generated by rider-generated pedal force and vibrations, making it a promising solution for recharging batteries. In typical road conditions, the system demonstrates an average voltage output of 0.845 V, further validating its adaptability as a pedal component on bicycles. In the context of today's world, characterized by ongoing discussions on environmental pollution and energy crises, this research advocates the use of rechargeable batteries to minimize such pollution and presents an in-built power source, capable of continuously recharging batteries during bicycle rides, all while promoting eco-friendliness. Looking ahead, numerous opportunities for further development and optimization exist. These include adapting the system into a universally compatible pedal design, optimizing the utilization of vacant spaces within the system to capture more vibration energy, optimizing the electrical circuit design for efficient energy storage with minimal losses, integrating various energy harvesting principles in combination like electromagnetic induction or triboelectric nanogenerators that could boost the overall energy output.

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