
A Systematic VDI 2221 Methodology for Piezoelectric Energy Harvesting in Ergonomic Lumbar-Support Wearables Product

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Abstract — The need for sustainable, portable renewable energy sources is increasingly crucial, especially for human activities in remote areas with minimal access to electricity. The research aims to develop Piezo-Powered Ergo-Lumbar Support Device prototype, an ergonomic lumbar support cushion-backpack integrated with a portable renewable energy source through a piezoelectric energy harvesting system. A combination of VDI 2221 and Human-Centered Design (HCD) methods was applied to simultaneously optimize the technical and ergonomic needs of users. A technical-economic evaluation was used to determine the best design solution concept. Vibration simulation test in Solidwork software confirmed that the product can accommodate vibrations up to an average of 1218 Hz, which is required to activate 32 piezoelectric elements arranged in parallel to optimally convert kinetic energy into electrical energy. This research results in a final prototype with dimensions of 38.5 x 26.5 x 10 cm and a weight of 475 grams with a power storage capacity of 1200 mAh. Evaluation conducted on 43 respondents proved that the product increases comfort and improves body posture (88.4% of respondents agreed), and the feature of generating renewable energy independently is considered innovative and useful. This product offers a promising integrated ergonomic-energy solution for sustainable energy innovation.

Keywords – renewable energy, ergonomics cushion, piezoelectric, VDI 2221, Human-centered Design

I. INTRODUCTION

The use of low-power electronic devices is increasing significantly and the issue of global energy crisis creates a need for sustainable renewable sources of electrical energy [1,2,3,4]. This need is becoming increasingly crucial with increasing human mobility, which drives the need for portable power sources. However, not all areas of the world are covered by electricity supplies. Access to electricity remains very limited, especially in remote areas such as wilderness, forests, or mountains [4]. Although currently there are portable energy storage media, such as batteries or power banks, they have limited storage capacity and limited lifespan, have the potential to pollute the environment [1] and ultimately remain dependent on electricity sources for charging [4]. During human mobility in the wild, electricity is nearly impossible to find. Access to electrical lines and networks doesn't reach remote areas. This creates an opportunity for the procurement of portable electrical energy sources, which can independently generate electricity from human and natural activities. The development of renewable, low-cost, and environmentally friendly

energy sources is crucial to meeting human energy needs [5,6].

Piezoelectric technology is an electronic component that is capable of converting mechanical energy from vibration and pressure into electrical energy [2,7], offering a promising solution for energy harvesting systems by utilizing the natural movements of humans and nature [8]. Piezoelectricity was first discovered and technically applied by Pierre and Jacques Curie in 1880 [7]. Piezoelectricity is widely used in harvesting mechanical energy from vibrations, human movement, mechanical loads, etc., and converting it into electrical energy for low-power devices [6]. Energy harvesting is an attempt to convert ambient energy into electrical energy that can be stored or used to power other devices [4]. The working principle of piezoelectricity is based on the piezoelectric effect, namely the ability of certain types of materials to generate electrical voltage when given mechanical pressure. Conversely, when an electric current flows, the piezoelectric material will vibrate, which is known as the reverse piezoelectric effect [2,6,9]. Physically, piezoelectrics excel in flexible and compact forms, such as thin-film piezoelectrics, which facilitate their integration into

various product structures [10] without adding significant volume or weight. Finally, their minimal maintenance nature, due to their lack of physically moving mechanical parts, makes them highly durable and reliable for long-term use. Thus, piezoelectrics as sustainable energy harvesters offer a promising solution [7] to replace conventional batteries [1]. Generally, piezoelectrics are implemented in various fields, which can be generally grouped into two main functions, namely as sensors/actuators and as energy harvesters [1]. The role of piezoelectricity as an energy harvester is highly relevant in the context of sustainability and energy independence. This technology is capable of capturing and converting mechanical energy that is usually wasted (such as machine vibrations, footfall pressure on the floor, or mechanical deformation of footwear, vehicle vibration or jolt, etc.) into usable electrical energy [5,9,10,11]. The capacity of piezoelectricity to generate energy from mechanical pressure has been well recognized and is being used to create renewable energy [2]. Piezoelectric technology improves energy efficiency, and addresses energy needs [11].

One of the most common human activities is carrying a backpack. Humans naturally have a habit of carrying bags (especially backpacks) when doing outdoor activities, or in daily activities that require carrying items. The activity of walking while carrying a backpack naturally generates kinetic energy through body movement and the swinging of the load [4], which is usually wasted. This presents an opportunity to integrate piezoelectric systems into products that are closely related to human behavior when carrying a bag. Piezoelectric systems are suitable for integration into wearable products. Because piezoelectrics have the following advantages: 1) it has a very fast response to changes in pressure or vibration [6], making them efficient in capturing dynamic human movements; 2) it has high sensitivity so they can generate significant electrical power [8,11], even from low-frequency vibration sources such as walking or carrying loads; and 3) it is small, flexible, and lightweight, making it easy to integrate into the system [1,8]. This capability underlies the integration of piezoelectrics into portable and wearable personal devices. The challenge in this research is how to integrate piezoelectric elements into wearable products to ensure optimal electrical energy production without compromising user comfort [4] and ergonomic principles.

Several studies related to piezoelectricity have been conducted. Research by Mahapatra et al., 2021 [6]; He and Briscoe, 2024 [8]; Xiao et al., 2025 [1] discusses how piezoelectricity is used as an energy harvester, its characteristics, and its practical implementation. There is also research that discusses the practical implementation of piezoelectricity. Research by Farooq et al., 2021 [5] discusses the implementation of a piezoelectric system on a speed bump. The idea is to utilize the compressive energy that arises when a vehicle passes over a speed bump. Research by Najini and Muthukumaraswamy, 2017 [12] discusses the concept of generating energy from road traffic using

piezoelectrics. This study uses a simulation method to provide an actual picture regarding the practicality and feasibility of piezoelectric systems as renewable energy generators. Almost similar to the previous study, the study by Sabri et al., 2018 [3] also discusses energy generation on highway speed bumps to meet the electricity needs of traffic lights. However, this study utilizes a mechanical generator as its main energy generating system. The research of Zizivadze et al., 2023 [10] discusses the use of vehicle suspension as an alternative energy source, using piezoelectrics. The research of Rudra et al., 2024 [2] discusses the installation of piezoelectric sensors on coastal structures on the seaside, as a wave-powered electricity generation system. This method combines the function of wave damping structures with renewable energy generators in various coastal constructions. The research of Yeboah et al., 2023 [11] discusses the application of piezoelectrics as energy harvesters in the stadium floor area. The results of the study show that the use of piezoelectrics as energy producers is more efficient than the use of solar panel roofs. Almost in line with the research of Aydin and Celebi, 2023 [9] and research by Sekhar et al., 2021 [7] discussed the opportunity to implement piezoelectricity as an additional energy source in buildings or construction. Research by Granstrom et al., 2007 [4] developed a renewable energy harvesting backpack that can generate electrical energy from the differential force between the user and the backpack. This study developed a theoretical model of a bag strap integrated with piezoelectricity so that it generates electrical energy without compromising the quality of the strap and user dexterity. Based on previous literature reviews, piezoelectric systems are generally applied to mass-use products, but the opportunity for their implementation in personal products is opened as a novelty in this research.

The purpose of this study is to design, build, and evaluate the performance of a prototype Piezo-Powered Ergo-Lumbar Support Device. The Piezo-Powered Ergo-Lumbar Support Device is an innovative product in the form of an ergonomic lumbar support cushion integrated with a piezoelectric-based energy harvesting system. Current lumbar support products on the market generally focus on ergonomic aspects. Although effective in distributing loads, these conventional solutions often lack innovative features that provide significant added value beyond the basic support function. This indicates a gap in product development. This study focuses on developing a framework that is able to combine comfort and ergonomic criteria with simultaneous electrical performance optimization. To achieve this goal, the VDI 2221 systematic design method was applied in combination with the Human-centered Design (HCD) approach in the early stages of user needs identification. This combination of methodologies was chosen to ensure that the resulting design solution is not only technically optimal and manufacturable, but also truly addresses the problems and expectations of end users, resulting in an innovative product that is practical, comfortable, and easy to adopt.

II. RESEARCH METHOD

This research begins with identifying the opportunities from piezoelectric technology in user's accessories, especially in waist support product and backpack. The main principal of this research is to install a piezoelectric module integrated to the product structure, so that it doesn't interfere user comfort and doesn't require an excessive user adaptation. Furthermore, user needs are identified and converted into a functional requirements table that must be fulfilled by the product.

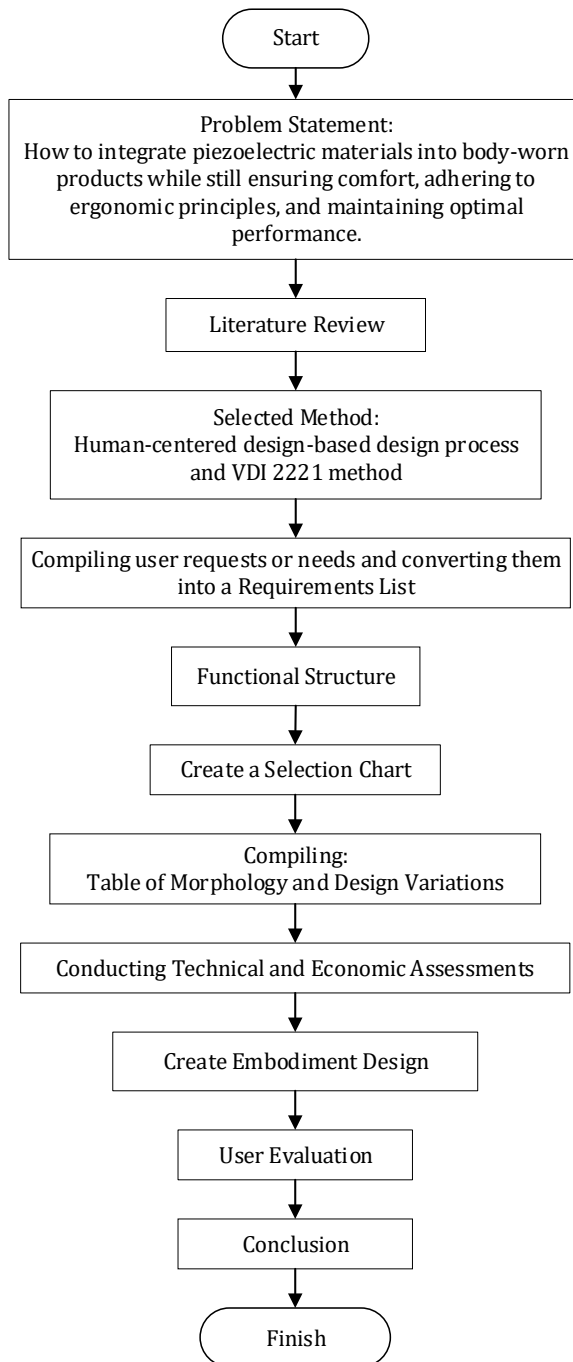


Fig.1. Research flow diagram

Based on the functional requirements, a product structure is built. This functional structure is used to map the user's role, their interaction with product's work

mechanism and the energy flow that occurs within the system [13]. The next step is designing a product concept followed by user evaluation. Both steps are done iteratively and continuously until the final design with specific function, safety, and comfort criteria is optimally created. Overall, the steps of research methodology are visualized in Fig 1.

The product design in this research is applying VDI (Verein Deutscher Ingenieure) 2221 method developed by Gerhard Pahl and Wolfgang Beitz. This method is using a systematic approach to design a system and product engineering, also to optimize the design process based on the user needs. VDI 2221 has the advantage to decompose a complex problems and user needs, so that it enables balanced integration between the principal of optimal product work and ergonomic needs. The process structure of design concept plan and realization will help the designer to find the best solution which fulfills function, safety, and comfort criteria. Therefore, the use of VDI 2221 method to design the Piezo-Powered Ergo-Lumbar Support Device product is appropriate. In this research, human-centered design approach is implemented in VDI 2221 first step, which is problem identification process until the functional structure arrangement. The data received from problem identification process will be stated in the requirement list Table 1.

Table 1. Requirement list

| Requirement List | Piezo-Powered Ergo-Lumbar Support Device | |
|------------------|---|-----------------|
| | Input: Anthropometry and User Behavior | |
| | Output: Lumbar support with renewable energy source | |
| D / W | Condition | Quantification |
| | PRODUCT GEOMETRY | |
| D | Dimensional max. | 50 x 30 x 15 cm |
| W | Product weight | < 750 gr |
| | HUMAN GEOMETRY | |
| D | Human body height | 150 – 185 cm |
| D | Human body weight | 55 – 100 kg |
| D | Human body width | 80 cm |
| D | Human waist circumference | 60 – 105 cm |
| D | KINEMATIC - Vibration freq. | > 1000 Hz |
| D | FORCE - compressive load resistance | 588,6 N |
| D | MATERIAL - light and strong | |
| D | MATERIAL - supports ergonomic shape | |
| D | SAFETY - water resistance | |
| D | ERGONOMIC - support the waist against the bag | |

The requirements list includes the main criteria that must be met along with quantification data for the fulfillment. Ismartaya et al., 2024 [13] stated that the criteria in the requirements list are categorized into two levels: Demand (D) or necessity and Wish (W) or expectation. The product is expected to have a maximum size of 50x30x15 cm according to the dimensions of the human body. The product weight is expected to be less than 750 grams, so that it doesn't add burden to the user. The material used is expected to be able to withstand a compressive load of up to 60 kg,

adjusting to the maximum volume of backpacks circulating in the market. The design is expected to be able to support the number of vibrations up to 1000 Hz, in order to produce sufficient electrical energy for the available piezoelectric. Another key point in the requirements list is the design must meet ergonomic elements so that it can support the backpack perfectly without causing discomfort to the user. The final step in the function identification stage is to embody how the product works into a functional structure [13]. The functional structure includes three main elements: energy, material, and signal. In the functional structure, all three are identified in detail based on the scheme that occurs to convert input into output. In this design, the Piezo-Powered Ergo-Lumbar Support Device function is to convert kinetic energy into electrical energy. In the process, the user moves (human energy) as part of the energy generation effort. The functional structure is shown in Fig 2 below.

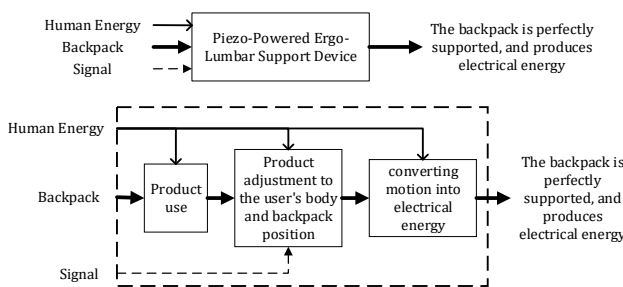


Fig.2. Functional structure of product

III. RESULT

After the functional structure is determined, the process continues to the morphological design step. Morphological design is created to decide concrete component alternative that is possible to fulfill the product function. After the solutions are identified, variety of solutions are created consisting of a combination of solutions from each product's sub-function. The results of this morphological design process and alternative design solutions are shown in Fig 3, Fig 4, and Fig 5 below.



Fig.3. Alternative design 1 (mock up)



Fig.4. Alternative design 2 (mock up)



Fig.5. Alternative design 3 (mock up)

Alternative cushion designs are then evaluated and analyzed according to user needs and desires based on technical and economic considerations to simplify the next design concept step [13]. This process is carried out to obtain one best design variation with the highest score that balances in technical and economic criteria. It is important to evaluate the technical and economic feasibility to provide a strategic perspective on the design being created [12].

Table 2. Technical-economic assessment

| Technical Criteria | Alternative assessment | | |
|---|------------------------|-------------|-------------|
| | Alt 1 | Alt 2 | Alt 3 |
| Effectively generates electrical energy | 3,6 | 2,8 | 3,8 |
| Movement flexibility | 3,5 | 1,7 | 3,6 |
| Meets ergonomic elements | 2,2 | 2,5 | 3,8 |
| Ease of adapting body position | 3,2 | 2,8 | 3,8 |
| Safety | 4 | 4 | 4 |
| Easy to use | 3,5 | 3 | 3,5 |
| Average point | 3,33 | 2,87 | 3,7 |
| Point (normalized) | 0,83 | 0,72 | 0,93 |
| Economic Criteria | Alternative assessment | | |
| | Alt 1 | Alt 2 | Alt 3 |
| Low material cost | 3,5 | 2,5 | 3,2 |
| Low manufacture cost | 3,6 | 2,8 | 3,6 |
| Low assembly cost | 3,5 | 3,5 | 4 |
| Low component count | 3,2 | 2,7 | 3,8 |
| Average point | 3,45 | 2,875 | 3,53 |
| Point (normalized) | 0,86 | 0,72 | 0,88 |

The technical assessment justification focuses on functional effectiveness as a support and energy generator, as well as user comfort (ergonomics), which are core values and prerequisites for product acceptance. Meanwhile, the economic assessment justification focuses on material and manufacturing costs, aiming to ensure production feasibility and commercial viability of the design. The combination of these two approaches creates a holistic evaluation, ensuring the selected design is both performance- and cost-competitive. The assessment range is determined with a minimum score of 0 and a maximum score of 4 to reduce the potential for bias. The technical-economic factor assessment is conducted by 12 product designers. The results of the technical-economic assessment can be seen in Table 2.

The VDI method determines the best variation by using a minimum design variation value approach of 0.8 for each technical-economic assessment, and a design variation with the best combination result of technical-economic assessment that approaches the ideal/middle line [13]. The technical-economic assessment approach is presented graphically in Fig. 6, where Alternative 1 (Red), Alternative 2 (Green), and Alternative 3 (Blue). It can be concluded that Alternative 3 is the best design selected in this assessment.

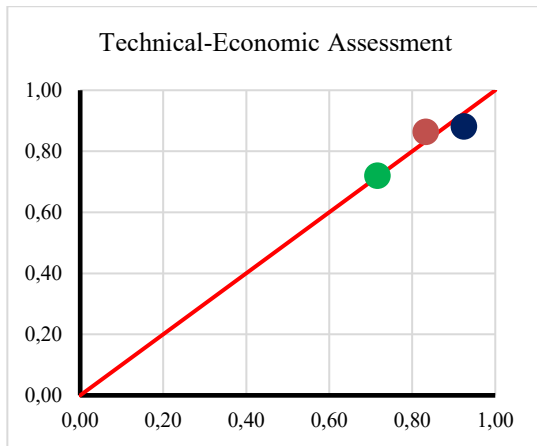


Fig.6. Technical-economic assessment

Alternative 3 is less superior in material costs due to the use of relatively expensive memory foam, but it is commensurate with the technical advantages obtained. The technical advantages of alternative 3 are primarily driven by the use of memory foam material contoured to the anatomical shape of the waist. This encourages high technical assessment in the ergonomic design section, as well as ease of adjustment to body shape (adaptation). In terms of safety and ease of installation, alternatives 1 and 3 are relatively balanced. Alternative 2 is considered difficult to install and inflexible in movement due to its size and width. This makes alternative 2 considered ineffective in generating electrical energy, although theoretically this design can accommodate a larger number of piezoelectric. Alternative 3 design has an advantage in terms of

flexibility of movement, so it effectively produces greater electrical energy (due to more movement). This is also proven by testing using vibration simulation in Solidwork Education 2025 software, which shows the distribution of vibration areas and the intensity of the number of vibrations (or movements) measured in Hertz (Hz). Simulation-based system design replicates real-world system implementation [12]. Simulation testing software helps researchers visualize potential vibrations that could arise during real-world implementation [2]. Fig. 7 shows the results of vibration simulation testing on alternative design 3.

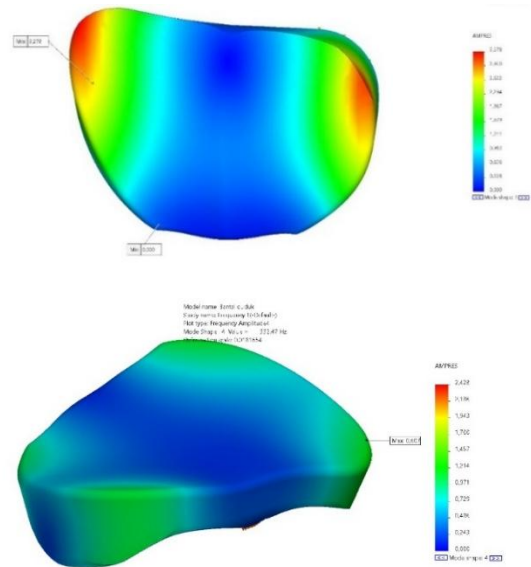


Fig.7. Vibration testing simulation on Solidwork Education 2025

Fig. 7 shows the difference in the amount of vibration in each area of the product, represented by different colors. Red is the area that produces the highest vibration, while blue tends to have low vibration. This is because the backpack will be supported evenly on the center side of the product (the blue area), so that it pushes the magnitude of vibration in the red area which tends to be freer. The results of the vibration simulation test show that this design is able to receive and distribute vibrations up to 1000 Hz, as shown in Fig. 8 regarding the simulation results. This has met the requirements for the amount of vibration requested in the requirements list table. It was found that the designed product can produce the requisite amount of vibration to generate energy.

| 16:53 | | Tuesday | | Aug 26, 2025 | |
|-------------------------|---------------------|-------------------|------------------|--------------|--|
| Study name: Frequency 1 | | | | | |
| Mode No | Frequency (Rad/sec) | Frequency (Hertz) | Period (Seconds) | | |
| 1 | 7071,1 | 1125,4 | 0,00088857 | | |
| 2 | 7358,2 | 1171,1 | 0,0008539 | | |
| 3 | 7595,4 | 1208,8 | 0,00082724 | | |
| 4 | 7621,2 | 1213 | 0,00082443 | | |
| 5 | 8648,9 | 1376,5 | 0,00072648 | | |

Fig.8. Vibration testing simulation result (5 times)

The next stage is embodiment design. The design is made in 3D using Solidworks Education 2025. The results of the embodiment design stage and its components are shown in Fig. 9 below. Meanwhile, Fig. 10 shows the ergonomic contours of the Piezo-Powered Ergo-Lumbar Support Device product viewed from the front, bottom, and side.

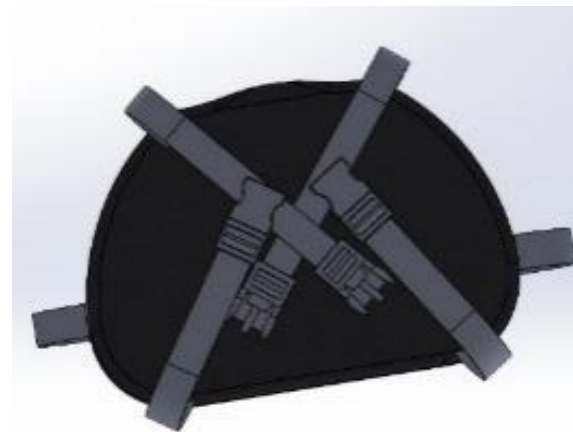
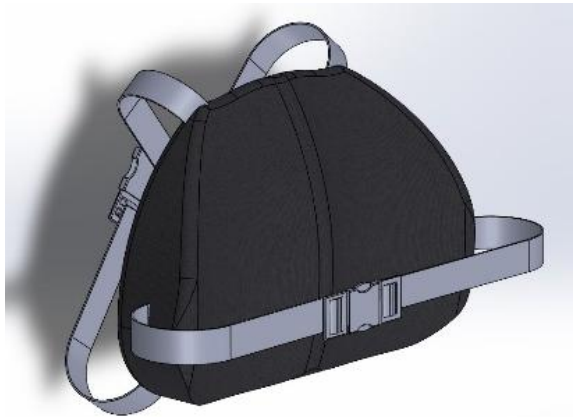


Fig.9. 3D CAD Product image



Fig.10. Ergonomically designed cushions: bottom view, side view, and isometry view

Meanwhile, the piezoelectric circuit is shown in Fig. 11. This circuit is installed independently from the bearing. It is designed to ease the maintenance or repair process if necessary. Thirty-two piezoelectrics with a diameter of 5 cm are arranged in a parallel circuit to optimize the electrical energy generated by the piezoelectric. The electrical energy is then stored in a 1200 mAh Lithium-Polymer battery. A USB type-A port is attached to this circuit as an output.

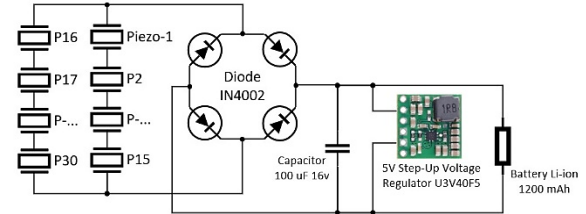


Fig.11. Piezoelectric energy harvester and power storage unit circuit

The final step is to create a prototype of the Piezo-Powered Ergo-Lumbar Support Device. The prototype is shown in Fig. 12 below. The overall dimensions of the product are 38.5 x 26.5 x 10 cm, with an actual weight of 475 grams. This meets the dimensional limitations listed in the requirements list. The product is equipped with buckle strap and three main locking points. The product is equipped with buckle strap and three main locking points. The strap can be extended up to 96 cm, so that it can accommodate the large-bodied users.





Fig.12. Prototype of Piezo-Powered Ergo-Lumbar Support Device (front look, back look, and isometry)

Fig. 13 shows how the piezoelectric is installed in the prototype. The piezoelectric circuit is installed on the back of the inside of the product. The goal is to optimally receive vibrations from the backpack's movement without any significant obstructions. There are 32 piezoelectrics connected in parallel and positioned spread across the back of the product. The USB type-A port is planned to be positioned on the right side of the product, to provide user access.



Fig.13. Simulation of piezoelectric installation on Piezo-Powered Ergo-Lumbar Support Device prototype (opened and closed)

IV. DISCUSSION

The final step of the design process is to test the prototype on user respondents. Researchers tested the prototype on 43 respondents. It is important to conduct experimental testing of the product to identify its performance when applied to users [4]. Researchers conducted prototype testing involving 43 respondents.

Fig. 14 shows how the prototype Piezo-Powered Ergo-Lumbar Support Device was used by users.



Fig.14. Visualization of the use of the Piezo-Powered Ergo-Lumbar Support Device prototype

The results of the respondent evaluation were then documented and analyzed. The majority of respondents (38 people) felt that the Piezo-Powered Ergo-Lumbar Support Device prototype met the ergonomics of the user's body and increased comfort in using the backpack. Meanwhile, the remaining (5 people) felt uncomfortable with the prototype because the padding was still too thick, making the backpack feel far from the user's body. All respondents agreed that this product helps users improve posture when carrying a backpack. This advantage is shown in Fig. 15. According to the visual calculation in Fig 15, there is an increase in the perpendicularity of the body posture (α) of 4.81°; from the original 9.95° (left image) to 5.14° (right image). In addition to improving user posture, all respondents also agreed that the presence of the product helps support the backpack perfectly, so that the bag's position is more stable against the user's body. All respondents also agreed that the feature of converting kinetic energy into electrical energy is new and is the main attraction for this product. This feature is considered very useful by all respondents, especially in emergency situations, although some respondents (21 people) considered the

1200 mAh storage capacity to be inadequate. In addition, some correspondents (28 people) suggested using a USB type-C port as an energy output, while the remaining (15 people) stated that a USB type-A port is appropriate because of it is more universal.

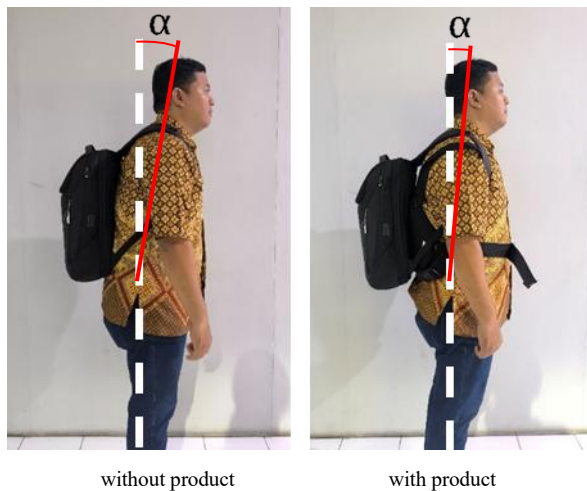


Fig. 15. Visualization of improved body posture after using Piezo-Powered Ergo-Lumbar Support Device prototype

V. CONCLUSION

The research successfully implemented the VDI 2221 design method with a Human-centered Design approach to create a Piezo-Powered Ergo-Lumbar Support Device. The final product has compact dimensions (38.5 x 26.5 x 10 cm) and weighs 475 grams, fulfilling the primary needs of users for an ergonomic backpack support device while being integrated with innovative renewable energy-generating features. Simulation results show that the product design accommodates the need for vibrations up to an average of 1218 Hertz. For future development, several improvements that can be made are: evaluating the design thickness to minimize the distance between the upper back and the user's body, increasing battery capacity for greater electrical energy storage, and using a USB Type-C output port to improve compatibility with modern devices.

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