**RIGA TECHNICAL UNIVERSITY**
Faculty of Materials Science and Applied Chemistry
Institute of Design Technology

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# INTEGRATION OF HUMAN MOTION ENERGY CONVERTER INTO CLOTHING

**Summary of the Doctoral Thesis**

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**DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES**

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 8 November 2019 at the Faculty of Materials Science and Applied Chemistry of Riga Technical University, 6 Ķīpsalas Street 6, Room 117.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Gaļina Terļecka ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 3 chapters; Conclusions; 91 figure; 25 tables; 4 appendices; the total number of pages is 138. The Bibliography contains 262 titles.

# CONTENTS

# GENERAL DESCRIPTION OF THE THESIS

## Introduction

Over the last decade, clothing functions have extended significantly. Electronic systems are integrated into clothing, which perform health control, environmental pollution monitoring, communication, finding location and other functions. In fact, all systems are based on integration of different sensors and actuators into clothing elements. Their successful operation requires a mobile and easy-to-use energy source. In order to make an integrated electronic system independent of external sources and their maintenance/replacement, a possibility of using the energy of human motion for their powering is studied.

## Goal of the Thesis

Integration of electromagnetic energy converter into clothes.

## Research Tasks

- To perform an analytical review of smart products with integrated generators/converters and trends of their development.
- To create electromagnetic energy converters with flat architecture that can be integrated into clothing and optimize their parameters.
- To explore possible locations for integration of electromagnetic energy converters into clothing.
- To explore the effect of hydrothermal processing on the inductive elements of the converter.
- To create inductive elements using multiple technologies.
- To determine the dependence of the amount of energy generated by the energy converter on the shape of the inductive element.
- To create smart textile product prototypes by integrating an electromagnetic energy converter.

## Theses to be Defended

- The created human motion energy converter is two-dimensional and can be integrated into clothing without changing its appearance and functionality.
- The testing methodology for the created apparel with integrated energy converters allows to determine the optimal location and number of elements.
- The use of thermoplastic adhesive coatings allows the creation of washing-resistant inductive elements of the converter.

### Scientific Novelty and Practical Significance of the Doctoral Thesis

As a result of the research, a flat electrodynamic convertor of minimum volume and mass for conversion of mechanical energy of motion into electrical energy was developed.

Optimum configuration of the generator parts and placement in clothing was determined experimentally.

### Approbation of the Results

The author of the Doctoral Thesis has acted as a researcher in the research project: *Establishment of interdisciplinary research groups for new functional properties of smart textiles development and integrating in innovative products.* The results of the Doctoral Thesis are partly included in the report of the research project.

The results of the research carried out in the framework of the Thesis have been presented in the following international scientific publications.

### Book chapter

Blums J., Vilumsone A., Jurkans V., **Terlecka G.** and Gornevs I. «Wearable Human Motion and Heat Energy Harvesting System with Power Management» in *Energy Harvesting*, D. R. Manyala, Ed., Rijeka: InTechOpen, 2018.

### Articles in Scientific Journals

1. Blūms J., **Terļecka G**., Viļumsone A. The Electrodynamic Human Motion Energy Converter with Planar Structure // Advanced Materials Research, 2011, Vol. 222, pp. 36–39.*
2. Blūms, J., **Terļecka, G**., Gorņevs, I., Viļumsone, A. Flat Inductors for Human Motion Energy Harvesting. SPIE Proceedings, 2013, Vol. 8763: Smart Sensors, Actuators, and MEMS VI, pp. 876311–876318. ISSN 0277-786X. Available: doi:10.1117/12.2016995.*
3. **Terļecka G**., Viļumsone A., Blūms J., Gorņevs I. The Structure of the Electromechanical Converter and Its Integration in Apparel. RTU Scientific ProceedingsMaterials Science, 2011, Vol. 6, pp. 123–129.
4. Eglīte, L., **Terļecka, G.**, Blūms, J. Energy Generating Outerwear. Materials Science. Textile and Clothing Technology. Vol. 10, 2015, pp. 67–71. ISSN 1691-3132. e-ISSN 2255-8888. Available: doi:10.7250/mstct.2015.010.

### Articles in Scientific Proceedings

1. **Terļecka G**., Viļumsone A., Blūms J. The Electrodynamic Human Motion Energy Harvester in Smart Clothes // 150 Years of Research and Innovation in Textile Science: Book of Proceedings. Vol. 2, France, Mulhouse, 8–10 June 2011. pp. 866–870.
2. **Terļecka G**., Viļumsone A., Blūms J. Washability for the Inductive Elements of the Energy Harvester Integrated into Clothing // 12th World Textile Conference AUTEX

* Scientific articles indexed in *Web of Science* and/or *SCOPUS* data bases.

2012 “Innovative Textile for High Future Demands”: Book of Proceedings, Croatia, Zadar, 13–15 June, 2012. pp. 1459–1464.
3. Viļumsone, A., **Terļecka, G**., Blūms, J., Dāboliņa, I. Placement of Flat Generator in Garment. No: XIIIth International Izmir Textile and Apparel Symposium, Turkey, Izmir, 2–5 April 2014. Izmir: 2014, pp. 67–72. e-ISBN 978-606-33-8043-6.
4. **Terļecka, G.**, Blūms, J., Viļumsone, A., Pavāre, Z. Wearable Power Harvester for Medical Applications. No: 4th International Interdisciplinary Scientific Conference “Society. Health. Welfare”, Latvia, Riga, 22–23 November 2012. Scranton: Marywood University, 2014, pp. 00046-1–00046-8. ISBN 978-2-7598-0801-4. Available: doi:10.1051/shsconf/20141000046

**Abstracts**

1. Blūms J., **Terļecka G**., Viļumsone A. The Electrodynamic Human Motion Energy Converter with Planar Structure // The 9th International Conference on Global Research and Education: Inter–Academia 2010: Digest, Latvia, Riga, 9–12 August 2010. pp. 80–81.
2. Blūms J., **Terļecka G**., Gorņevs I., Viļumsone A. Apģērbā integrējamais cilvēka kustību enerģijas pārveidotajs // Apvienotais pasaules latviešu zinātnieku III kongress un Letonikas IV kongress: sekcija “Tehniskās zinātnes”: tēžu krājums, Latvija, Rīga, 24.–27. oktobris, 2011. 26. lpp.
3. Viļumsone, A., Blūms, J., Vališevskis, A., Baltiņa, I., Krieviņš, I., Ziemele, I., Šitvjenkins, I., **Terļecka, G**., Parkova, I., Šahta, I., Ābele, I., Dāboliņa, I., Grecka, M. Viedie apģērbi cilvēka drošībai un veselībai // Apvienotais pasaules latviešu zinātnieku III kongress un Letonikas IV kongress “Zinātne, sabiedrība un nacionālā identitāte”: tēžu krājums, Latvija, Rīga, 24.–27. oktobris, 2011. 25.lpp. ISBN 9789934102271.
4. **Terļecka, G**., Baltiņa, I., Viļumsone, A., Blūms, J. Durability for Smart Clothing with Wearable Energy Source. No: Riga Technical University 53rd International Scientific Conference : Dedicated to the 150th Anniversary and the 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni: Digest, Latvia, Riga, 11–12 October 2012. Riga: RTU Press, 2012, pp. 285. ISBN 9789934103605.
5. Blūms, J., **Terļecka, G.**, Gorņevs, I., Viļumsone, A. Human motion energy harvesters for wearables. No: 9th International Symposium on Flexible Organic Electronics. Workshop on Smart Textiles. Greece, Thessaloniki, 4–7 July 2016. ISFOE16, Book of Abstracts, p. 80.

# 1. LITERATURE REVIEW

With the development of technologies new ways are emerging for their application. The extension of the functional capabilities of electronics and the rapid reduction of element geometric dimensions, mass and energy consumption as well as the use of new types of materials in their manufacture make it possible to insert or integrate electronic systems into textiles, footwear and accessories making them mobile and imparting the products additional functionality.

Successful operation of integrated electronic systems requires an energy source [1]. To this end, mostly rechargeable batteries or disposable, replaceable batteries are used [2], [3]. Batteries must be replaced after use and special recycling is required in the post-operational phase, while accumulators need to be recharged from another source of energy also consuming electrical energy and natural resources at the same time. In order to save non-renewable natural resources and reduce pollution, the possibility of using renewable energy sources [4]–[6], such as wind or solar energy is being explored. Human body produced energy can also be used as a source for powering of electronic devices integrated into clothing [6] [8].

Alternative sources for operating of electronic systems allow for battery recharging or replacing as well as operating jointly to maximize system performance safety in general and prevent potential interruption of power supply.

Energy converters that convert the energy of human mechanical motion into electricity are, according to many researchers, considered to be the most promising and universal wearable energy source [9], [10].

Energy conversion devices can be classified in different ways considering what provides energy for conversion, the type of energy converted and the energy conversion principle, the way the device is placed, and so on. Based on the literature analysis, it can be concluded that there are three ways of energy production by means of smart products:

- interaction of the smart product with human (mechanical motions of the human body are used);
- interaction with the environment (solar and wind energy is used);
- interaction with both, the human and the environment (changes in the human body or/and in ambient temperature).

Power converters in smart products should ensure the following:

- Low service requirements: the user does not have to spend a certain amount of time each day to replace or recharge batteries.
- Extended service life: the operating cycle of the energy converter must be equal to or greater than the life cycle of the object (footwear, clothing or other objects in which it is integrated).
- Visually inconspicuous: the energy converter must be small in size, low-weight, easy to use, and it should not interfere with or affect the wearer's movements and present additional load.
- Independent from a specialized infrastructure, it should work anywhere and in any situation, and be ecological and cheap.

### Electromechanical Generators

One of the options for creating an energy source for an electronic system integrated into clothing is conversion of energy produced by human mechanical motions into electric current, and its subsequent storage in a battery. Energy conversion can be realised on the base of the electromagnetic induction: the electromotive force is induced electric current in the conductor as the magnetic field direction and/or value changes.

In literature sources one can find various portable electromagnetic generators or such as can be integrated into  footwear and other wearable products: electromagnetic rotational generators and eccentric rotational generators (a hybrid device that converts linear vibration into rotational motion), electromagnetic linear generators with a magnet moving in a coil, a coil movement in a magnet [11] , with a magnet movement based on the approximation and withdrawal of the coil [12], with a magnet moving along the coil, with the coil in a parallel plane [13], however, an electromagnetic generator for direct integration into a garment is not found.

### Types of Inductive Elements and Their Integration Into Smart Garments

Several publications show that it is possible to use flat spiral type coils as wearable electronic system elements in garments [14]–[16] and inductors of an electromagnetic converter [17]–[22]. The energy sources to be integrated into clothing should be as flat as possible so that they can be placed on the garment surface or between the layers of clothing.

The integration of flat inductive elements (FIE) into smart clothing can be done in two ways, depending on the degree of integration, by adapting/placing in clothing and concealing them between the layers of clothing, as well as designing the inductive elements on the basis of the textile material, that is, forming them as elements of design. Inductive elements as elements of garment design can be created manually in various handicraft techniques (embroidery, crochet, winding, etc.) [23], by jet or stencil printing on the surface of textiles (conductive inks, etching foil, etc.) [24], [25], and embroidering or sewing on with automated sewing machines [14], [26].

### The Effect of Magnets on Human Health

Considering the effects of magnets on human health, declarations (instructions) for textiles with electromagnetic energy converters with flat structure should include information on potential health hazards or adverse effects associated with constant presence of magnets on the human body with electronic cardiac pacemakers and cardiac defibrillators.

# 2. MATERIALS AND METHODS

**The structure of the research** is shown in Fig. 2.1.

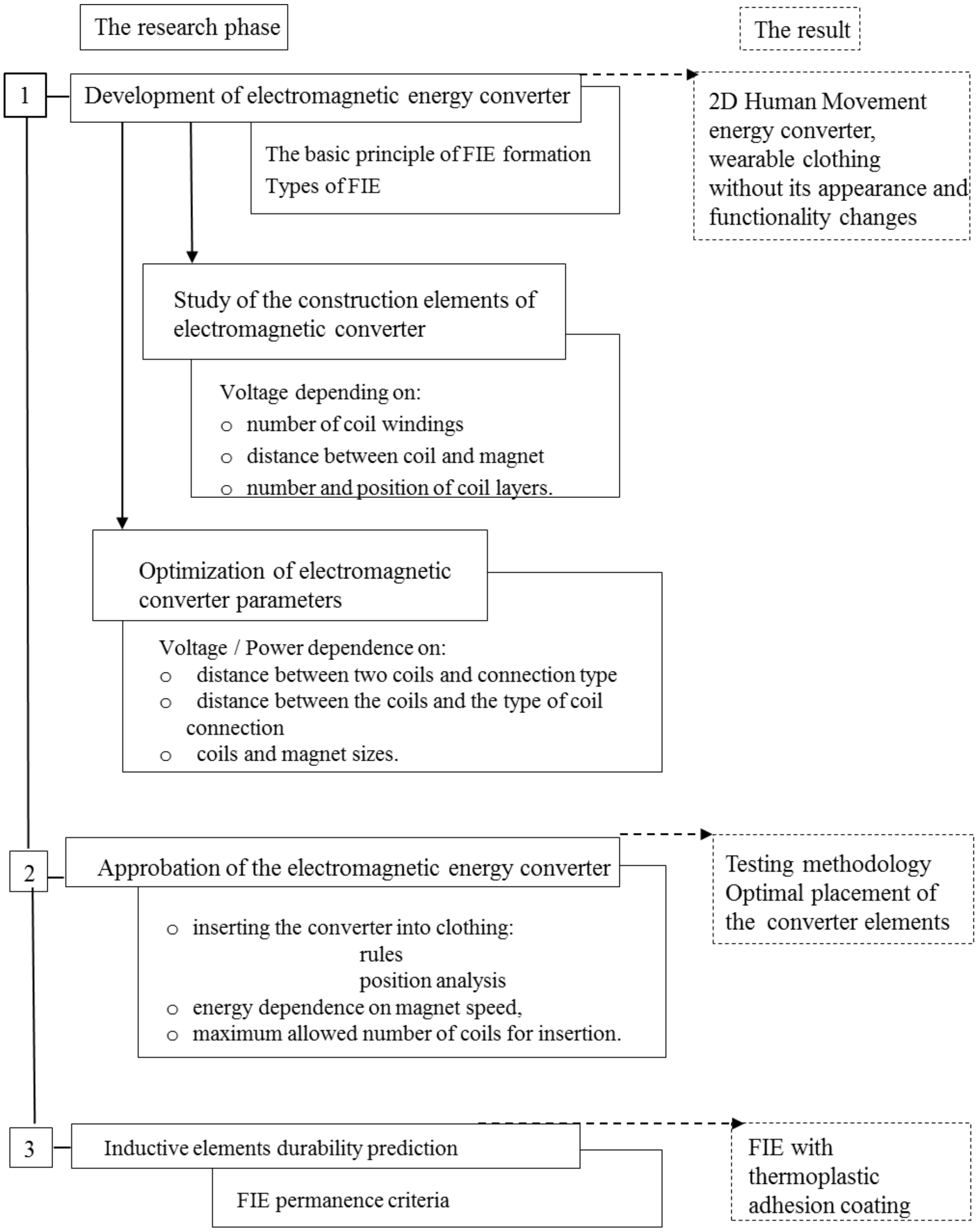



Fig. 2.1. The structure of the research.

In order to achieve the research purpose and to solve the research tasks, experimental research was carried out in the process of elaboration of the Doctoral Thesis, during which the conditions of each subsequent experiment were determined by the results of earlier experiments. The research process was carried out in three consecutive blocks.

## 2.1. Materials for Creating an Electromagnetic Converter

The electromagnetic energy converter consists of a flat induction element (a coil) and a permanent magnet.

Inductive elements, or coils, differ from each other by:

- the number of turns (5 to 25 with a constant outside diameter (16 mm));
- number of turns and diameter (diameter of coils varied from 4 mm (8 turns) to 80 mm (158 turns);
- copper wire diameter (0.1 mm and 0.22 mm);
- number of layers (from 1 to 5);
- insulating layer between coils and protective coating (Figs. 2.5 and 2.6);
- design solutions (rectangular, astroid, hypocyclic and round);
- type of material (copper wire, conductive filament or copper foil);
- manufacturing technology (manual or mechanized: embroidery, sewing or etching).

Magnets used in the experiments differ in:

- shape (rectangular parallelepiped, ring part);
- magnet type (neodymium or yttrium);
- linear dimensions;
- magnetic field induction (from 0.1 T to 4 T);
- magnetic field structure (ordinary or double – two (2) magnets connected in series so that the opposite poles lie in the same plane).

## 2.2. Methods of Measurement and Testing

### 2.2.1. Technology used to Create Inductive Elements

The coil of the electromagnetic energy converter is made in the same plane as a spiral structure with an increasing radius of curvature, placing the turns so that they do not touch. Turn insulation from one another prevents unwanted electrical contact between adjacent turns due to movement and deformation of the garment parts. The flat coil geometry ensures a minimal volume of the converter, so it can be fully inserted into the garment.

Copper wire coils in the shape of Archimedean spiral wound manually on a flexible and insulating substrate (non-woven fabric with an adhesive layer) (Fig. 2.2) were used in the basic experiments.

Fig. 2.2. One-layer coil.

Figs. 2.3 and 2.4 show information on five-layer coils with different insulating layers prepared for the washing test:

1 – non-woven, non-thermoplastic fabric with an adhesive layer;

2 – a flat coil of copper wire;

3 – a film with double-sided adhesive layer;

4 – additional protective coating – laminating or protective coating;

5 – thermoplastic adhesive coating (adhesive tape).

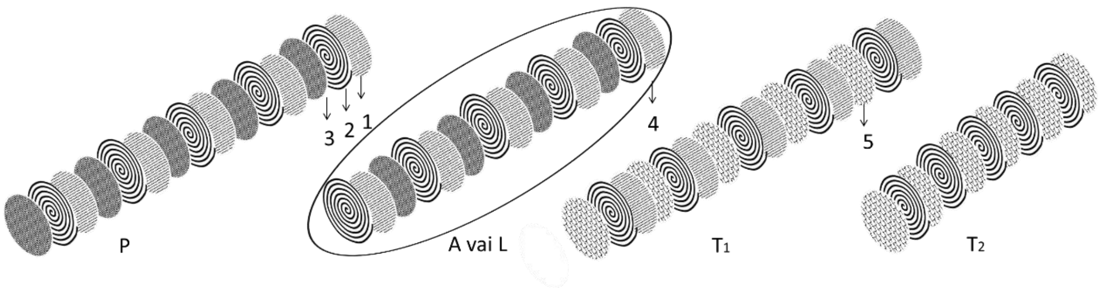



Fig. 2.3. Types of coil layers.

P – a coil with the primary wire coating. A – a coil with double-sided protective coating. Protective coating, which does not change its thickness and smooth structure during exposure to water, has been created in the Faculty of Materials Science and Applied Chemistry (RTU), and the names and descriptions are a commercial secret for now. Using a laminating device and a 125 micron thick laminating film, a coil with double-sided protective coating (L) is made. Thermoplastic Adhesion Coating is made covering the inductive element with a thermoplastic polymer fabric (adhesive tape) (T1 and T2).

A L P T

Fig. 2.4. The inductive elements with various protective coatings according to Fig. 2.3.

During the research inductive elements with various design solutions using embroidery machines (Figs. 2.5 and 2.7) and PCB (Printed Circuit Board) technology (Fig. 2.9) were developed.

Embroidery of the flat inductive element of the electromagnetic energy converter was performed by lock-stitch Brother PR600 embroidery machine (Fig. 2.6). To embroider the structures to be investigated, the conductive thread is used as the bottom bobbin thread, so that it would be less exposed to multiple mechanical effects. Embroidery is done with the fabric clamped in the embroidery frame.

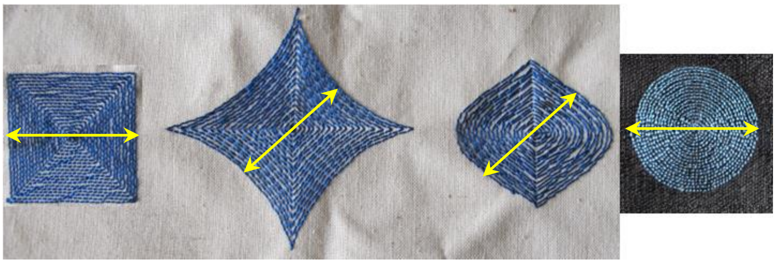


Fig. 2.5. Automatically embroidered flat coils (rectangular, astroid, hypocycloid and spiral shapes).

Fig. 2.6. Embroidery process (author U. Briedis).

The copper wire flat inductive element can be obtained not only manually, but also by sewing technology using the automated embroidery machine SZK JCL 0100-585. The sewing technology allows the use of an electric conductor (which is more fragile than an electrically conductive thread), since the conductive wire is subjected to less stress in comparison with the automated embroidery. The electrically conductive wire is fed separately to the embroidery area by means of a special attachment and attached to the fabric surface or to a water-soluble material with zig-zag stitches (Figs. 2.7 and 2.8). The coils are designed as Archimedes spirals with a diameter of 25 mm each and differ from each other in wire diameter (0.2 mm and 0.3 mm) and number of turns (25 and 50).

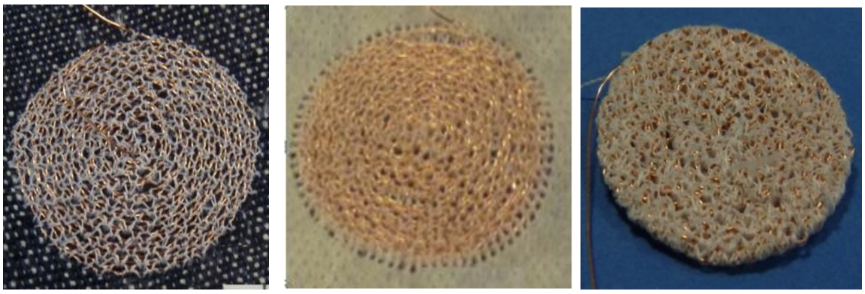


Fig. 2.7. Automatic machine sewed on flat coils (on the surface of the fabric and on the water-soluble material before and after exposure to water).

Fig. 2.8. The sewing on process (author V. Mečnika).

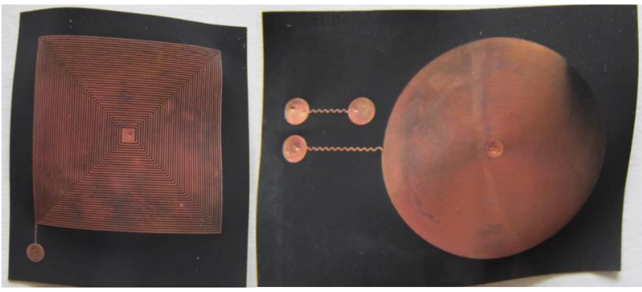


Fig. 2.9. Coils created with PCB (Printed Circuit Board) technology.

The PCB technology coils – the spiral-shape element is made with electrochemical etching technology on a flexible dielectric substrate (Fig. 2.9).

The electromagnetic energy converter was tested using five and four layer spiral inductive elements. The multi-layer coils are made by soldering single-layer coils connected in series, which are arranged one above the other, with the same direction of winding and an insulating layer between the coils. The diameter of each coil is 25 mm and the number of coil turns is 50, the turns are made of copper wire 0.22 mm in diameter.

### 2.2.2. Principle of Electromagnetic Energy Converter Operation

The electromagnetic energy converter with a flat structure operates on the principle of electromagnetic induction by converting human periodic mechanical motions into electricity. The electromagnetic energy converter consists of a flat inductive element (a coil) and a permanent magnet (Fig. 2.10).

The periodic movement of the magnet along the coil in a parallel plane forms a periodically variable magnetic flux that crosses the coil and results in electric current in the coil.

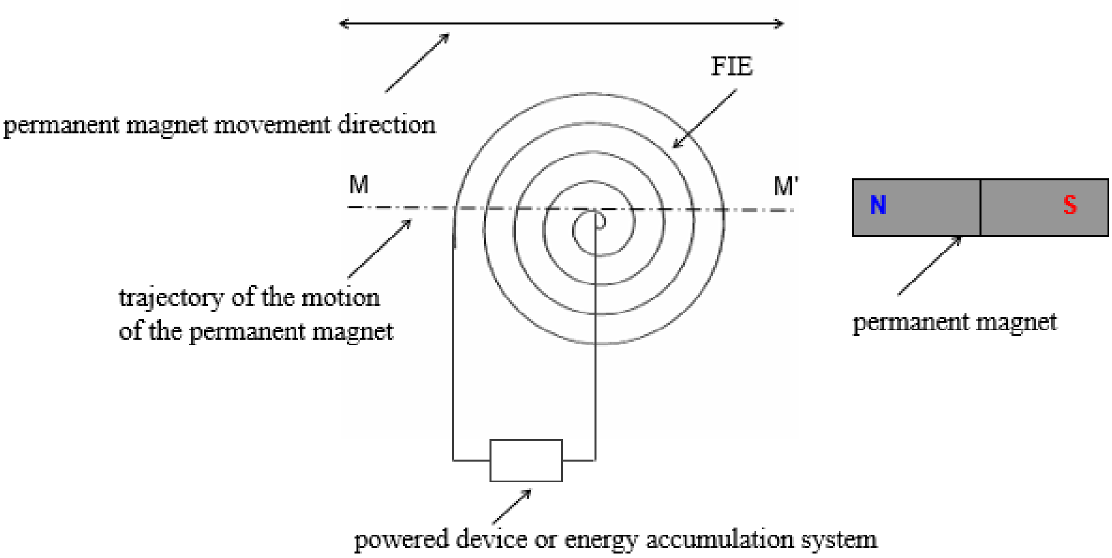



Fig. 2.10. Components of an electromagnetic energy converter.

Continuously changing magnetic flux can be achieved if the permanent rectangular magnet axis (south-north direction) coincides with the magnet movement direction relative to the coil. (Fig. 2.10, straight line MM'). In this case, the frequency of the generated alternating current will be equal to the magnetic oscillation frequency (in the case of a single coil), which also depends on the shape/structure of the magnetic field. To have the magnetic flux rate of change at each moment of time when the magnet moves above the coil not equal to zero, the magnet length should be close to or coincide with the outer diameter of the coil [28].

**Determination of characteristics of the flat electromagnetic energy converter**

As the magnet moves along the flat inductive elements (FIE), a magnetic flux that changes over time induces electrodynamic force in the coil, which, in turn, generates electric current in a closed circuit.

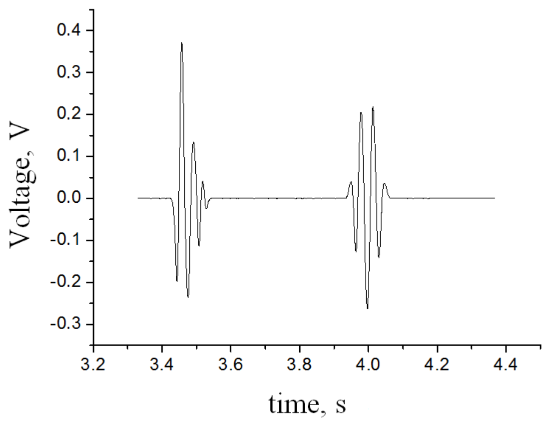



Fig. 2.11. Electrodynamic force generated by a flat inductive element.

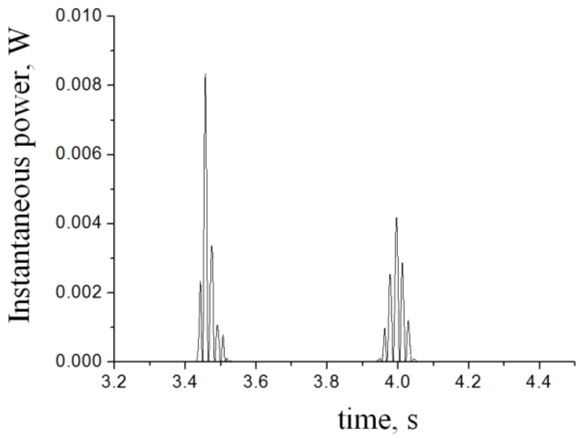



Fig. 2.12. Instantaneous power developed by the converter.

Experimentally determining the total energy and power of the flat inductive elements voltage pulses (Fig. 2.11) were recorded at the FIE; using the voltage values obtained the average resulting power was determined as the energy generated when the person is walking at a constant speed, divided by the time of movement.

The developed **power** [W] is calculated as the average instantaneous power value over time (Fig. 2.13).

$$P = \frac{1}{\tau}\int_0^{\tau} P\mathrm{d}t = \frac{W}{\tau}. \quad (2.1)$$

Efficiency (the energy generated as a part of the kinetic energy of the magnet, expressed as a percentage)

$$k = \frac{2W}{mv^2}100. \quad (2.2)$$

**Insertion of electromagnetic energy converter into clothing and testing**

Magnets with markers, by means of which the trajectory of magnet movement is marked simulating human walking (Fig. 3.6), are attached to clothing at the planned insertion points of the parts of the energy converter. The obtained magnet trajectory curve corresponds to the location of the EMC inductive element centres (Fig. 3.8).

**Characteristics of washing procedures**

Home washing is done according to ISO 6330:2012 [29].

Characteristics of washing procedures:

- automatic front loading type A washing machine was used, water temperature – 40 °C during the wash cycle – 70 minutes, using detergents – PersilColorGel, cold rinse cycle and mechanical water removal from the washed sample;
- drying at room temperature (22 ± 2) °C.

Coils are inserted in jackets before washing.

**Measurements of the electrical resistance** of the inductive element were made using the digital multimeter Velleman DVM860BL with two contacts (Fig. 2.13).

The electrical resistance conformity of the produced coils was checked before and after 1, 5 and 10 washing and drying cycles.

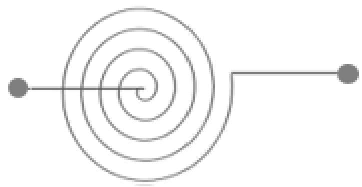


Fig. 2.13. Electrical resistance measurement.

**Measurement of EMC voltage and data recording** was performed using Tektronix TDS 2014 digital oscilloscope and Picoscope 2205 to observe the change of voltage over a given period of time.

OriginPro 8.5. and Excel computer programs were used to **process experimental research data** of the energy converter inserted into clothing, as well as the calculations and statistical analysis of generated energy and power, graphical visualization of data and other actions.

# 3. RESULTS AND DISCUSSION

By replacing the traditional cylindrical inductive element (coil) with a flat spiral coil in a power converter and replacing the traditional magnet movement in coil or coil movement in a magnet with a magnet motion along a flat inductive element (without passing through its plane), it is possible to realize the human motions mechanical energy converter from flat structure elements that can be fully integrated into moving parts of clothing.

## 3.1. Study of the Construction Elements of Electromagnetic Converter

### Comparison of the converter efficiency using inductive elements made in various shapes and in different ways

The value of power was chosen as the efficiency criterion of the converter. To find out the effect of the coil geometric shape, the fabrication technology and the direction of the magnet movement along the coil on the efficiency of the converter, the power developed by the inductive elements made using PCB technology and of various shapes of spiral-shape embroidered inductors (Fig. 3.1) are compared. The numerical values are summarized in Tables 3.1, 3.2 and 3.3.

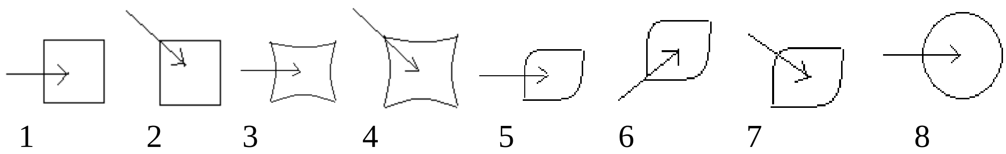



Fig. 3.1. Coil shape and direction of magnet movement.

Table 3.1

The Experimentally Determined Performance Parameters of PCB Technology Inductive Elements

| **Coil shape and magnet motion, according to Fig. 3.1** | **Coil type and parameters** | **Energy per pulse, µJ** | **Pulse duration, s** | **Mean power (during the pulse), µW** |
|---|---|---|---|---|
| 8 | Hand-made copper wire coil, diameter 3 cm, number of turns 60. $R$ = 2.2 Ω | 113.82 | 0.130 | 875.54 |
| | PCB coil, diameter 3 cm. $R$ = 116 Ω | 4.31 | 0.146 | 29.62 |
| 1 | Square PCB coil. $R$ = 10.1 Ω | 6.35 | 0.126 | 50.39 |
| 2 | | 9.41 | 0.116 | 81.12 |

The power values of the PCB technology coil are significantly lower than those of the manually made coil as it has a very high internal resistance due to the very small cross-section of wires. As a result, the voltage values are higher (max. one coil 200 mV), but the amount of energy released is less. In turn, the manually fabricated coil has higher developed power (practically, 30 times higher when comparing two round coils), but the generated voltage is lower than the average (about 120 mV maximum). However, it should be noted that in the rectangular PCB variant, coil resistance is 11 times less than in the circular variants, the average energy and power can be increased 1.5 times by moving the magnet diagonally.

Table 3.2
The Experimentally Determined Performance Parameters of Embroidered Inductive Elements

| **Coil shape and direction of magnet movement, according to Fig. 3.1** | **Line density, line/mm** | **Resistance $R_{sl}$, Ω** | **Energy per pulse, µJ** | **Pulse duration, s** | **Mean power (during the pulse), µW** |
|---|---|---|---|---|---|
| 1 | 1.5 | 8.8 | 1.99 | 0.088 | 22.69 |
| 2 | | | 1.16 | 0.081 | 14.64 |
| 3 | 1.5 | 10.1 | 2.05 | 0.073 | 28.28 |
| 4 | | | 1.38 | 0.062 | 22.46 |
| 5 | 1.5 | 8.0 | 2.18 | 0.071 | 31.11 |
| 6 | | | 1.94 | 0.074 | 26.60 |
| 7 | | | 1.41 | 0.080 | 18.00 |
| 8 | 1.5 | 8.3 | 2.21 | 0.075 | 29.84 |

The embroidered coils have a smaller number of turns than a manually fabricated coil and a relatively high internal resistance, thus the average values of energy and power are not high when compared with a manually fabricated coil. By moving the magnet diagonally, the average energy and power decrease.

Table 3.3
The Experimentally Determined Performance Parameters of Sewed Inductive Elements

| **Coil shape and direction of magnet movement, according to Fig. 3.1** | **Copper wire diameter, mm** | **Resistance $R_{sl}$, Ω** | **Energy per pulse, µJ** | **Pulse duration, s** | **Mean power (during the pulse), µW** |
|---|---|---|---|---|---|
| 8 | 0.2 | 0.70 | 6.62 | 0.072 | 91.25 |
| | 0.3 | 0.47 | 6.55 | 0.076 | 86.09 |

Energy and power values for sewed on coils are smaller than for manually made coils, which can be explained by the fact that the number of turns of such coils is twice smaller, nevertheless they significantly exceed the power of the embroidered inductive element.

## 3.2. Optimization of Electromagnetic Converter Parameters

In order to optimize the converter parameters to maximize the power generated per volume unit, the study was continued by changing the coil connection and connection type, the number of coil layers, and their mutual placement.

- Voltage dependence on distance between two coils and connection type (Fig. 3.2).
- Developed power dependence on the dimensions of the coil and the magnet (Fig. 3.3).
- Developed power depending on spacing between coils and coil connection type (Fig. 3.5).

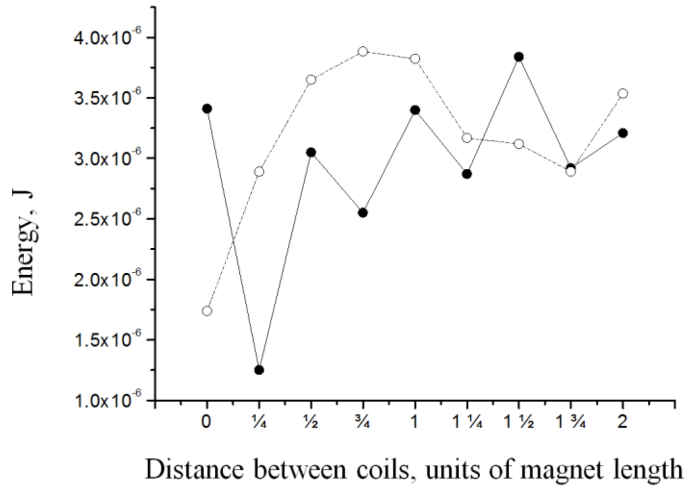



Fig. 3.2. The generated energy depending on the distance between the coils: o – the energy generated in two coils connected in series; • – total energy generated in two isolated coils.

- Electromotive forces (EDS) will be directed in the same direction and amplify each other if simultaneously in the second coil there is an increasing flux of one magnet pole, while in the first coil there still exists declining flux of the opposite pole.
- The constructive summation of the induced EDS (voltage pulses amplify one another) is most effective when the distance between the coils is ¾ of the length of the magnet. The total generated energy is about 4 mkJ, the maximum developed power is 58 mkW and the maximum EDS is 54 mV.

The diameter of the coils varied from 4 mm (8 turns) to 80 mm (158 turns).

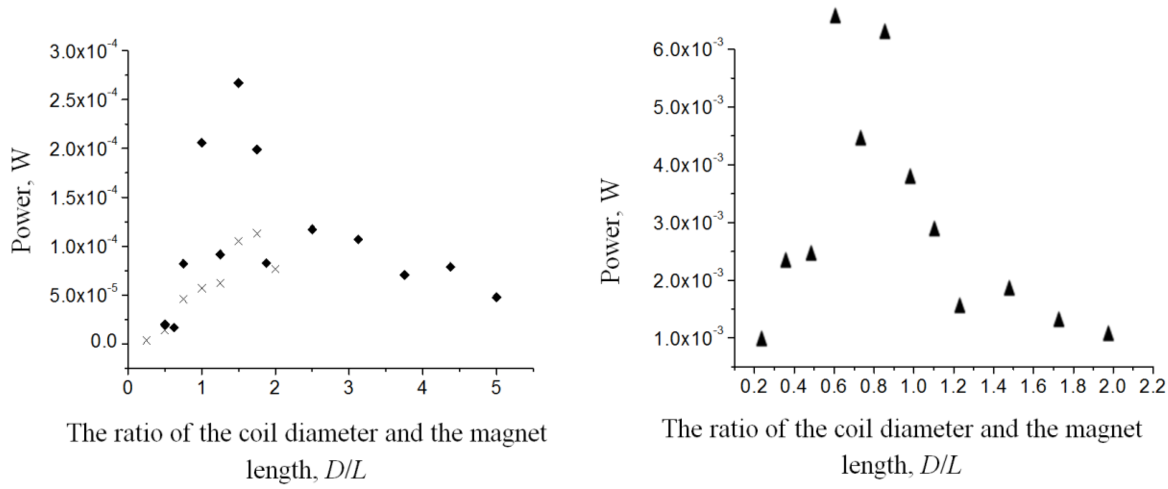
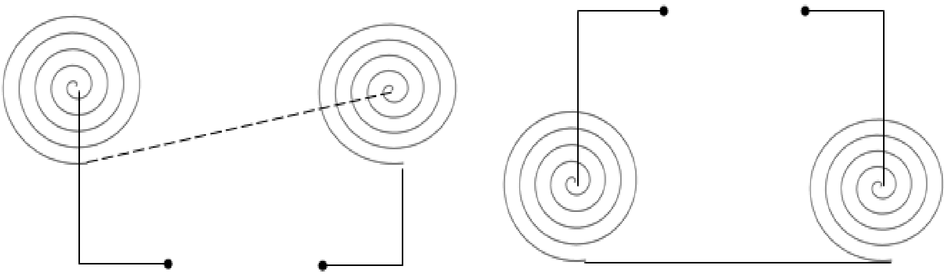



Fig. 3.3. Dependence of the generated power on diameter D of the coil and the ratio of length *L* of the magnet, *D*/*L*: ♦ – 1. magnet *L* = 8 mm; *x* – 2. magnet *L* = 20 mm; ▲ – 3. magnet *L* = 40 mm.

Power peak was observed: rectangular magnets at *D*/*L* = 1.5 (magnet 1), *D*/*L* = 1.75 (magnet 2) and circular magnet (magnet 3) *D*/*L* = 0.625.

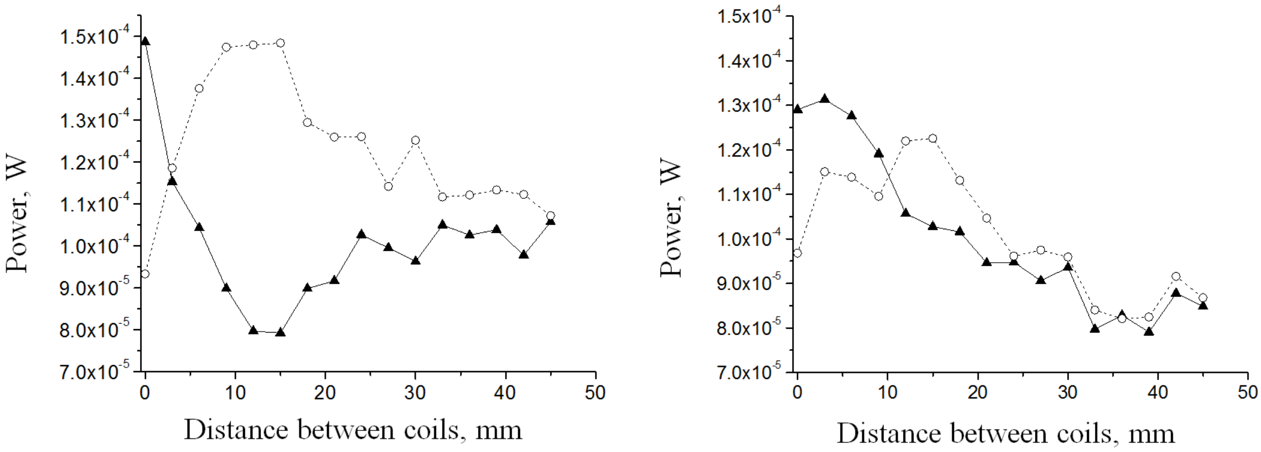
The highest power output of 6.83 mW was obtained using a circular magnet with a double magnetic field structure (magnet 3) and a coil with 50 turns and a diameter of 25 mm.

Experiments performed on two coil connections: in the first case the two coils are connected so that the generated voltage pulses have the same polarity; in the second case, the voltage pulses have the opposite polarity (Fig. 3.4). The dependence of the power developed in coils on the distance between them is shown in Fig. 3.5.



a b

Fig. 3.4. Coil connection type: a – voltage pulses of the same polarity; b – voltage pulses have opposite polarity.




*a* *b*

Fig. 3.5. The total developed power for two coils in series as a function of the distance between the edges of the coils: *a* – using magnet 4 with a double magnetic field; *b* – using magnet 5; ○ – the generated voltage pulses have the same polarity; ▲ – the generated voltage pulses have opposite polarity.

The distance between the coils, at which the maximum value of the developed power is observed, depends on the type of coil connection. By connecting the coils so that the generated pulses have opposite polarity, it is possible to reduce the distance between the coils to zero, thus increasing the power developed by the electromagnetic energy converter. The graph (Fig. 3.5 a) shows that practically the same power can be achieved at the same polarity by increasing the distance between the coils (10–15 mm). Power peak (Fig. 3.5 b) is observed for generated voltage pulses with opposite polarity (5 mm).

## 3.3. Inserting an Electromagnetic Energy Converter Into Wearable Textiles

Effective operation of the electromagnetic energy converter requires several conditions to be met:

- parts of the converter must be positioned so that they move in relation to each other along with the corresponding parts of the garment during its movement;
- pieces with EMC parts should move along each other as close as possible;
- the location of the inductive elements should be as flat as possible and should not be subjected to deformation during movement;
- the parts of the converter must not alter the characteristics of the garment and the appearance;
- it is desirable to provide the maximum speed of magnet movement along inductive elements because the amount of energy generated is directly proportional to the energy of the magnet movement.

All of these conditions can be met by placing the electricity converter pieces in the garment parts that during movement are as close to each other as possible, which, in turn, will move the magnet in relation to the inductive element during human motion, and thus the inserted converter will transform the human mechanical movements into electricity.

### 3.3.1. Inserting an Electromagnetic Energy Converter Into a Jacket

The components of the electromagnetic energy converter are placed in the garment elements that move along each other during human motions. The periodic movement of the magnet along the coil forms a periodically varying magnetic flux that crosses the coil and generates electric current in the coil.

The placement points of coil and magnet, the number of coil layers and coils is determined experimentally. In the created prototype (a men’s jacket) the elements of the energy converter are inserted (Fig. 3.6) at the wrist base level between the fabric layers, maintaining symmetry:

- a magnet is inserted in the sleeve bottom seam in the wrist base area;
- the inductive element is located at the front of the jacket (the side pocket area).

The insertion of magnets and coils is achieved without deformation of the base layer of the jacket; their location is practically not visible from the outer side of the product, although the hardness of the fabric package has, of course, increased.

In the prototype, two power converters are placed on the left and right at the same time with the option of choosing the operational mode – EMF and resistive mode. Electromagnetic energy converter was tested at a speed of 3 km/h; 4.5 km/h and 6 km/h, corresponding to a man’s slow, moderate and fast walking.

On the right side, a five-layer inductive energy converter was tested in two modes. During the tests, the digital oscilloscope Picoscope 2205 recorded the voltage pulses of the converter at the resistive load (Fig. 3.7). The characteristics of the energy converter are presented in Table 3.4.

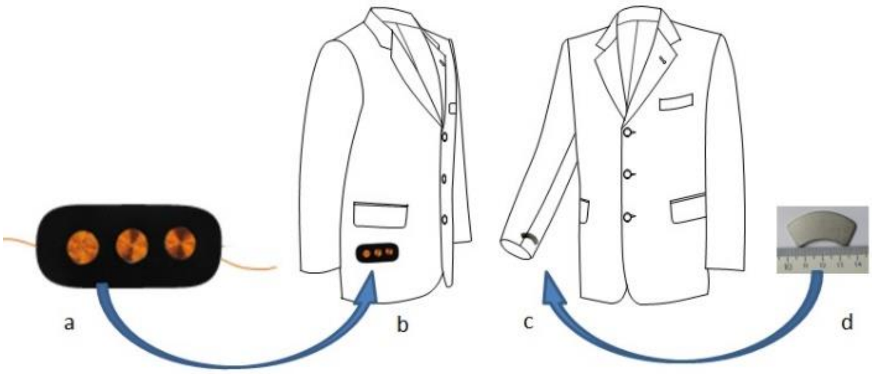



Fig. 3.6. Elements of the electromagnetic converter and their arrangement in clothing: a – spiral-shape inductive element; b – placement of inductive element; c – magnet placement; d – a permanent magnet.

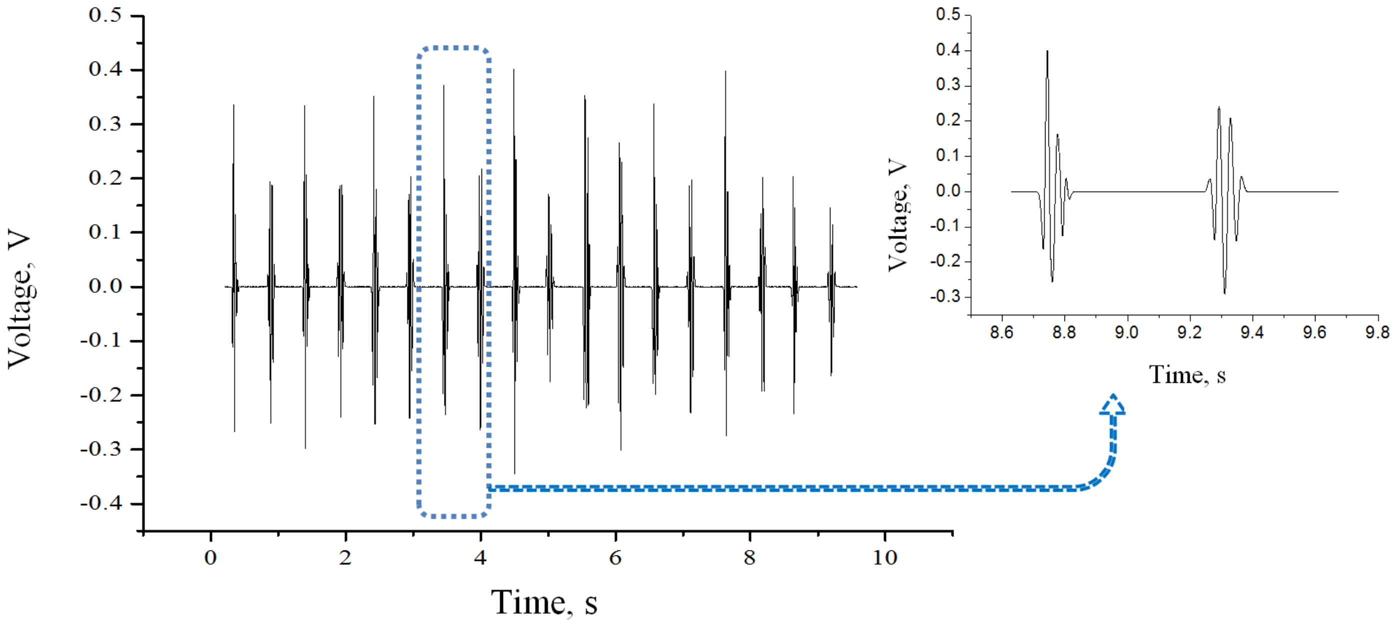



Fig. 3.7. The evolution of the voltage pulses generated during nine full walking cycles and one cycle pulses at the movement speed of 6 km/h. Full walking cycle – a double step period – is summed up with each arm moving back and forth.

During the tests there was a certain asymmetry in the pulses associated with the trajectory of the sleeve motion and the individual motion stereotype.

Table 3.4

Power Generated by the Power Converter at Different Movement Speeds

| **Speed of motion, km/h** | **Steps in 1 min** | **Maximal instantaneous power, µW** | **Average power, µW** | **Mean density of power, µW/cm$^3$** |
|---|---|---|---|---|
| **3.0** | 80 | 3000 | 37 ± 16 | 8 |
| **4.5** | 103 | 14 000 | 77 ± 20 | 16 |
| **6.0** | 115 | 10 000 | 199 ± 20 | 41 |

Maximum instantaneous power (14000 μW) has been observed at a speed of 4.5 km/h and the maximum mean developed power of 199 μW (human walking at 6 km/h). The test results with a speed of 6 km/h can be considered homogenous.

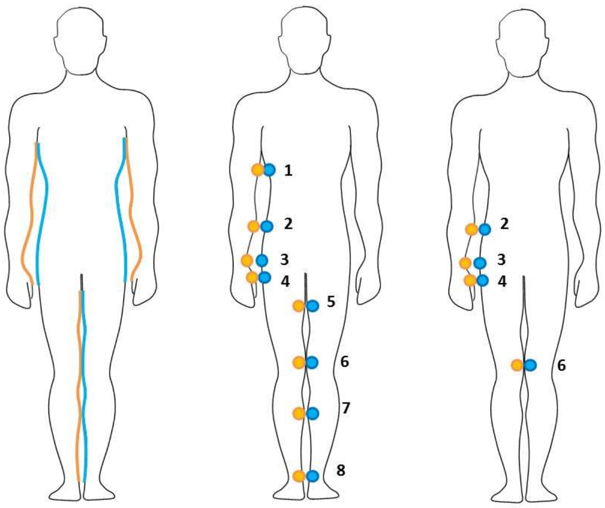
### 3.3.2. Analysis and testing of potential electromagnetic energy converter insertion places

The energy converter elements are not combined in one housing and can be placed in virtually all types of clothing and/or accessories (e.g. bags) that have two moving parts close to each other during human motions.

Possible places for the placement of the energy converter parts are arms and surfaces exposed to unintentional natural reciprocal movement as well as the inside surfaces of legs. Possible placement points of the magnet are marked with orange, but the placement of inductive elements with blue colour (Fig. 3.8 a).

The maximum speed of magnet movement along the inductive elements can be achieved by positioning the elements of energy converter in position 4 according to the upper part of the body and in position 8 at the lower extremities. In turn, speeds at positions 1 and 5 are minimal.

From the point of view of the anatomical structure of the human body, the most suitable places for inserting the converter are the contact points of upper extremities and the torso at the side (positions 1–4). In the case of medium height, the minimum distance between the elements of the energy converter in positions 1 and 2 is possible.




a b c

Fig. 3.8. Locations for the components of the electromagnetic energy converter: a – possible placement locations; b – initial test locations; and c – selected locations for repeated testing.

When designing the elements of energy converter for insertion into pants (positions 5–8), not only the shape of the lower extremities should be taken into account, but also the peculiarities of gait. The shape of the lower extremities may differ from the standard shape in relation to the location and angles formed by the thigh and lower leg bones. This means that for insertion in positions 5–8 individual adjustments should be made that may not always be successful [30].

The initial testing was performed at eight locations (Fig. 3.8 b) by measuring the voltage pulse values of the electromagnetic energy converter. Given the magnitude of the pulse generated, the best places for insertion of the energy converter are selected (Fig. 3.8 c). For the test subjects they are: position 2 – the anterior superior iliac spine/illiac crest level (about 8 cm below the waist); position 3 – the base level of the wrist; position 4 – the middle of the wrist; position 6 – the knee level. At locations marked with numbers 1, 5, 7 and 8, there was no voltage pulse, or it was minimal because the amplitude of the magnet movement along the inductive element (positions 1 and 5) was not sufficient and due to the long distance between the EMC parts (7 and 8), which is related to the anatomical and gait peculiarities of each individual.

Further experiments took place at the Rehabilitation Centre "Vaivari" of the Riga Stradiņš University, where it was possible to measure the voltage pulses of the electromagnetic energy converter during a test person's walking at various fixed walking speeds: 3 km/h; 4.5 km/h and 6 km/h for men; and 2.6 km/h; 3.4 km/h; 4 km/h and 6 km/h for women corresponding to slow, moderate and brisk pace for walking, as well as to determine the speed of movement of EMC elements during walking (Fig. 3.9).

Characteristics of the converter over a full walking cycle are summarized in Tables 3.5 and 3.6.

a b c d

Fig. 3.9. Electromagnetic energy converter performance testing: a – jacket model 1; b – jacket model 2; c – windbreaker with a nonwoven fabric insulation; d – belt bag and removable wristband.

Table 3.5

Electromagnetic Energy Harvester Prototype Used in Women Garment

| Type of clothing | Speed of motion, km/h | Coil placement position | Mean power, µW | Mean power density, µW/cm$^3$ |
|---|---|---|---|---|
| **Jeans** | 4.0 | 6. | 179.03 ± 33.33 | 38.67 |
| **Women jacket** | 6.0 | 2. | 269.18 ± 85.97 | 58.14 |
| **Women jacket** | 4.0 | 2. | 135.12 ± 37.40 | 29.18 |
| **Women jacket** | 4.0 | 3. | 133.03 ± 47.77 | 28.73 |
| **Women jacket** | 3.4 | 3. | 73.86 ± 46.50 | 15.95 |
| **Women jacket** | 2.6 | 3. | 119.89 ± 48.28 | 25.89 |
| **Belt bag and removable wristband** | 4.0 | 3. | 90.80 ± 80.21 | 19.61 |

The maximum power of 269 μW was obtained at a speed of 6 km/h when the elements of the energy converter were in the women's jacket in position 2. The second best result is 179 μW at a speed of 4 km/h with the elements of the energy converter in jeans in position 6.

Table 3.6

Electromagnetic Energy Harvester Prototype in use at Men Garment

| **Type of clothing** | **Speed of motion, km/h** | **Coil placement position** | **Mean power, μW** | **Mean power density, μW/cm$^3$** |
|---|---|---|---|---|
| **Jacket model 1 (with reduced volume at the wrist base part and hemline of the jacket)** | 3.0 | 2. | 43.24 ± 4.48 | 9.34 |
| | | 3. | 10.99 ± 2.33 | 2.37 |
| | 4.5 | 2. | 13.89 ± 2.06 | 3.00 |
| | | 3. | 25.70 ± 6.00 | 5.55 |
| | 6.0 | 2. | 50.73 ± 5.06 | 10.96 |
| | | 3. | 1.80 ± 0.75 | 0.39 |
| **Jacket model 1** | 4.5 | 2. | 60.14 ± 4.38 | 12.99 |
| | | 3. | 2.59 ± 1.65 | 0.56 |
| **Jacket model 2** | 3.0 | 4. | 6.00 ± 1.04 | 1.30 |
| | | 2. | 33.27 ± 8.43 | 7.18 |
| | 4.5 | 4. | 13.10 ± 2.85 | 2.87 |
| | | 2. | 53.96 ± 10.73 | 11.65 |
| | 6.0 | 4. | 15.79 ± 10.66 | 3.46 |
| | | 2. | 52.81 ± 10.19 | 11.41 |
| **Jacket with non-woven fabric insulation** | 3.0 | 2. | 181.40 ± 23.80 | 39.18 |
| | 4.5 | 2. | 260.68 ± 63.85 | 56.30 |
| | 6.0 | 2. | 502.22 ± 100.14 | 108.47 |
| **Belt bag and removable wristband** | 4.5 | 3. | 236.68 ± 56.87 | 51.12 |

The best generated power outputs of 502 μW and 261 μW were achieved with inserted parts of the power converter in position 2 of the jacket with a non-woven fabric insulation at speeds of 6 km/h and 4.5 km/h.

Consequently. the highest generated power is obtained when the distance between the components of the electromagnetic energy converter due to the size of the jacket and the anatomical peculiarities of the body is stable, the magnet with the coil stays firmly at the attachment points and a precise magnet movement trajectory along the centres of the inductive elements is provided.

The results of the analysis suggest the following:

- the most suitable EMC placement at any speed is for a set of about 8 cm under the waist of a garment for upper or whole body and the level of the wrist base;
- maximum power values can be achieved with the person walking briskly;
- the most appropriate type of garment for insertion of the converter can be a jacket with a non-woven fabric insulation, stable shape, and small breast and hip level ease allowances.

The dependence of the voltage pulses on the location of the coil was studied by placing two five-layer coils in series (number of turns 50) in the movement course of one magnet in a jacket with a non-woven cloth insulator about 8 cm below the waist. The coils are connected in such a way that the generated voltage pulses have opposite polarity and the distance between the coil edges is 0 mm. The coils are positioned so that the side seam[1] of the jacket lies between the coils (Fig. 3.10). Moving the coils to the right and left by 1 cm showed that the highest value of the voltage pulses was reached when the side seam of the jacket lies between the coils.

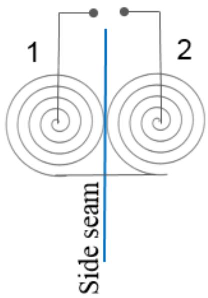



Fig. 3.10. Coil placement position.

In order to increase the total power of the converter, four coils were placed in the course of the magnet with the above conditions to determine *the maximum permissible number of coils* for insertion. Voltage pulse values for each coil were investigated by changing the coil positions relative to the jacket seam. During the experiment it was found that the maximum number of coils for insertion into the jacket is three.

### 3.3.3. Energy Dependence on the Speed Of Magnet Movement

In the experiment, infrared-reflective markers are attached in two positions on the human body: the location point of position 2 is about 8 cm below the waist, and the position 4 and FIE points are located at the wrist level (Fig. 3.8). In the system used, digital cameras record three-dimensional trajectories of human marked anatomical point movements. From the data obtained, the computer software creates a virtual model for further analysis [32]. When processing the acquired EMC element movement speeds for walking times, speeds and other parameters for individual points calculated when the magnet (in position 4) moves along the coils (FIE point) (Table 3.7).

[1] The side seam in this study is always situated in the middle of the side surface (the width of the front and back pieces is equal).

Table 3.7

Converter Performance Parameters

| **Walking speed, km/h** | **Point movement speed, m/s** | | | **Relative speed of the magnet in respect of the coil, m/s** | **Generated energy, µJ** | **Pulse period, s** | **Average power, µW** |
|---|---|---|---|---|---|---|---|
| | Position 4 | Position 2 | FIE | Position 4+FIE | | | |
| **3.0** | 0.9 | 0.6 | 0.26 | 1.16 | 7.53 | 1.25 | 6.00 |
| **4.5** | 1.4 | 0.8 | 0.3 | 1.70 | 14.44 | 1.10 | 13.13 |
| **6.0** | 2.0 | 1.2 | 0.4 | 2.40 | 15.58 | 1.00 | 15.58 |

The speed of movement of the magnet is influenced both by the speed of human movement and by the peculiarities and possibilities of movement, which in turn depend on the peculiarities of the body structure. For example, the speed of movement does not depend on the size of the body. Execution time of certain movements, such as the one-step execution time, increases in proportion to the increase in the linear size of the body (under other unchanged conditions), while the maximum intensity of movements decreases in proportion to the body's linear dimensions increase [32]. The table shows that the increase in magnet speed is proportional to the walking speed.

## 3.4. Prediction of Inductive Element Durability

Two factors must be taken into account in the process of making smart garments: the comfort and design of the garment must be ensured simultaneously ensuring the functionality and usability of the energy converter as well as both durability and reliability [33].

Creating clothing with an inserted electromagnetic energy converter it is essential to maintain the possibility of garment care. The most common type of garment care is washing at home. It is important that after washing a smart garment with an energy converter it would not lose its quality, size and appearance, and conversion capacity and efficiency. The washing process can be described as a set of physico-chemical and mechanical factors. Physico-chemical factors include detergent exposure, temperature and humidity, and mechanical factors include mutual friction of wet material parts and their contact with washing machine surfaces, multiple tensile, compressional and torsional deformations.

The effect of washing on FIE durability was studied. The criteria for determining the durability of FIE, which determine the unsuitability of a coil for further operation, are:

- unsatisfactory electrical conductivity of the coil;
- destruction of the coil (damaged coil structure).

Five-layer coils with different types of protective coating and insulating layers were used in the experiment (Figs. 2.3 and 2.4).

The tests of coil structure and measurement of the electrical resistance of the coils were made before and after the 1, 5 and 10 washing and drying cycles using a digital multimeter Velleman DVM860BL. Measurement results are summarized in Table 3.8.

Table 3.8

Electrical Resistance Values of Different Coils Before and After Washing

| Symbol of coil | Before washing | | After washing and drying | | |
|---|---|---|---|---|---|
| | **Initial resistance, Ω** | **Resistance after the application of protective coatings, Ω** | **Resistance after 1 cycle, Ω** | **Resistance after 5 cycles, Ω** | **Resistance after 10 cycles, Ω** |
| **A** | 5.7 | 5.7 | 5.7 | | |
| **L** | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 |
| | | | 5.4 | 5.4 | Infinitely large |
| **P** | 5.5 | – | 5.5 | Infinitely large | |
| $\mathbf{T_1}$ | – | 5.6 | 5.6 | 5.6 | 5.6 |
| $\mathbf{T_2}$ | – | 5.4 | 5.4 | 5.4 | Infinitely large |
| | | 5.6 | 5.6 | 5.6 | 5.6 |

For further experiments, the structure of the inductive element with thermoplastic adhesion coating was improved. The inductive element is created manually so that all five layers are wound continuously from the first layer to the fifth, one over the other without the coil wire breaking, which eliminates the soldering procedure and makes the coil edges smoother (Fig. 3.11).

a b

Fig. 3.11. Inductive element before (a) and after (b) optimization.

## 3.5. Comparative Analysis of the Energy Generated by the Energy Converter, the Developed Power and the Geometric Shape

1. The power converter inserted into clothing was tested using a mechanical stand for controlled magnet movement to provide a constant magnet speed (1 m/s) and distance between the coil and magnet (~5 mm). The developed power is (2610 ± 149) µW. Comparison of the test results of the energy converter with the results of a balanced movement of the human body (Table 3.6) shows that the usable part of the power is 7 % at a speed of 3 km/h (corresponds to magnet movement speed of 1 m/s). By increasing the speed of the movement it is possible to increase the usable part of the power up to 19 %.
2. Accumulating the energy produced by the prototype within 1 hour of walking, it may ensure the operation of electronic devices in accordance with Table 3.9 (data from the power converter testing in a jacket), the table adapted according to [34]. Data in

Table 3.9 indicate that the power of the energy converter is sufficient to operate the sensors integrated in clothing.

Table 3.9

Energy Consumption in Battery Operated Devices

| Device type | Power consumption | Energy autonomy | Energy converter power supply possibilities |
|---|---|---|---|
| **Smartphone** | 1 W | 5 h | 2 s |
| **MP3 player** | 50 mW | 15 h | 30 s |
| **Hearing aid** | 1 mW | 5 days | 0.4 h |
| **Pacemaker** | 50 μW | 7 years | 8 h |
| **Quartz watch** | 5 C | 5 years | 80 h |
| **Wireless sensor node** | 100 μW | Eternal (battery + power converter) | 4 h |

3. The obtained power densities are comparable to the results of the different forms of electrodynamic converters of other researchers, summarized in the article by Mitcheson and co-authors [9], but given that these converters operate at higher frequencies (e.g. [35] $P/V$ = 2200 μW/cm$^3$ at $f$ = 320 Hz), it can be seen that using flat spiral inductors it is possible to obtain power density values that at the same operating frequencies are comparable with the best three-dimensional converters.
4. By comparing the generated energy converter with the flat-shaped electromagnetic converters of other researchers, summarized in Zhao's study [36] (Table 3.10), one can see that none of them is intended for integration into clothing.

Table 3.10

Characteristics of Flat Electromagnetic Energy Converters

| Researchers | Volume, cm$^3$ | Mass, kg | Power, W | Application | Energy source |
|---|---|---|---|---|---|
| P. Zeng et al. | 116 | 0.86 | 0.83 | Foot pad | Foot Horizontal |
| Z. Yang et al. | 520 | 3.25 | 7.2 | Backpack | Center-of-mass |
| P. Niu et al. | 903 | 2 | 0.784 | Backpack | Center-of-mass |
| I. Stamenkovic et al. | 10 | 0.096 | 0.059 | Foot pad | Foot Horizontal |

5. Comparing the results of the energy converter testing with the results of the different types of converters of other researchers according to the energy source summarized by Carroll [37] (Table 3.11), it can be seen that using flat spiral inductors it is possible to obtain power values comparable with the average generated energy of other converters.

Table 3.11

Characteristics of Arm Motion Energy Converters

| Researchers | Power | Volume, cm$^3$ |
|---|---|---|
| Niu | 10 mW | Not mentioned |
| Nightstar | 200 mW | Not mentioned |
| Renaud | 40 μW | <1 |
| Renaud | 47–600 μW | 14 |
| Li | 0.3 μW | Not mentioned |

The proposed energy converter has several advantages:

- The **weight** of the energy converter **is insignificant** in relation to the weight of the product and **provides** the same *freedom of movement* as wearing clothes without the energy converter.
- An energy converter with a flat induction element **does not require an additional volume for magnet movement**, since the coil and magnet are placed in different parts of the garment that move in relation to each other when worn and can be placed in virtually any garment.
- The elements of the energy converter are flat, with a low weight, so they **can be inserted in the garment without changing its shape and appearance**.
- Due to the two-dimensional geometry of the converter created, the **movement of the garment elements** along one another during the wearer motions **can be used for powering the energy converter directly**.
- The design elements of the energy converter **are not combined in one housing** and can be placed in virtually **any type of clothing** taking into account their operating principles, matching the appropriate structural elements (magnets and inductive elements) and insertion points.
- Changing the dimensions of the inductive elements, material, geometry, number of coils and their placement **the parameters of the energy converter can be altered in a wide diapason of values**.
- The flat geometry of the converter allows **minimizing the volume occupied** by the converter reducing it to the total volume of the elements that in comparison with other converters provides **higher power density**.
- The **non-inertial nature** of the created energy converter, which provides the same good performance over a wide frequency range rather than at a given resonant frequency, can be considered as another advantage. Accordingly, such a system does not need to be adapted to the speed of motions of a particular user (the wearer of the garment), still the peculiarities of the motion trajectories can reduce the energy generated by the device. In order to minimize this negative effect, it is necessary to look for the places in clothing that are moving closest to each other during motions of a particular wearer.
- The investigated electromagnetic energy converter **is simple to use** and can be used as **a mobile and environmentally friendly energy source**.
- The dependence of the output parameters of the energy converter on the speed of magnet movement and distance of the magnet to the FIE, which is affected by the human factor criteria, i.e. the speed and type of motions of the wearer (balanced or unbalanced motion, as well as the peculiarities of human motions, which in turn depend on the peculiarities of body structure, **can be considered a drawback**. It is possible to control the operation of the energy converter, but it is difficult to predict it, because the energy generating system used depends on the different “human factor” criteria mentioned above.

# GENERAL CONCLUSIONS

1. The mechanical energy converters (generators) with the conventional cylindrical inductive element (coil) or flat coils proposed up to date are designed as three-dimensional devices that are not suitable for integration into human clothing. In the Doctoral Thesis, the electromagnetic energy converter of human mechanical motions into electrical energy with flat architecture has been developed, and the possibilities of optimizing energy converter parameters (achieving the maximum generated power per volume unit) by changing the coil connection and its type, number of coil layers and their mutual placement have been experimentally studied. The generated energy and the developed power increases with the increase of the coil turns and the number of coil layers, by connecting the coils in series in such a way that the generated pulses have opposite polarity and the distance between the coils is zero.
2. The Thesis investigates the desirable conditions for integrating mechanoelectric (electromagnetic) energy converters into clothing: the impact of the assortment of clothing, the volume of clothing and location of inductive elements on the amount of energy generated. The highest power of 502 μW ± 100 μW and 261 μW ± 64 μW was reached with the parts of the energy converter integrated about 8 cm below the waist in a jacket with a non-woven fabric insulation at motion speeds of 6 km/h and 4.5 km/h respectively.
3. Investigation of effects of washing on the life cycle of inductive elements show that the electrical resistance of inductive elements with lamination and thermoplastic adhesion coating does not change after washing, however, the dimensions of the laminated inductive elements are increasing.
4. To prevent the FIE conductive wire breaking during washing, insertion of the electromagnetic energy converter elements must be designed so that it can be removed from the garment before washing and care.
5. The flat inductive element can be adapted to the smart clothing garment by clothing technology or can be created as a design element on a textile basis by coating technology and/or integrating electro-conductive threads or electric conductors. Comparing manual, embroidery, stitching, and printing technologies for fabrication of flat induction coils has shown that the manually made induction coils have higher energy and power values than the coils fabricated using other technologies. It can be explained by the fact that the sewed on coil has twice the number of turns, the embroidered coils have fewer turns and relatively high internal resistance and the PCB technology coils have high internal resistance due to the small cross-sectional area.
6. The proposed electromagnetic energy converter can be used as a mobile and environmentally friendly energy source, which does not fundamentally change the visual characteristics of garment fabric structure, dimensions and weight. The methodology developed during elaboration of the Doctoral Thesis for integration of

FIE into clothing allows determining the optimum placement and number of the integrated elements.

7. The generated electrical energy may be used to power various devices (sensors, detectors, etc.), transmit information to remote receivers and/or be accumulated for later use.
8. Considering the effects of magnets on human health, the declarations (instructions) of textile products with electromagnetic energy converters with flat structures should include information on possible health hazards or adverse effects on the human body with electronic cardiac pacemakers and cardio-defibrillators due to the permanent presence of magnets.

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