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Sensing of Body Movement by Stretchable Triboelectric Embroidery Aimed at Healthcare and Sports Activity Monitoring †

Hasan Riaz Tahir *, Benny Malengier, Granch Berhe Tseghai and Lieva Van Langenhove

Department of Materials, Textiles and Chemical Engineering, Ghent University, 9000 Ghent, Belgium; benny.malengier@ugent.be (B.M.); granchberhe.tseghai@ugent.be (G.B.T.); lieva.vanlangenhove@ugent.be (L.V.L.)
* Correspondence: hasan.tahir@ugent.be; Tel.: +32-47-293-6221

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Abstract: In this work, we introduced an embroidery-based stretchable (up to 60–70%) triboelectric nano-generator that could be attached to different parts of the human body such as fingers, knee, elbow, back, or shoulders, to sense the body movement. It can be used as activity recognition for health care and sport activity monitoring. The sensor was composed of different yarns embroidered on a stretchable conductive substrate, allowing it to sense diverse mechanical deformation of different body parts. Different stitching styles, patterns, stitch lengths, and shapes have been selected to cater to the unidirectional, bidirectional, and multidirectional force and obtain the maximum movement flexibility. In order to do embroidery on a stretchable substrate, a non-stretchable water-soluble second substrate has been added before embroidering, and is afterwards removed by application of steam. A sample of 1.5 × 6 cm^2 was used for sensing finger movement and generated a peak to peak voltage of 274.5 mV. The amount of generated voltage depended upon the application area on the body and its deformation, thread type, stitch type, stitch length, and shape of embroidery. A stitch length of more than 2 mm with a line density of 1 line per mm resulted in a stretchable sample. The state of the art of the developed sensors is their low price, flexibility, and low weight. They are all obtained with commercially available embroidery yarns and commercially available technology for their development.

Keywords: stretchable sensor; embroidery; triboelectric yarns; activity monitoring; flexible; mechanical deformation

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1. Introduction

Electronic textiles (e-textiles) have received significant attention because of their remarkable application in wearable electronics [1–4]. In recent years, the interest in stretchable and deformable wearable electronics has grown due to their potential application in several fields, including sports [5] and healthcare [6,7]. In addition, activity recognition is a crucial parameter that plays a vital role in healthcare monitoring [8] and can be achieved with e-textiles. However, all these require power, and the friction between two different materials can generate an electrostatic charge that can be harvested by a conductive substrate [9,10].

Stretchable sensors are usually made with stretchable carbon-based materials or textile structures. Different efforts have been made to develop stretchable and wearable sensors by different processes, including highly stretchable single electrodes triboelectric nanogenerator (TENGs) based on conductive nanowires and an ultrathin dual-mode patch acting as a self-powered sensor [11–13]. However, these are high-cost solutions. In this research work, we developed body movement sensors for healthcare and sports activity monitoring from commercially available embroidery yarns from Madeira, Germany, and with standard semi-professional embroidery machines.

2. Methodology and Results

To develop these body activity monitoring sensors, the following commercially available Madeira embroidery yarns were used.

1. Madeira 100% Viscose (VIS);
2. Madeira PES-100% Polyester Embroidery Thread (PES);
3. 60% Polybutylene Terephthalate (PBT)/40% Polypropylene (PP) Madeira;
4. Polyneon 100% Polyester Madeira (PN PES);
5. 100% Aramid Madeira (AR).

In order to cater to the different kinds of forces (unidirectional, bidirectional, multi-all directional) which are present upon application at different locations on the body, a selection of stitch types and shapes has been made to obtain a maximum peak to peak voltage while retaining the flexibility of the structure. The stitch length of 2 mm, with a stitch line density of 1 line per mm, has been selected to give flexibility to the embroidery structure.

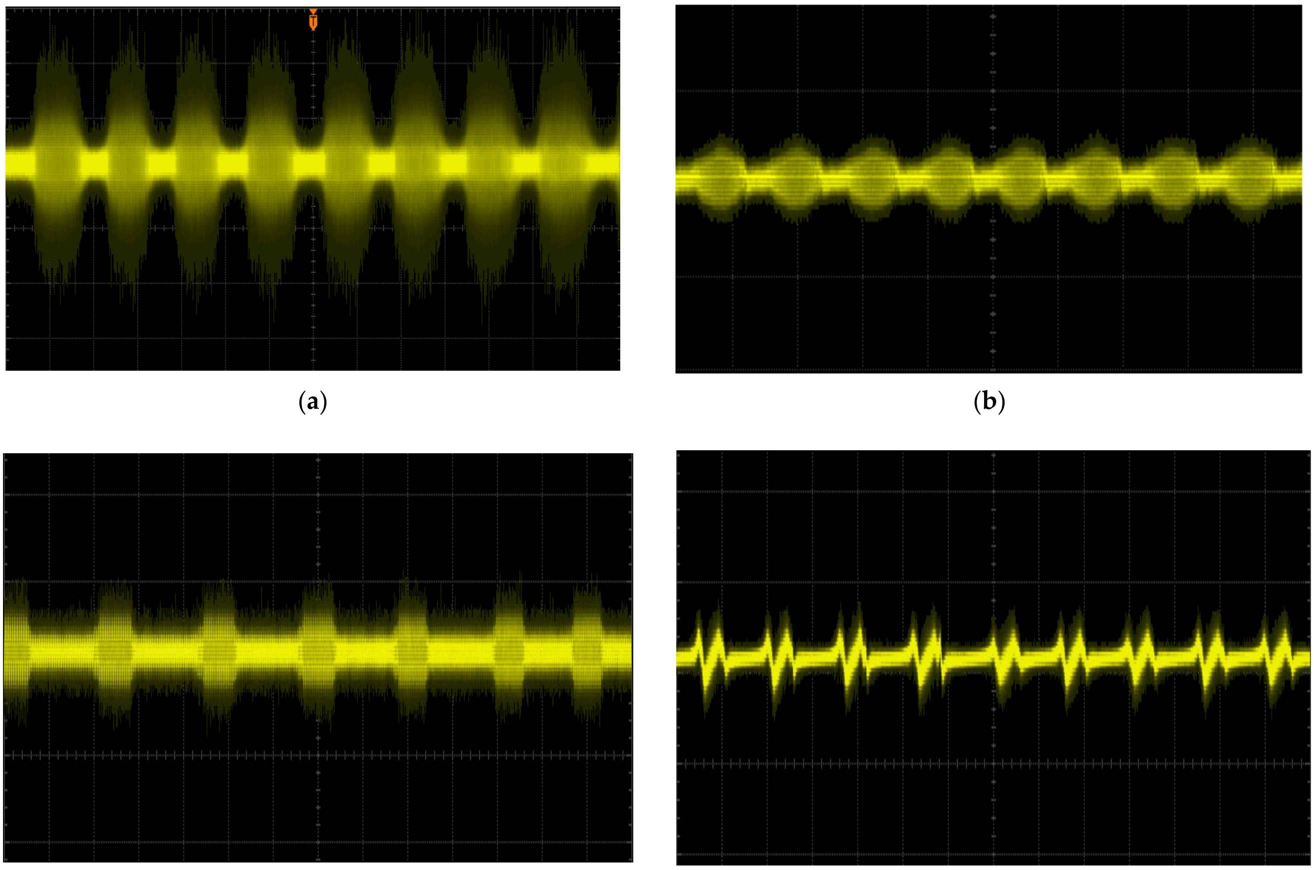
Figure 1 shows the different stitch types and shape selection according to the application area of the body so that the generator allows maximum flexibility of movement. The most critical and challenging part was to perform the embroidery on a stretchable conductive substrate. As a substrate, Shieldex ® Technick-Tex P130+B (Statex Produktions- und Vertriebs GmbH, Bremen, Germany), a two-way stretchable knitted fabric consisting of 22% elastomer and 78% polyamide, was chosen. This conductive fabric was purchased from Statex Produktions- und Vertriebs GmbH Kleiner Ort 9-11, 28357 Bremen, Germany. The fabric's GSM (Gram per square meter) is 132 g/m^2 with a thickness of 0.55 mm.

Figure 1. This figure shows the different body movement sensors with compression sleeves, physio tape and selection of four stitch types that give the maximum flexibility of movement (**a**) knee sensor with knee bandage; (**b**) knee sensor with physio tape; (**c**) elbow sensor with elbow bandage (**d**) finger movement sensor (**e**) elbow sensor with piping stitch and rhombus shape for maximum flexibility of movement (**f**) back movement sensor with physio tape (**g**) shoulder movement sensor with physio tape (**h**) selection of stitch types (Fill, Prog. Fill, Piping, and Flexible spiral stitch).

It is not possible to embroider directly on a conductive stretchable substrate. In order to solve this problem, a water-soluble non-stretchable sheet was attached so that the stretchable substrate does not go into the machine parts during the embroidery process. After completion, the water-soluble non-stretchable substrate was removed by applying steam, and the sample became stretchable again. In order to have body activity monitoring, the prototypes and different waveforms are shown in Figures 1 and 2. They were applied to the moving parts of the body through compression sleeves or physio tapes.

The characterization is performed by directly attaching the sensors to an oscilloscope. The body activity monitoring sensors generate a voltage waveform captured with an oscilloscope RIGOL DS2102A as summarized in Table 1. Table 1 shows the stitch type, shape, application area, body part, and the resulting peak to peak voltage under movement. The maximum generated peak to peak voltage was 1073 mV obtained with polyester yarns and flexible spiral stitch at a stitch length of 2 mm with physio tape and application on the knee joint. The generated voltage is the consequence of the inter friction of different yarns and the friction of the conductive substrate with the applied material during the stretching and/or bending movement.

State of the art: The state of the art of the presented triboelectric nano-generators is their low price, flexibility, and low weight, all obtained with commercially available embroidery yarns and commercially available technology for their development.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. The effect on the waveform for different application area and stich type: (**a**) waveform for knee movement developed with Polyneon 100% Polyester Madeira (PN PES) using fill stitch; (**b**) waveform for elbow movement developed with 60% PBT/40% PP Madera using pipping stitch; (**c**) waveform for finger movement developed with viscose and polyester Madera using Prog. Fill stitch; (**d**) waveform for knee movement developed with polyester Madeira yarn and through compression sleeves.

Table 1. Stretchable sensors stitch type, shape, application area, and the triboelectric results.

Yarn Type	Stitch Type	Shape	Size (cm^2)	Application by	Application Part	Peak to Peak mV	Current Density $\mu A\ cm^{-2}$	Power Density $nW\ cm^{-2}$
VIS/PES	Prog. Fill	Rectangle	1.5×6	Physio Tape	Finger	274.5	0.0305	8.37
VIS	Piping	Rhombus Rectangle	6×6 4.5×6	Bandage Bandage	Elbow Knee	126.0 178.0	0.0035 0.0066	0.441 1.17
PES	Flexible Spiral	Square Round	4×4 9.5	Bandage Bandage	Elbow Knee	219.2 1073	0.0137 0.0151	3.00 16.25
60% PBT/40% PP	Piping	Rectangle	7×4	Physio Tape	Knee	223.8	0.0080	1.79
PN PES 100%	Fill	Rectangle	4×6	Physio Tape	shoulder	105.9	0.0044	0.47
AR	Piping-longer stitch length	Rectangle	4×5	Physio Tape	Back	111.2	0.0056	0.62

3. Conclusions

Embroidery on the stretchable conductive substrate was challenging but possible with a soluble substrate. After embroidering, steam is applied to disintegrate the non-stretchable part. The stitch length and stitch line density play an essential part in obtaining a stretchable structure. The stitch length of 2 mm and line density of 1 line per mm has been selected, with particular patterns, to obtain the desired stretch. At lower stitch length and stitch density, it is not possible to have this stretch. Additionally, the stitch type of the pattern is essential. The following four stitch types were selected: Fill, Prog. Fill, Piping, Flexible spiral. These stitch types are essential to get the stretchable structure with the selected stitch length.

The resulting waveform under movement depended mainly upon the body's application area and the stitch type, stitch length, and shape of embroidery. The state of the art is their low price, flexibility, and lightweight, with commercially available embroidery yarns and standard embroidery equipment for their development. The most important application is for activity recognition in health care and sports activity monitoring.

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Conflicts of Interest: The authors declare no conflict of interest.

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