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Introducing Leather in Wearable Triboelectric Generators

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Article

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ABSTRACT

Leather is a well-known material with a wide range of applications in clothing, footwear, protection, accessories and furnishing. Further on it is reported in only a few triboelectric series tables, as a material which has an intensive tendency to become positive. In the hereby study, its triboelectric potentials are examined to be used as part of a triboelectric generator which would be part of clothing. Natural leather from cows and sheep was used. Samples of 25 cm^2 area were cut and examined together with Polytetrafluoroethylene (PTFE) material, using a prototype measuring triboelectric generator device under a force of 0.5 N. The highest V_{pp} values were given by the front (grain) side of cow and sheep thin samples, reaching a mean V_{pp} of 1293 and 1233 mV respectively. In all the tests, the front side of the samples performed better than their back (flesh) as a triboelectric surface. Additionally, the thin samples performed better than the thick ones and the less stiff samples performed better than the stiff ones. The outcoming voltages seem promising in comparison to other ordinary natural materials previously studied. The results point to the potential of leather usage in wearable triboelectric generators.

KEYWORDS

leather, triboelectricity, wearable electronics, triboelectric generator, clothing

INTRODUCTION

Nowadays, leather products carry back a rich process technology and a deep knowledge about it. The leather broadly used is a natural material mainly coming from cows after leather tanning processes. It is a structure made of collagen fibres and it previews two different sides, that is the front or grain side and the back or flesh side. Leather has been traditionally used for apparel and footwear, clothing accessories, furnishing and protective equipment, because of its resistance to wear and tear plus its aesthetic appearance and pleasant touch.

But beyond the limits of the above traditional applications, leather can be also used in smart products. For example, research has been made to use it as a substrate for embedded NFC antennas [1], to make gloves compatible with the operation on touch screens thus avoiding the need for their removal [2], to provide its surface for electromagnetic radiation shielding [3] etc. As leather is naturally not conductive, the improvement of its conductivity has been studied as it is necessary for smart products [4,5].

Over the last decade, the term triboelectricity has been appearing increasingly in the scientific literature. It gained significant interest thanks to the sustainable electrical energy it may offer to supply low-consumption devices which mainly lie in the categories of wearable electronics and self-powered sensors [6–8]. Thus it is a possible way to provide electric power bypassing the use of batteries which need replacement, cause pollution, and have a rigid form and more weight. Triboelectricity is a natural phenomenon under which mechanical energy is converted into electrical based on the combination of triboelectrification and electrostatic induction which happens upon the contact of two material surfaces [9,10]. In the case of wearables, the mechanical energy might be e.g. the motion of a man walking or running.

To achieve the harvesting of electrical energy from ambient mechanical energy, structures of various sizes and designs known as triboelectric generators (TEGs) have been built. They were first introduced in 2012 by Wang et al. [11]. Since then tremendous research progress has been made based on four distinct modes of motion [9], complicated structures [12] and various contacting materials [13–15].

In this direction, numerous efforts have been made to study synthetic or natural materials for their triboelectric potentials. Materials have been classified into the triboelectric series tables, following their tendency to get charged negatively or positively upon the phenomenon [16,17]. Lately, studies have been applied to the use of ordinary natural materials like cotton [18,19] and silk [20], which are environmentally friendly, biodegradable and also friendly to the human skin.

Leather can constitute a strong substrate or body for the application of triboelectric materials in TEGs thanks to its excellent strength. Examples are respectively the attachment of conductive MXene film on leather's surface to build a tactile sensor [21] or the penetration of MXene dispersion into leather's body to build a sensor for the real-time monitoring of human movements [22]. Additionally, leather shavings have been also used to build triboelectric surfaces. In such a case the collagen coming from leather shavings has been processed to build biodegradable nanofibers to use as a triboelectric material in TEGs [23].

However, not adequate attention has been paid to studying the triboelectric potentials of leather in its ordinary commercial form. Neither is a leading material instead of serving as a supporting substrate. It is also remarkable that only a few triboelectric series tables include it in their list [16,24]. Consequently, the limited results on the leather's triboelectric potentials have created a springboard for the current study. In an attempt to approach the potential of leather usage in wearable triboelectric generators, hereby leather samples of different characteristics were paired successively with a reference sample, and their outcoming triboelectric potentials were compared.

EXPERIMENTAL

Materials

Following the principle of triboelectricity, two material surfaces are needed to trigger the phenomenon. In this study, commercial leather was chosen as the primary material and PTFE as the second. According to the triboelectric series, leather and PTFE have opposite tendencies to get positive and negative charges respectively.

This study focused on the comparison of available commercial leather like cow and sheep. Four different natural leather samples were prepared and supplied by the Textile and Fashion Department of the Polytechnic University of Tirana (Table 1). Their thickness was 2 mm for sample 1 (coming from the butt section of the animal's hide) and 1 mm for samples 2, 3 and 4 (coming from the shoulder section of the animal's hide). Samples 1, 2 and 3 were coming from cows, while sample 4 was coming from sheep. Their stiffness was evaluated by applying the ASTM D1388 standard, which uses an approach of cantilever bending due to the sample's weight. The visual difference between the two sides of the leather samples can be seen in Figure 1. The front (grain) side which was the surface of leather that faces the hair was smooth and its hair pores were visible. The back (flesh) side was fibrous. The testing dimensions of the samples were 5 cm x 5 cm.

Table 1. Characteristics of the tested materials

	Sample 1	Sample 2	Sample 3	Sample 4
Thickness	2 mm	1 mm	1 mm	1 mm
Animal	cow	cow	cow	sheep
Bending length	6 mm	5 mm	27 mm	30 mm

The PTFE fabric was supplied by Fiberflon company. It consisted of a composite structure made of woven glass fibres coated with a PTFE film. The fabric's thickness was 0.08 mm and its PTFE content was 68%. It was cut into 5cm x 5cm dimension.

Additionally, PTFE was selected as the second triboelectric material of the hereby used measuring TEG for two main reasons. Firstly, it has excellent resistance to chemicals, UV radiation, and high temperatures and it can be cleaned very easily. Secondly, it has an excellent tendency to get negatively charged upon the triboelectric phenomenon as it is always positioned at the bottom of the triboelectric series tables. Consequently, its use in a wearable triboelectric generator could induce high electrical outputs, while at the same moment, it could also withstand wear resistance due to clothing usage.

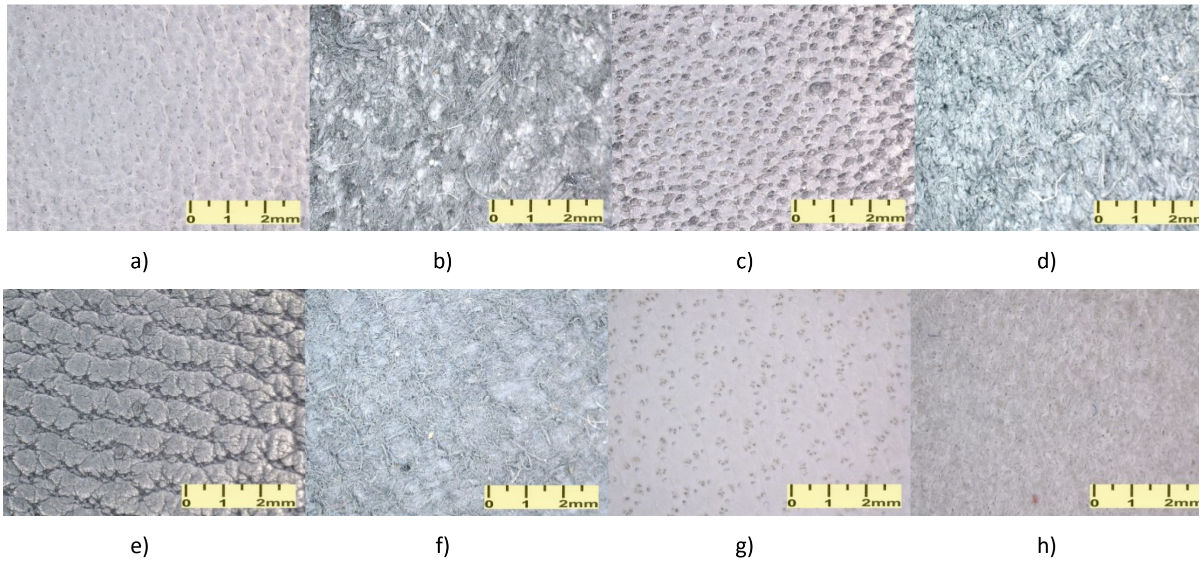

Figure 1. Optical microscope images showing the front (grain) and back (flesh) side of the leather samples: (a) sample 1 front; (b) sample 1 back; (c) sample 2 front; (d) sample 2 back; (e) sample 3 front; (f) sample 3 back; (g) sample 4 front; (h) sample 4 back

Method

The applied method targeted the examination of the triboelectric behaviour of four different natural leather samples as if they were parts of a wearable TEG. In this direction, a simulation was applied as if the two triboelectric surfaces were attached to a garment: one on the lateral side and the other on the inner side of the sleeve. This was achieved by using a measuring TEG which has been also used in previous studies and has been designed and developed by the University of West Attica [25]. The TEG combined the contact-separating and sliding modes of motion. It consisted of a steady frame which upholded two 3D-printed units (Figure 2). The upper unit consisted of a sample holder and a pair of movable arms which were linked to a mechanical actuator. This unit could execute a quasi-elliptical orbit over the lower unit to simulate realistically the motion of a moving arm in the clothing during walking. The lower unit was steady and it was positioned below the first one. It consisted of a sample holder and a load sensor attached to its base to measure the applied load between the two samples. Electrodes were attached to both sample holders. They were necessary to transfer the outgoing electrical charge from the surfaces of the participating samples. They were made of FR-4 which is a common material for printed circuit boards (PCBs), they had a 5 cm x 5 cm dimension and also one side laminated with a thin layer of copper to provide conductivity.

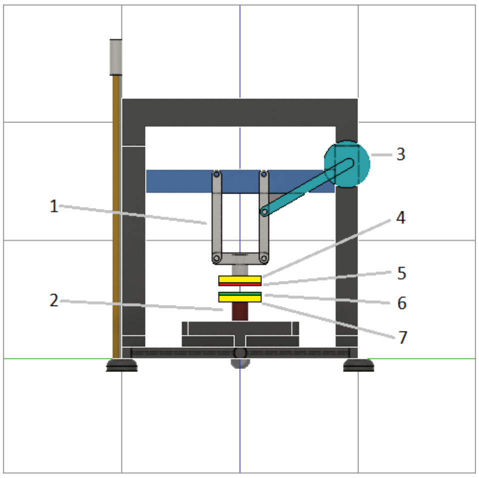

Figure 2. Sketch of the used prototype TEG measuring device showing (1) and (2) the upper and lower samples holding units respectively; (3) the motion actuator; (4) and (7) the electrodes; (5) and (6) the samples

The method used is as follows: Each of the sides of each leather sample was successively attached to the electrode surface of the upper sample holder. Additionally, the PTFE-coated fabric was attached to the electrode surface of the lower sample holder unit (Figure 2). When the upper unit was triggered to move, the attached leather sample was executing a quasi-elliptical orbit over the PTFE-coated fabric. Thus two samples were coming in continuous contact, sliding and separating, resulting in the creation of triboelectricity. The upper sample holding unit was attached opposite from the lower PTFE-coated fabric sample into such a distance so that a force of 0,5 N was measured upon their contact. The procedure of contact, sliding and separating was repeated 10 times for 50 sets, with a 1 Hz frequency. A digital storage oscilloscope (Agilent Technologies DSO3102A, 1 GSa/s sample rate, 1 MΩ ± 1% input resistance) was used to measure the open circuit voltage, which was created during the contact, rubbing and separating of the pair of triboelectric materials. To achieve this, the oscilloscope's probes were connected with the measuring TEG's electrodes. The measurements were recorded by connecting a computer to the oscilloscope and using appropriate data management software. Finally, a data analysis T-test was applied to evaluate the measurements.

The ambient conditions during the measurements were 23±1 °C temperature and 40±2 % relative humidity. Moreover, to ensure accuracy during the measurements, the samples were electrically neutralized before measuring by grounding them with the attachment of grounded copper plates.

RESULTS AND DISCUSSION

To compare the outcoming triboelectric voltages from leathers of different animal species, cow (sample 3) and sheep (sample 4) leathers were examined. These had the same thickness and stiffness. When the front and the back side of cow leather (sample 3) were paired with the PTFE fabric in the

TEG, they provided a mean V_{pp} of 1293 mV and 621 mV respectively. Similarly, the sheep leather (sample 4) provided a mean V_{pp} of 1233 mV and 568 mV respectively. A data analysis T-test showed that there was no significant difference between the front sides of the sheep and cow samples, thus they performed very similarly. A significant difference was found between the back sides of the sheep and cow samples. However, from Figure 3 it can be observed that both the two samples from different animal species followed a very similar behaviour.

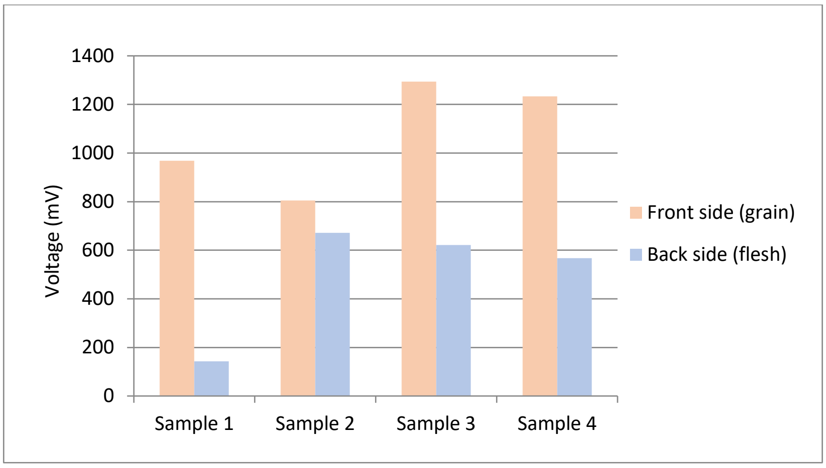

Figure 3. The V_{pp} mean values coming from the front (grain) or back (flesh) side of each leather sample when used with the PTFE-coated glass fabric in the hereby presented TEG

Moreover, the outcoming triboelectric voltages from leathers of different stiffness were compared. In this case, samples 2 and sample 3 were examined. These had the same animal origin and the same thickness. Sample 2 was stiffer, bending less than sample 3. When the front sides of samples 2 and 3 were paired with the PTFE fabric in the TEG, they provided significantly different mean V_{pp} of 805 mV and 1293 mV respectively. Thus the front side of the less stiff leather sample provided 61% higher V_{pp} values than the stiffer one. Moreover, when the back sides of sample 2 and sample 3 were paired with the PTFE fabric, they provided a mean V_{pp} of 672 mV and 621 mV respectively (Figure 3). In this case, no significant difference was detected according to the data analysis T-test. Consequently, stiffness affected the results only in the case of the front sides, and the lower it was, the higher the outcoming voltages. A possible explanation for this might be that high stiffness means a more solid structure or more mass density. But considering that leather is an insulator, the high density consequently equals high electrical resistance, thus weakening the triboelectric phenomenon. It shall be also mentioned that sample 4 (which was similarly stiff and thick as sample 3) followed the aforementioned observations for sample 3, although it was coming from a different animal species (sheep). More specifically, its front and back sides provided a mean V_{pp} of 1233 mV and 568 mV respectively.

The effect of leather thickness on the outcoming triboelectric voltages was also compared by examining sample 1 and sample 2. These animal samples had different thicknesses of 2mm and 1mm respectively, but they had the same stiffness and animal species origin. When samples 1 and 2 were paired with the PTFE-coated glass fabric, their front sides provided a mean V_{pp} of 968 mV and 805 mV respectively, while their back sides provided 143 mV and 672 mV. Consequently, it seems that a 50% decrease in the thickness of cow leather drove to a 369% increase in the mean V_{pp} of the back side, while the front side was not affected that much (Figure 3). A possible explanation for this might relate to the fact that the back side of sample 1 was more fibrous than sample 2, as it had double thickness. Consequently, its protruding fibres worked like a sticky brake, preventing a proper sliding motion of its back side over the PTFE fabric.

During the measurements, the highest V_{pp} values were given by the front side of samples 3 and 4, with a mean V_{pp} of 1293 mV and 1233 mV respectively (Figure 4). On the other hand, the lowest V_{pp} values were given by the back side of sample 1, with a mean V_{pp} of 143 mV (Figure 5).

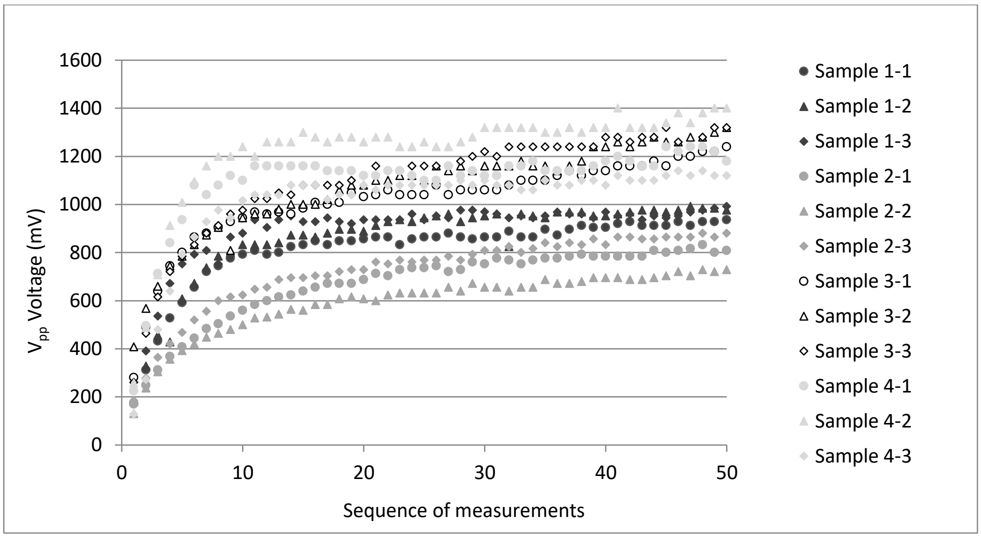

Figure 4. Repeated open circuit V_{pp} voltage measurements during the execution of contact, sliding and separating of the front (grain) surface of each leather sample with the PTFE-coated glass fabric (force 0.5 N, 23±1 ^{o}C, RH 40±2%)

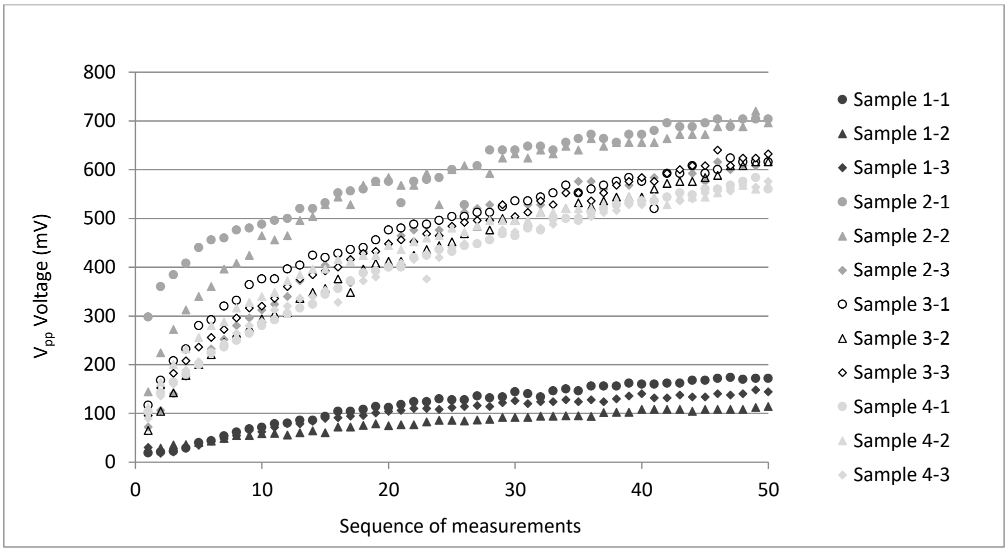

Figure 5. Repeated open circuit V_{pp} voltage measurements during the execution of contact, sliding and separating of the back (flesh) surface of each leather sample with the PTFE-coated glass fabric (force 0.5 N, 23±1 ^{o}C, RH 40±2%)

For all the leather samples it comes that the coming V_{pp} of the front sides was always higher than that of the back sides. The front sides provided mean V_{pp} values increased by 575%, 20%, 108% and 117% compared to the back sides of samples 1, 2, 3 and 4 respectively. According to the data analysis T-test the differences between the front and back sides for each of the samples 1, 3 and 4 were significant. This might be explained in a similar way to the case of sample 1: the leather front sides might allow the execution of proper contact, sliding and separating, thus performing better, while the fibrous back sides prevent a proper execution, thus reducing the outcoming result.

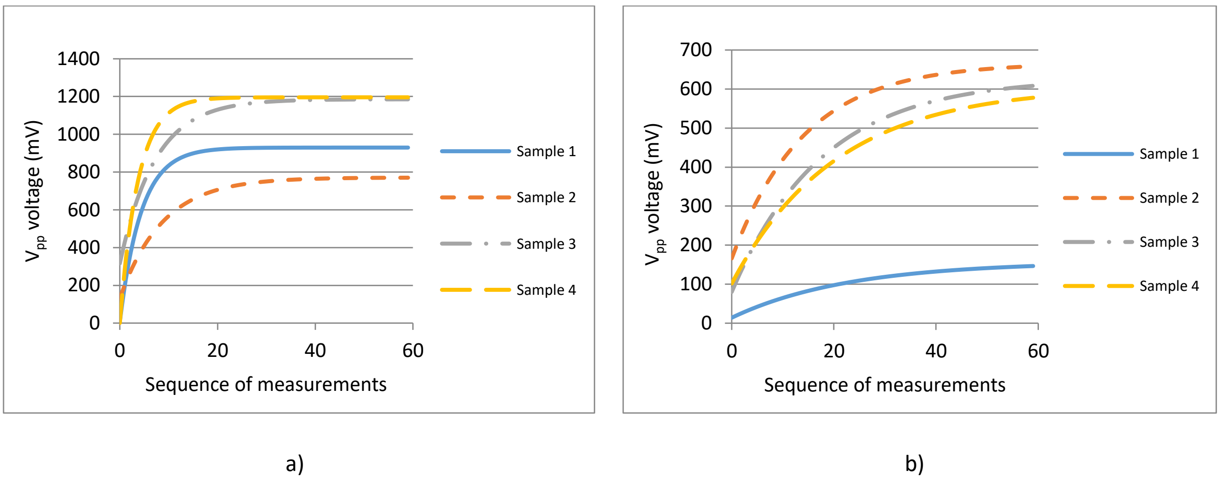

Figure 6. Comparison of the exponential changes of V_{pp} overtime during the execution of 60 repeated contact-sliding-separating cycles for the (a) front side (grain) and (b) backside (flesh) of leather samples with the PTFE-coated glass fabric

Moreover, it can be observed that the V_{pp} increased exponentially with a tendency to stabilize over time during the execution of contact, sliding and separating between each sample and the PTFE fabric. To present this tendency more clearly, the exponential graphs of Figure 6 were created after processing the measurement data which cover the behaviour of each sample.

A significant conclusion which comes from the V_{pp} observations is that the front sides of the hereby examined leather samples are capable of providing remarkable electric outcomes to be used for the activation of electronic diodes. It must be mentioned that in electronics, for an ordinary P-N Si diode, the minimum threshold of voltage needed between the anode and cathode for the flow of electric current is 700 mV. In the present study, the outcoming voltages refer to the use of a very small contact area (25 cm^2) and the application of a low force load (0.5 N). Therefore it comes out that the use of bigger leather areas and higher loads between the front sides of the leather samples and the PTFE fabric would provide satisfactory and promising voltages able to activate P-N Si diodes.

The outcoming voltages coming from the hereby used small leather areas seem promising, however as in the case of all wearable TEGs, there are technical challenges which will have to be faced to improve the efficiency and reliability of leather's usage in wearable TEGs. The optimization of its thickness and stiffness, the reliable application of conductive parts to transfer the coming charge and their washability are such examples.

Moreover, the future use of a current preamplifier in the measurement set-up might extend this study. It would allow the measurement of the outcoming current and the consequent calculation of the TEG's output power which is significant for the characterization of wearable applications.

CONCLUSION

This study proposes the use of natural leather material for the structure of wearable TEGs. Leather is very popular in clothing and fashion, however, it has not been extensively approached as a possible triboelectric material. Leather samples from cows and sheep were examined as if they were part of a garment TEG. They were paired successively with a PTFE-coated glass fabric on a specially designed and developed prototype measuring TEG. This could simulate the motion of the materials as if they were attached on the lateral side and the inner side of the sleeve of a garment during walking. After the actuation of the TEG the V_{pp} open circuit voltage was measured.

Results showed significant outcoming V_{pp} values considering that the used contact area was very small (25 cm^2) and the load application was low (0.5 N). More specifically, a remarkable mean V_{pp} of 1233 and 1293 mV was given by the front (grain) side of a sheep and cow leather respectively. Additionally, for all the samples it has been observed that their front (grain) side performed better than their back (flesh). The stiffness of leather was found to affect significantly the triboelectric effect only when the front side was used. It was also shown that the back side of the thick sample provided significantly lower values than the thin one. Moreover, in the current study, no significant differences were detected in the voltage outcomes between sheep and cow leather samples.

It hereby becomes clear that wider research is interesting in the direction of comparing leather samples from various ordinarily used animal species. The further examination of different parts from hides would be also of high interest as they are characterised by different thicknesses.

The present study is the first approach to introduce natural leather as an interesting triboelectric material, which in combination with its unique and robust properties might be efficiently used on wearable TEGs.

Author Contributions

Conceptualization – Repoulias A; methodology – Repoulias A; formal analysis – Repoulias A and Galata SF; investigation – Repoulias A; resources – Kazani I and Cela S; writing-original draft preparation – Repoulias A; writing-review and editing – Vassiliadis S, Kazani I and Galata SF; visualization – Repoulias A; supervision – Vassiliadis S. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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