Wearable Human Motion Monitoring Using Vertical Contact Separation Mode Triboelectric Nanogenerator

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Abstract. Wearable human motion monitoring has become an integral part of the paradigm shift that is on the horizon in the field of healthcare for a wide variety of biomedical applications. In recent years, there has been incessant advancement in smart wearable technology capable of human motion monitoring ranging from strain sensors to piezoelectrics. This paper proposes to fabricate a Triboelectric Nanogenerator based on Vertical Contact Separation (VCS) mode with design characteristics of flexibility, low cost, simple and easy to fabricate design for real-time monitoring of human body movements. The output performance of fabricated VCS-TENG is analysed by finger tapping. In order to conduct human motion monitoring, VCS-TENG is affixed on different body parts, and the corresponding signal is analysed. The developed prototype can be further integrated with advanced electronics to deliver promising technology in the field of healthcare diagnostics and monitoring.

Keywords: Wearable devices, Human motion monitoring, Triboelectric nanogenerator, Vertical contact separation mode, Biomedical, Healthcare.

1. Introduction

Wearable sensors have emerged as a new platform for user-friendly, accurate, unobtrusive and non-invasive human motion monitoring. The movements of the body play a vital role in understanding the behavioural pattern and physiological conditions of human beings [1]. Wearable human motion monitoring is significant in a wide spectrum of healthcare applications [2], such as gesture recognition [3], posture correction [4], tactile and electronic skin [5], gait recognition [6], sleep quality assessment [7], physical rehabilitation and adapt disease progression for patients suffering from Parkinson’s [8], paralysis [9], multiple sclerosis [10], Huntington’s disease[11], certain types of dementia [12] etc. The healthcare system has experienced a paradigm shift from standard clinical procedures to personalised assessment tools for automated health monitoring. This technological drift is accompanied by innovative technologies such as intelligent wearable devices. With this technological advancement, physicians can evaluate the dynamics of disease progression, early health risk prognosis, tailor personalised therapeutic tools, and in turn, effectively cut the expenses that are encumbering medical care systems globally [13]. There are several techniques that have been explored to monitor motions of the human body, such as strain sensing [14], ultrasound [15], doppler sensor [16], piezoelectric devices [17], hybrid devices [18], triboelectric nanogenerators [19] etc. However, most of the methods used to date are quite expensive and complex. Therefore it is necessary to select easy fabrication methods and low cost materials to develop human motion monitoring devices. By using such technologies, a lot of useful information can be derived by analysing signals and transform future healthcare and lifestyle.

In this paper, a paper-based Vertical Contact Separation (VCS) - Triboelectric Nanogenerator (TENG) is developed with characteristics of flexibility, low cost, light-weight and easy fabrication for real-time human motion monitoring. The output performance of the VCS-TENG is measured by finger
tapping with the force of approximately ~5N. The paper-based TENG is affixed on inner elbow and back of knee to monitor the corresponding human locomotion. The proposed work will open new routes for automated healthcare monitoring and lifestyle management.

2. Triboelectric Nanogenerator
Triboelectric nanogenerator was developed in the first place by Wang group in 2012[20]. A typical TENG consists of two triboelectric layers and two metal electrodes on each side of the triboelectric layers. The material for triboelectric layers is selected in such a way that they are located far apart in the triboelectric series and are of opposite tribopolarity. The device works on the amalgamated principle of triboelectrification and electrostatic induction. The friction ("tribo") caused by continuous contact and separation or relative sliding between the two triboelectric materials induces electrostatic charges on the surfaces of triboelectric layers resulting in electron flow between the metal electrode films. As shown in Figure 1, TENGs basically operates in 4 operating modes – Vertical Contact Separation mode (VCS), Single Electrode mode (SE), Lateral Sliding mode (LS), Free - Standing mode (FS).

![Figure 1. Operating modes of TENG [20]](image)

2.1. Vertical contact separation mode
A typical vertical contact separation mode TENG consists of two dissimilar dielectric films acting as triboelectric layers separated by a certain distance and metal electrodes deposited on top and bottom surfaces of triboelectric layers. In this mode, the relative motion is perpendicular to the interface. With the application of external force, the two triboelectric surfaces come in contact with each other and opposite charges are created, i.e. one surface behaves as an anode and the other as a cathode. When the two layers are separated due to the release of external force, the surfaces maintain the charges and induces electric potential between the two triboelectric surfaces. These charges flow freely between the metal electrodes due to the electrostatic field. The continuous contact and separation generate potential drop, and current flows through the circuit, thereby generating AC power.

2.2. Single – electrode mode
The single-electrode mode involves the motion of only one material. In this mode, the ground is used as the reference electrode, which remains static and is used for electron injection to the mobile material. The potential drop will be created with contact and separation of mobile material with the static electrode such as human hand, human jogging, etc or vice-a-versa.
2.3. **Lateral sliding mode**  
The lateral-sliding mode utilises two dissimilar triboelectric materials rubbing with each other in a lateral direction with different effective contact areas. In this mode, the relative displacement of frictional surfaces is in the direction parallel causing frictional sliding, thereby inducing potential difference between the two electrodes. The potential difference changes periodically due to change in the effective contact area and generates triboelectric power.

2.4. **Freestanding mode**  
The freestanding triboelectric-layer mode comprises a dielectric film with a pair of symmetric electrodes under it with the thickness of electrodes of the same order as the gap with the moving film. The electron flow occurs due to asymmetric charge distribution arising from the movement of the mobile dielectric film [21-22].

3. **Design and Fabrication of TENG**  
The proposed TENG is designed to operate in vertical contact separation mode. A typical TENG consists of two parts – a triboelectric layer of positive charge affinity with metal electrode film deposited on top and another triboelectric layer of negative charge affinity with metal electrode film deposited on the bottom. In this work, a very simple and easy to fabricate TENG with characteristics of flexibility is fabricated to monitor human motion in real-time. A strip of dimension 25 mm x 90 mm is cut from a 75 GSM copier paper (Trident Spectra), and aluminium film of 15 mm x 80 mm along with a peeled connecting wire is affixed on it using cello tape. Herein, two parts of TENG are fabricated to be identical to each other but stacked in such a way that the contact and separation occur between paper and cello tape resulting in charge transfer between the surface and electrons flow through the aluminium foil. The two flexible parts of TENG are folded in opposite directions from the middle in order to create an air gap between the two triboelectric layers, and the two edges are sealed with ordinary adhesive tape (Figure 2).

![Figure 2](image-url)  
*Figure 2. (a) Schematic of Paper based TENG (b) Photograph of fabricated Paper based TENG*
4. Results and Discussion

**Figure 3.** Voltage signal corresponding to (a) slow and (b) fast finger taps on TENG

**Figure 4.** Real-time monitoring and corresponding voltage profile due to movement of elbow
The output performance of fabricated paper-based TENG was analysed by interfacing it with Arduino and MATLAB in order to acquire voltage signals. The contact and separation of TENG were achieved by tapping a finger on TENG. The voltage corresponding to 10 finger taps in slow motion and fast motion were recorded and are shown in Figure 3 (a) and (b), respectively. The maximum output peak to peak voltage recorded during slow finger tapping on TENG was 1.7 V whereas during fast tapping, it was recorded to be 2 V. The output voltage of TENG largely depends on the applied external pressure.

Figure 3. Real-time monitoring and corresponding voltage profile due to movement of knee

The fabricated TENG is affixed on different body parts to carry out human motion monitoring and interfaced with Mixed Signal Oscilloscope (Keysight Infinii Vision MSO-X 4024 A) for analysing the performance of TENG. The paper-based TENG is affixed on the inner elbow and back of the knee.
using double-sided tape to monitor the corresponding human locomotion. The continuous pressing and releasing between the triboelectric layers results in a transfer of charge and the development of electric potential between the aluminium electrodes. The corresponding voltage profiles are recorded using MSO as shown in Figure 4 and Figure 5. The maximum peak to peak voltage recorded due to movement of elbow and knee is 8 V and 1.4 V, respectively. The change in voltage is large enough to easily detect human motion. Therefore, the fabricated TENG device can successfully respond to body movements.

5. Conclusion
In this work, paper-based VCS - TENG of a very simple and low-cost design with characteristics of flexibility is developed for human motion monitoring. The performance of fabricated paper-based TENG of size 25 mm x 90 mm is analysed by finger tapping and the corresponding recorded voltage is 1.7 V and 2 V for slow and fast tapping, respectively. The fabricated prototype is tested to monitor the movement of the arm and leg by affixing it on inner elbow and back of knee, respectively. The recorded voltage was observed to increase and subsequently decrease on continuous contact and separation of paper-based TENG due to movement of the body part. Therefore, it is concluded that the paper-based TENG is capable of human motion monitoring which is used in a wide range of healthcare and other applications. The TENG can be further used to monitor sleeping patterns and other human motion states like walking, stepping, jumping, cycling, etc. The prospective research direction could be an integration of the developed TENG with advanced electronics to realise smart wearable devices for remote healthcare monitoring and diagnostics.

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