Development of strain energy harvester as an alternative power source for the wearable biomedical diagnostic system

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The human body is considered as a rich source of energy in the forms of body motion, heat etc. These energies can be trapped to develop a viable energy source, which confines the long-term serviceability. The battery drove wearable systems suffer from critical issues such as weight, limited lifespan and lack of biocompatibility. It is the main hurdle in gaining market acceptance for wearables. Rapid growths of wearable for biosensing motivate them to use it for health monitoring. This work describes the complete fabrication flow for low-cost energy harvesting device as an alternative power source for wearable biomedical diagnostic system with prime focus on biocompatibility, deformability and conformability. The conversion of body motional energy into electrical energy is carried out using zinc oxide piezoelectric material, polydimethylsiloxane substrate and silver fabric electrodes. The estimated power demand of the biomedical sensing modules lies in the range of 1–100 µW. It is observed that optimum power can be harvested when the device is placed between socks fabric and foot sole. The power level of 106 µWpeak or 22 µWrms has been recorded which reveals the feasibility as an alternative power source.

1. Introduction: In the current scenario, health care costs are rising so fast and become unaffordable, i.e. more than 20% of net income [1]. To avoid such a costly affair, it is the need of an individual to maintain physical fitness through regular wellness monitoring. Rapid change in lifestyle and stressful living has influenced human health to a great extent. In India, nearly 68% of populations cater to rural India and the ratio of physician to per person is 1:1000. In addition, above 20% of low-income population experiences a heavy burden from chronic deceases such as heart ailments, diabetes, mental disorder, high cholesterol and hypertension which necessitate regular health monitoring [2]. To bridge this gap, there is a need for an assistive technology solution which will not only lower financial burden but also improves the existing monitoring system. It will be boon for the population who suffer from chronic diseases, elder people and athletes.

The proposed solutions in the form of wearable biomedical diagnostic system (WBDS) will be health care efficient, cost-viable and improve awareness of physiological markers [3]. There are many such pieces of evidence reported worldwide, i.e. accelerometers to monitor walking speed/step counting, in-shoe pressure sensor, body temperature and wearable sensors to monitor the recovery of the patients [4].

Electronic textile (e-textile) is also known as smart fabric technology (SFT). The development in the low-power electronics and radio technologies, i.e. 802.15.4 (ZigBee), IEEE 802.15.4a (ultra-wideband) are rapidly progressing.

The SFT-based wearables have been commercialised and penetrating in the market which is considered as one of the prominent technological solutions to be used for biomedical sensing. It has been adopted due to its flexibility, and stretchability that enables tight coupling of sensors with comfort. The state-of-the-art biomedical sensing is carried out with the trio system comprises of the sensor, embedded system and battery pack [5]. This arrangement reveals short-range communication, i.e. sensing node to a mobile phone. However, the energy harvesting system has been proposed as an alternative to the battery in this work. The energy harvesting device (EHD) with a power management unit and supercapacitor as storage steer this system to the next level [6, 7]. The proposed and conventional approaches for WBDS are illustrated in Fig. 1.

This section elaborates the feasibility of EHD as an alternative power source. It is witnessed that body motion is considered as a potential source of energy, i.e. 150–675 mW and 675–2100 by walking and jogging activities, respectively [10]. The estimated power consumption of various loads is listed in Table 1.

In this Letter, device design, optimisation and low-cost fabrication of EHD are discussed with a perspective of in-fabric integration. It is the most favoured practise due to its higher conversion efficiency, long-lasting operability, no chemical disposal, miniaturisation, complementary metal–oxide–semiconductor fabrication compatibility and maintenance free.

The proposed system is the three-tier architecture as shown in Fig. 2. The first tier, i.e. sensor module can be deployed as per the need for clinical diagnosis [11]. Sensor data is processed and transmitted to android phones, which are ubiquitous today and have revolutionised capabilities. There are many android applications which can receive sensor data, process and display it. The system can be programmed to transmit an alert message to family members or an emergency service centre to provide on-site assistance to the patient in an emergency case(s) [12].

The second tier, i.e. power management unit is used to extract optimum power from EHD, rectify cum regulate it, store it in supercapacitor and deliver to the load when the set level of energy is accumulated [13]. The output voltage level is programmable in most of the power management unit such as LTC3588-1.

The third tier is energy harvester which is the main focus of this work. WBDS is suitable for low duty cycle operations, and hence not recommended for patients who need around the clock supervision or strong probability of medical emergency.

Rest of the Letter is organised in six sections. Section 2 covers energy hot spots and EHD mounting followed by analytical and simulation results in Section 3. Section 4 covers material synthesis and discussion on results in Section 5 followed by a conclusion in Section 6.

2. Energy hot spots and EHD mounting: The human body is a rich source of non-periodic, continuous/discrete levels of energy, which can be harvested [14, 15].

Although the human body is considered as a power house but identification of prominent spots called ‘energy hot spots’ in this

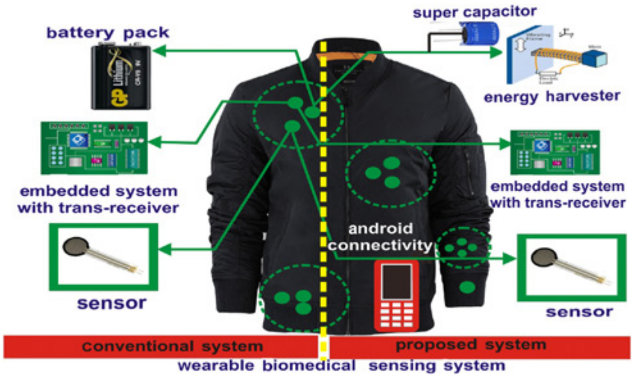

Fig. 1 *Wearable system for biosensing*

Table 1 Load versus power consumption [8, 9]

System	Power consumption
hearing aid	1 mW
wireless sensor node	100 µW
cardiac pacemaker	50 µW
quartz watch	5 µW
signal conditioning	50 µW
10 bits cyclic analogue-to-digital converter at 2 V	12 µW
quartz	100 nW
Radio-frequency identification tag	10 µW
hearing aid (medium)	100 µW

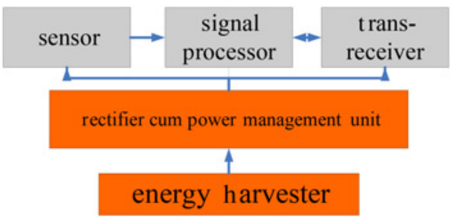

Fig. 2 *System architecture of self-powered WBDS*

work is very crucial. The spots are identified based on the optimum level of stresses experienced by the EHD [16] as shown in Fig. 3*a*.

EHD involves the conversion of mechanical strain energy, mostly generated by the recurring body movements to electrical energy. The harvested energy not only depends on device geometry but also on fabric tightness, textile material, the design of clothing etc [17]. The EHDs are mounted on energy hot spots, i.e. elbows, buttock and knees as revealed in Fig. 3*b*.

3. Analytical study and simulations: The EHD is based on film structure, in which zinc oxide (ZnO) is used as the piezoelectric material. It is sandwiched between two conductive fabric electrodes as shown in Fig. 4.

When the material is subjected to stress, suffers an electrical polarisation proportional to the induced strain. The EHD is highly frequency dependent hence analytical study helps us to design pilot device resonating to an available band of vibration. It is configured in sensor mode which is based on the principle of the direct effect of piezoelectricity. Equation (1) has been referred to as estimate resonant frequency. For a fixed-free beam (also called cantilever structure), in which substrate (passive layer) parameters are considered for calculating resonant frequency in hertz. Piezoelectric material parameters have less impact on frequency due to the additional thickness of few µm. The length, width and thickness of the

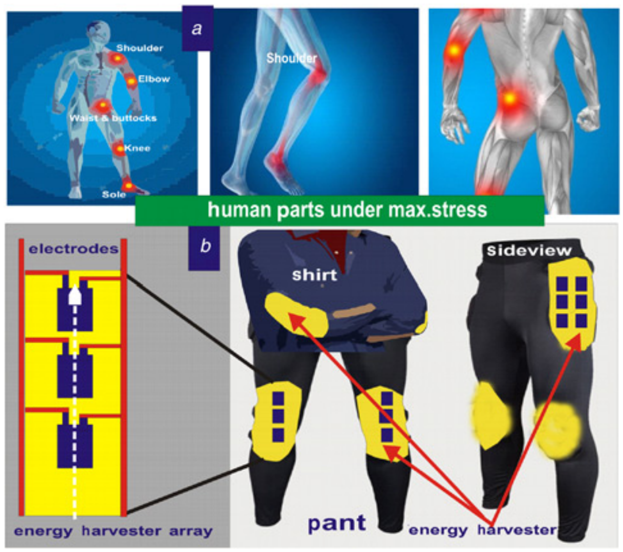

Fig. 3 *Identifed spots based on optimum level of stresses*
a Prominent energy hot spots
b Energy Harvesting mounting

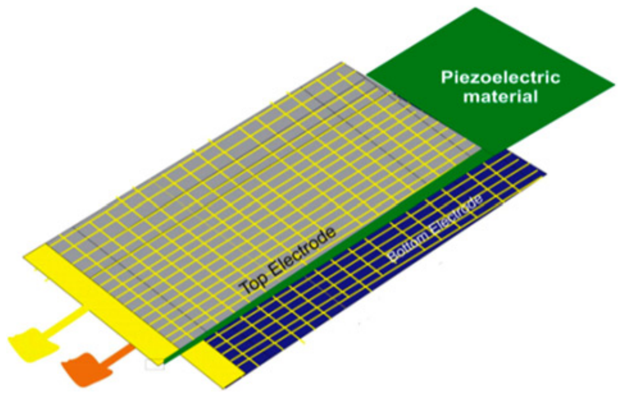

Fig. 4 *Energy harvesting structure*

Table 2 Material properties

Material	Density, kg/m^3	Young's modulus, Pa	Poisson's ratio
Ag	10,490	8.30×10^{10}	0.37
ZnO	5610	8.00×10^{10}	0.32
PDMS	965	100×10^{3} to 3.5×10^{6}	0.50

non-piezoelectric layer, i.e. polymer substrate were 23,000, 8000 and 2500 µm, respectively, whereas material properties are listed in Table 2

$$f \simeq \frac{Vn^2}{2\pi}\sqrt{\frac{\text{EI}}{m \times l^4}}$$

This equation can be further simplified to

$$f \simeq \frac{Vn^2}{2\pi}\sqrt{\frac{E \times h^2}{12 \times \rho \times l^4}} \quad (1)$$

where E is the Young's modulus; ρ is the density, h is the thickness, m is the mass, l is the length, V_n is the dimensionless nth-mode

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eigenvalue. The typical values of V_n are 1.87, 4.69 and 7.85 for the first, second and third modes, respectively. The resonant frequency for the device is calculated using the above equation and found to be 45 Hz [18–20].

The COMSOL^{TM} Multiphysics three-dimensional (3D) model was developed to analyse a simple film-based energy harvester followed by the tetrahedral meshing of finer size. Piezoelectric and structural mechanics physics were used for modelling and analysis. An acceleration ranging from 0.5 to 1 g was applied to the structure and the electric potential, total displacement was evaluated with respect to frequency. Eigen frequency and frequency domain studies were carried out for performance evaluation of this structure. The frequency domain analysis was carried out for the range of 10–150 Hz frequency. The simulation results reveal that 2.5 V peak electric potential can be harvested at the resonant frequency of 60 Hz and 170 µm of total displacements as shown in Fig. 5.

Material properties used in analytical calculations, simulations and fabrication are listed in Table 2.

The simulation results are used not only to validate analytical calculations but also to know the electric potential level, which is very complex and time-consuming for hand calculations. This simulation tool offers various provisions to incorporate different boundary conditions, damping effects, user-defined material properties, the magnitude of input, ease of alteration in geometry and its impact on performance and also useful for ‘proof of concept’.

4. Material synthesis and film deposition: ZnO was preferred because of its biocompatibility and environmental-friendly nature. ZnO has been synthesised using a sol–gel method, which is a wet chemical technique. Zinc acetate $Zn(CH_3COO)_2{\cdot}2H_2O$ −99.99% purity (MERCK) was used as a seed layer along with ethanol (CH_3CH_2OH) and 2-methoxyethanol ($CH_3OCH_2CH_2OH$) solvent and stabiliser. This solution is aged to turn solution in the glutinous gel.

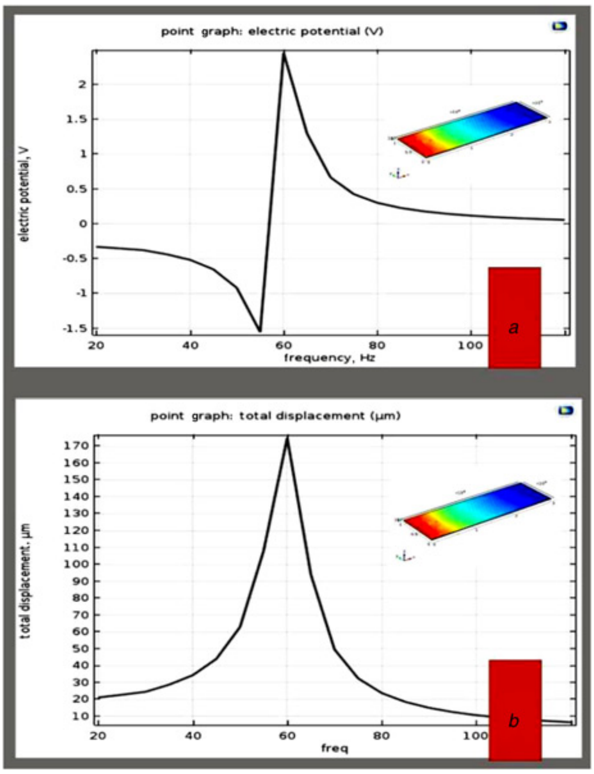

Fig. 5 *Simulation results*
a Electric potential vs frequency
b Total displacement vs frequency

Polydimethylsiloxane [PDMS-$(C_2H_6OSi)n$ from Sylgard 184, Dow Corning] polymer was used to fabricate a flexible substrate which can be mounted on the human body or embedded in the fabric.

The spin coating was used for multilayer deposition followed by annealing at 150°C for 10 h and allowed to dry slowly for self-organisation of piezoelectric material.

The device performance was enhanced by injecting ZnO material vertically as shown in Fig. 6. This concept increases the overall active surface area, improves adhesion and reduces device impedance. This work is an extension of our main work, i.e. polymeric substrate-based energy harvesters reported in [13]. Silver fabric electrodes were embedded with ZnO and encapsulated with a polymeric layer. It has a mesh structure which defends cracks and internal defects on straining. The fabricated device with layer information is as shown in Fig. 7. All experiments were performed at room temperature and pressure.

5. Results and discussion: Commercially available ZnO powder lacks glutinous property, which causes poor adhesion. To improve its adhesion property, ZnO has been synthesised in the laboratory followed by X-ray diffraction (XRD) and scanning electron microscopy (SEM) characterisation. These kinds of characterisations ensure material crystallinity, purity and orientations of the material.

6. XRD of material: The crystalline structure of ZnO powder was characterised by XRD patterns using EMPYREAN powder diffractometer for Cu-Kα ($\lambda = 1.540598$ Å) radiation.

All the XRD peaks have indices of (100), (002), (101), (102), (110) and (103), which match with the pure hexagonal crystalline structure (ICDD75-1526) as shown in Fig. 8. No other peaks are observed which attributes to impurities present in the synthesised material.

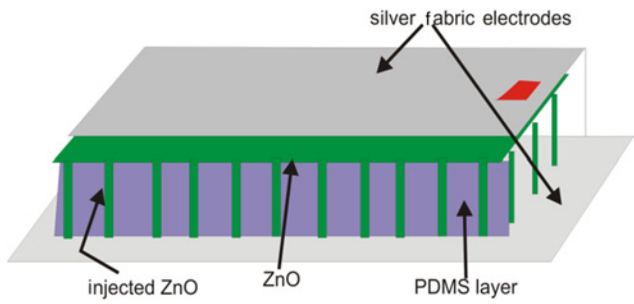

Fig. 6 *3D structure of EHD*

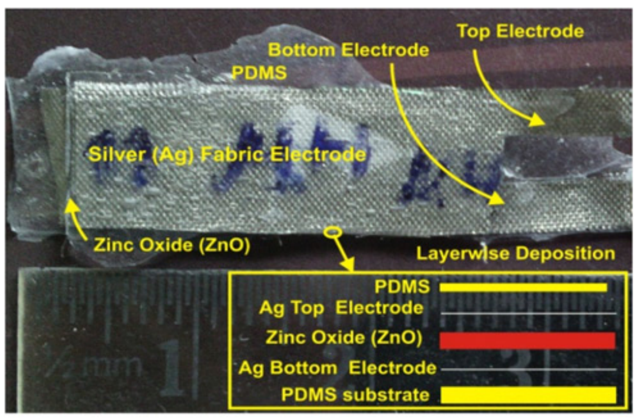

Fig. 7 *Fabricated EHD with layer information*

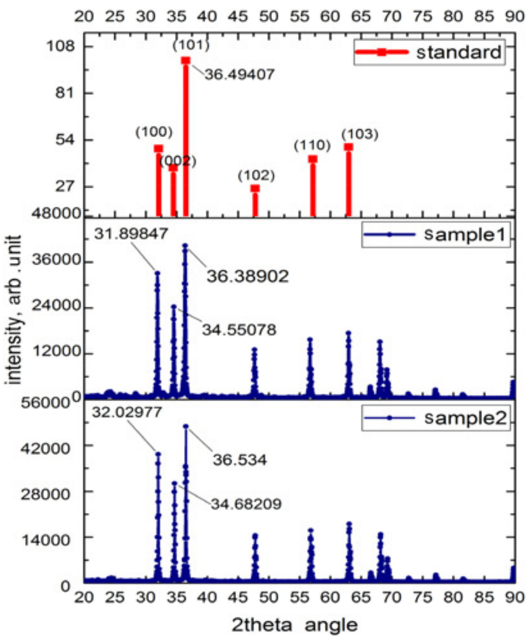

Fig. 8 *XRD of ZnO powder and standard XRD plot*

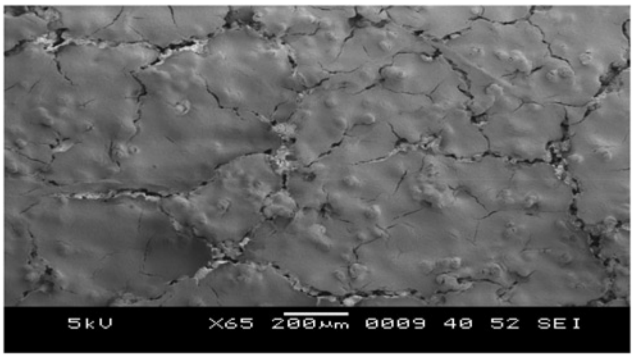

Fig. 9 *SEM micrograph of ZnO film*

7. SEM analysis: This analysis was carried out to examine the proper formation of grains, which is considered as an essential metric for crystallinity. Sodium hydroxide tablets were added to alter the pH value of gel, homogeneity of seed-solvent stabiliser and ageing of gel led to the better growth of grains and bigger trap sites among the large grains, which improves the material crystallinity and reduces internal defects as shown in Fig. 9. Low-temperature annealing gradually decreases surface roughness and grains become more uniform.

Fig. 10 reveals a mesh structure of conductive fibres, a well-aligned structure with a 30.31 μm diameter of silver yarn. The silver fabric has been used as a parallel plate electrode. There is the probability of shorting conducting layers due to a very thin layer of ZnO sandwiched between these electrodes during mechanical deformation. The PDMS layer is used not only to isolate two electrodes but also acts as a barrier against moisture, dust and other contaminants.

8. Electrical characterisation: NI LabVIEW software platform and data acquisition card (NI-6003 voltage DAQ) hardware have been used for electrical characterisation [21]. The complete characterisation setup is illustrated in Fig. 11.

We have mounted EHD on various body parts and characterised for peak and root-mean-square (RMS) electric potential as well as power. It has been experimentally verified for all the locations depicted in Fig. 12. It is observed that maximum power can be harvested when EHD is mounted in between socks fabric and sole of the foot.

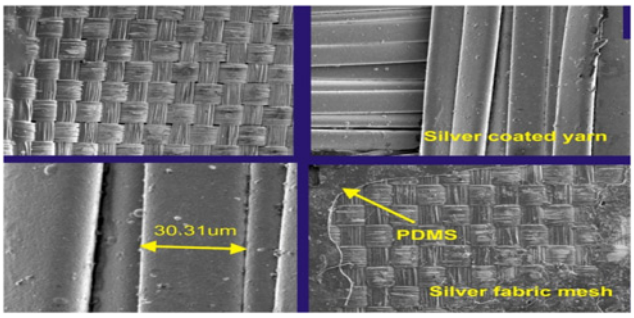

Fig. 10 *SEM micrograph of silver-coated yarn embedded with PDMS*

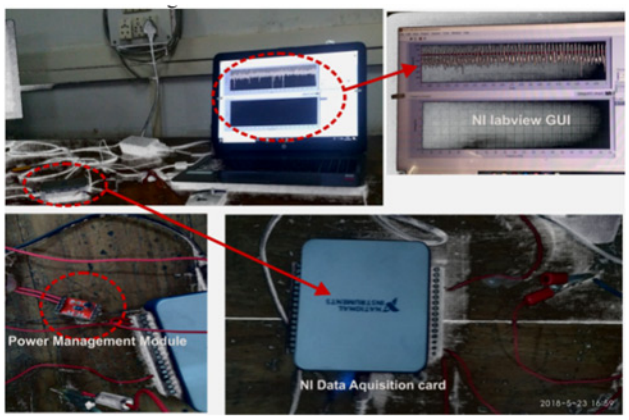

Fig. 11 *Electrical characterisation setup*

Fig. 12 *EHD mouthing on energy hot spots*

The bi-directional device stressing and concentrated body weight (highest as compared with other locations) are considered to be the prominent reasons for harvesting comparatively higher power.

The maximum electric potential of 7.3 Vpeak, 2.7 Vrms recorded for rhythmic body motion pattern. The computed harvested power was 106 μWpeak and 22 μWrms for 500 KΩ resistive loads. The experimental results for all energy hot spots are illustrated in Fig. 13 and listed in Table 3. The measurements have

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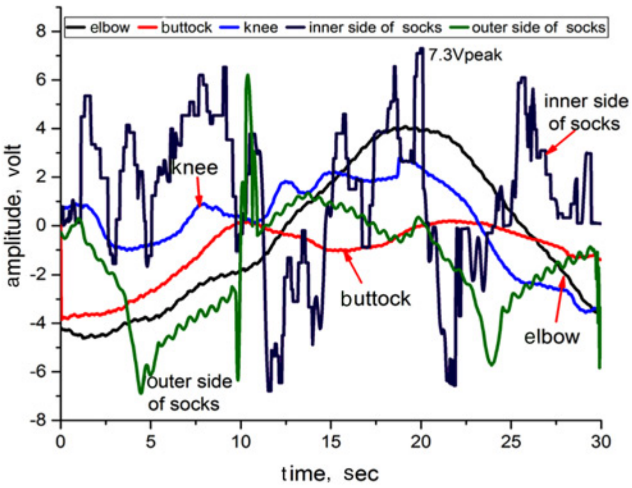

Fig. 13 *Electric potential for various hot spots*

Table 3 Experimental results

	Elbow	Buttock	Knee	Inner side of socks	Outer side of socks
peak voltage, V	4.6	3.8	3.5	7.3	6.8
RMS voltage, V	2.2	2	1.9	2.7	2.7
peak power, µW	42.4	28.9	24.5	106.5	94.7
RMS power, µW	17.1	5.4	5.8	22.1	14.4

been taken for 30 s duration and repeated several times and average values are tabulated.

It is concluded that socks fabric and sole of foot region is the best hot spot for EHD followed by outer side, elbow, buttock and knee.

9. Conclusions: The WBDS based on smart fabric is proposed to monitor human wellness and health status. Battery-operated system mainly suffers from uncountable reasons. The lifespan of the electronic systems, which are guaranteed for a few decades, does not mesh with battery technology. In this work, we have proposed EHD as an alternative perpetual power source for WBDS with prime focus on biocompatibility. The film structure has been simulated to validate proof of concept and found desired performance. ZnO has been synthesised and deposited using sol–gel and spin coating methods. XRD and SEM characterisations were carried out to ensure crystalline orientations, material purity and grains formation. The fabricated device generates 106 μW_{peak} power, which is enough for an ultra-low-power sensor node, and a network of EHDs is recommended for high-end microsystems. From experimental results, it is concluded that the EHD mounted in between the sole of foot and socks fabric can harvest the optimum power amongst other configurations. The fabricated device is flexible to mount on any part of the body with a higher degree of comfort.

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