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Energy Harvesting from Knee Motion Using Piezoelectric Patch Transducers

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Abstract

This paper presents a piezoelectric energy harvesting device that generates electrical power from knee motion during human gait. The device is composed of two MEMS-based piezoelectric patch transducers optimized for placement around knee joints with minimal footprint. Simulations were performed on COMSOL software to reveal maximum performance that can be achieved under normal walking conditions. The internal capacitance of the patch transducers was measured to be 80 nF, while the resistance was on the order of 470 kΩ. The patch transducers were inserted in a knee brace worn by a volunteer subject, and were characterized for voltage and power generation. During walking, the maximum open circuit voltage and rms power were measured to be 14 V and 6.2 μW, respectively. These values were observed to increase up to 14.4 V and 12 μW during a moderate running activity. The level of power achieved in the experiments shows the potential of this device as an independent onboard power component and as a continuous battery charger for wearable electronic devices.

Keywords: energy harvesting, piezoelectricity, knee motion, human gait, Power MEMS

1. INTRODUCTION

The advancements in microelectronics and sensing technologies have led to the proliferation of wearable devices such as smart watches, smart glasses, heart rate monitors, motion trackers, and biometric sensors. With the emerging internet of things technology, the applications of wearable devices are expected to expand particularly on consumer and biomedical electronics in the near future [1]. Such devices are generally powered by batteries having limited operation lifetimes, which mandates frequent recharge cycles and therefore restricts device functionalities [1-2]. To overcome this limitation, significant research efforts have been dedicated to the development of energy harvesters that can convert diverse forms of environmental energy into electricity, and support or completely replace batteries in wearable devices [3].

Compared to other ambient sources such as external vibrations, solar and radio frequency radiation, harvesting power from human body suits better for wearable devices as human activities possess abundant amounts of power [4-5], and the power can be generated on demand. Accordingly, many studies have been focused on generating power by utilizing various energy forms on human body. As an example, Moro *et al.* have demonstrated piezoelectric cantilevers mounted in shoe heels to generate power from human walking. The cantilevers were manufactured in a bimorph structure using lead zirconate titanate (PZT), and generated an average power on the order of 400 μW [6]. Shen *et al.* reported a similar device based on a linear magnetic architecture fixed on the side of a shoe. Charging of a 1.2 V-battery was demonstrated during walking [7]. Body heat and the resulting thermal gradients have also been exploited to generate power. Wang *et al.* reported wearable thermoelectric generators that consist of many thermopiles connected in series. When worn around the wrist, the device generated an open circuit voltage and output power of 0.15 V and 0.3 nW, respectively [8]. Similar devices with flexible properties have also been demonstrated with maximum power on the order of several microwatts [9-10].

Knee joints are normally subject to a heavy load and generate up to 36 W of biomechanical power for the body [3]. Therefore, this part of the body shows great potential for energy harvesting during gait motion. Donelan *et al.* presented a biomechanical energy harvester that mainly comprises a dc motor, a gear train and a one-way clutch in a knee brace configuration. An average power of 5 W was measured on subjects walking at a speed of 1.5 m/s [11]. Frequency upconversion methods were proposed to drive piezoelectric cantilevers for power harvesting using the low-frequency knee motion. In this technique, mechanical structures are fixed around the knee joints to obtain a relative angular motion. At each step, this motion is transferred to the cantilevers through mechanical or magnetic interactions, resulting in high frequency oscillations and power generation [12-15]. A maximum of 4.5 mW was reported during walking at a speed of 7 km/h [15]. The biomechanical knee-joint energy harvesters mentioned above are generally large in size, rigid, and therefore not comfortable to be worn [16-18]. Accordingly, flexible and patch-type piezoelectric generators are developed. De Pasquale et al. have reported such a piezoelectric fiber composite transducer for elbow

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and knee joints, and mounted it on a test setup simulating joint motion. The maximum peak-to-peak open circuit voltage and instantaneous power were on the order of 5 V and 40 μW, respectively [16]. A related study utilized a MEMS (microelectromechanical systems) based MFC patch transducer and reported an average 2.6 μW during a simulated running activity [17]. A conceptually similar device was presented in [18] using a PVDF film transducer, and placed in a tight suit to harvest power from various body joints. The maximum rms power was measured to be 2 μW obtained from the knees [18]. Finally, Kim *et al.* demonstrated a helical piezoelectric harvester fixed around four different body joints, namely shoulder, arm, knee, and hip. An open circuit voltage of 3.1 V was measured during walking around the knee area [19].

The patch piezoelectric energy harvesters reported so far were geared towards power generation from multiple body joints at the same time rather than knees specifically. This inevitably decreases the power output, and leads to a less efficient operation. In this work, we present a MEMS-based piezoelectric energy harvesting device optimized for power generation from knee joints exclusively. Composed of two piezoelectric patches, the size and arrangement of the device were designed to effectively harvest the mechanical energy around the knee while occupying minimal space. This paper reports the design, implementation, and characterization of the device during walking and running activities.

2. DESIGN AND SIMULATIONS

The device is designed by considering the knee kinematics during walking and running activities. The knee area has two main bending sites on the front and back side. Accordingly, the device utilizes two piezoelectric patches located on the two bending sites for harvesting more of the available mechanical power. Taking advantage of two bending sites simultaneously is one of the main novel design features that distinguishes this work from others in the literature. A schematic drawing of the patches is shown in Figure 1a. The size is also an important parameter in the device design. A large device may be inconvenient for the user to wear, while a smaller device may not induce a high voltage. The knee area measures around 10 cm in length depending on the overall body size. However, the bending site that actually induces high stress and voltage on the piezoelectric patch is even smaller. Accordingly, the patch length should be chosen just enough to cover the bending site to facilitate power generation, while taking minimum space and avoiding user discomfort. Considering these requirements and the commercial availability, the patches are selected to be soft PZT-based P-876.A12 MEMS piezoelectric patch transducers from PI Ceramic company. The patches are composed of two metal layers surrounding the piezoelectric material in between, and measure 6.1 cm × 3.5 cm × 500 μm in length, width, and thickness respectively. The actual piezoelectric material measures slightly smaller as 5 cm × 3 cm × 200 μm, which falls within the realm of Power MEMS technology, with a d_{33} piezoelectric coefficient of 400 pC/N. A picture of the piezoelectric patch transducer with soldered wires is shown in Figure 1b.

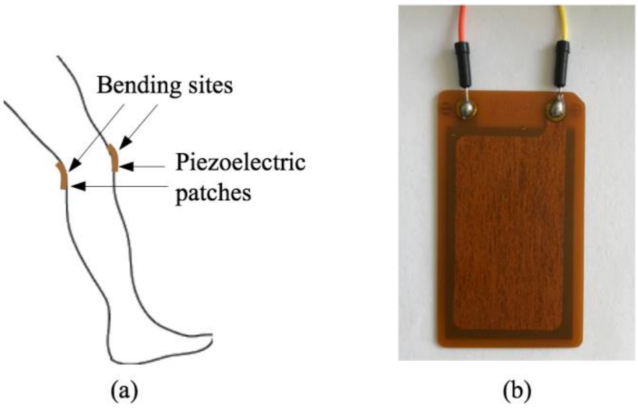

Figure 1. (a) Schematic drawing of the patch transducers located on the bending sites at the knee area, (b) Photograph of a piezoelectric patch transducer.

The kinematics of the knee joint during walking and running activities is extremely complicated [16], and therefore it is difficult to precisely estimate the device performance. However, the maximum angular displacement of the knee joint is shown to be around 60 degrees during walking [20]. This data is used to simulate piezoelectric voltage induction on the patches using the Piezoelectric Devices module of the COMSOL software.

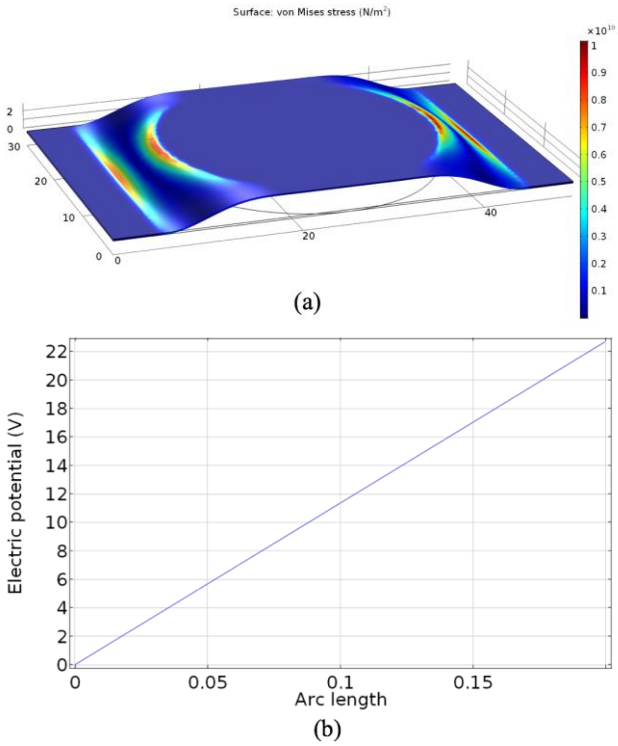

Figure 2. Simulation results of (a) the stress distribution on the piezoelectric patch at 60 degrees bending angle, (b) the voltage induced across the thickness of the piezoelectric material.

Initially, the piezoelectric material was drawn with the exact dimensions and material properties to create the simulation model. The two ends of the patch and its central part touching the middle of the knee were fixed. Finally, the structure is bent by 60 degrees in the software. The stress distribution on the patch and the resulting voltage across the thickness of the material are shown in Figure 2a-b, respectively. The simulations demonstrate that the patches can provide an open circuit voltage of 22.7 V during walking.

3. TESTING AND DISCUSSIONS

The internal capacitance and resistance of the piezoelectric patches were measured initially using a multimeter and an oscilloscope, and determined to be on the order of 80 nF and 470 kΩ, respectively. Next, the patches were fixed to a thin plastic backplate for mechanical support against possible fracture. The patches together with the backplates were then placed inside a knee brace for walking and running tests. The knee brace was worn by a volunteer subject in such a way that the locations of the patches were on top of the bending sites as in Fig. 1a. The subject was asked to perform walking and running activities, while the voltages induced on the patches were measured and recorded by a Tektronix MDO3024 oscilloscope. Open circuit voltages collected separately from the two patches are shown in Figures 3-6.

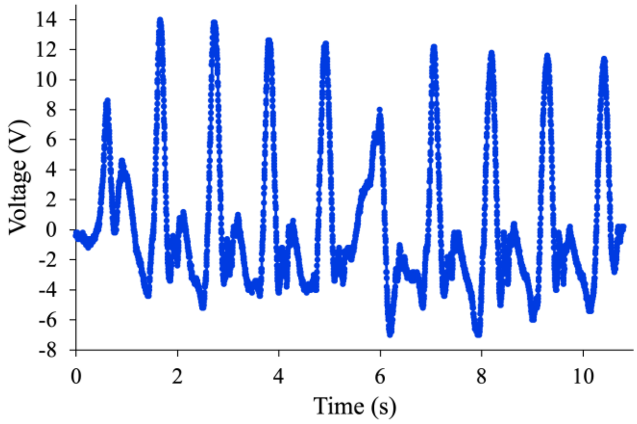

Figure 3. Open circuit voltage induced on the patch at the front side of the knee during walking.

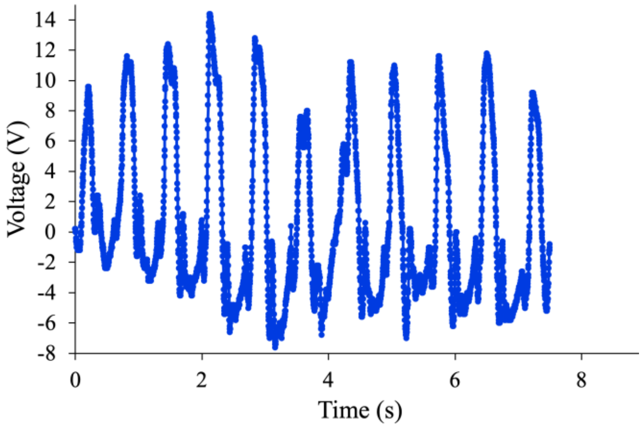

Figure 4. Open circuit voltage induced on the patch at the front side of the knee during running.

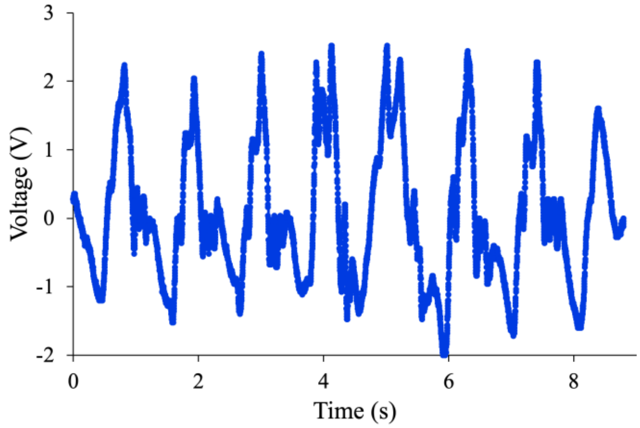

Figure 5. Open circuit voltage induced on the patch at the back side of the knee during walking.

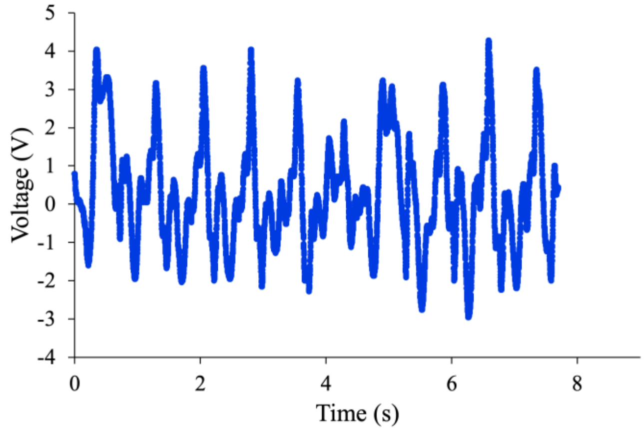

Figure 6. Open circuit voltage induced on the patch at the back side of the knee during running.

Throughout all these tests, the subject was moving normally without any forced steps, and at moderate speeds of around 3 km/h and 5 km/h during walking and running. The irregularities in the waveforms are associated with the natural fluctuations in the gait. Maximum amplitudes, peak-to-peak values and rms (root mean square) values of the open circuit voltages are summarized in Table 1.

Table 1. The summary of open circuit voltage values (in volts) obtained during walking and running.

Patch location	Activity	V_{max}	V_{ppmax}	V_{rms}
Front side	Walking	14	18.8	4.68
	Running	14.4	21	5.59
Back side	Walking	2.48	4.56	1.02
	Running	4.28	7.24	1.47

In all the cases, the maximum voltages were achieved by the patch located at the front side of the knee. Moreover, a phase difference always existed between the two patches, which avoided their serial connection to further amplify voltage. The amplitude and phase difference between the voltages on the two patches are attributed to the slightly imperfect placement of the patches on the bending sites and the complicated kinematics of the knee joint that lead to asymmetric bending motion on both sides. The maximum voltages were measured to be 14 V and 14.4 V during walking and running on the front patch. Since the knee bending angle does not change much in these two activities, the voltage values are close to each other. The rms values are also calculated to be 4.68 V and 5.59 V, respectively. The voltages on the back patch were measured to be 2.48 V, 4.28 V, 1.02 V rms and 1.47 V rms in the above order. The maximum 14 V achieved during walking is about 61% of the theoretically achievable 22.7 V shown in the simulations. The difference is believed due to a number of possible reasons including (i) a knee bending angle smaller than 60 degrees, (ii) imperfect placement of the patch transducers leading to a smaller stress on the piezoelectric material, and (iii) the use of the backplate again decreasing the stress on the piezoelectric material. The combination of all these likely reasons have direct negative effect on the induced voltage, leading to the values on Table 1. After open circuit voltage tests, the same experimental procedure is repeated by connecting a 470 kΩ resistor to the terminals of the patch transducers. This resistance value is chosen to realize matched load condition and generate maximum power. Voltage waveforms induced on the resistor during walking and running are given in Figures 7-10.

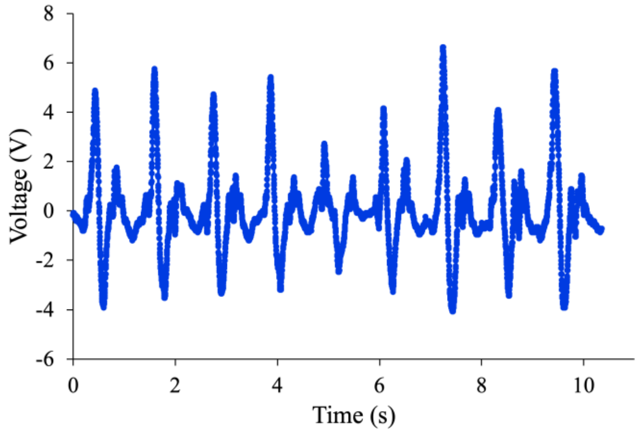

Figure 7. Voltage on the resistor induced by the patch at the front side of the knee during walking.

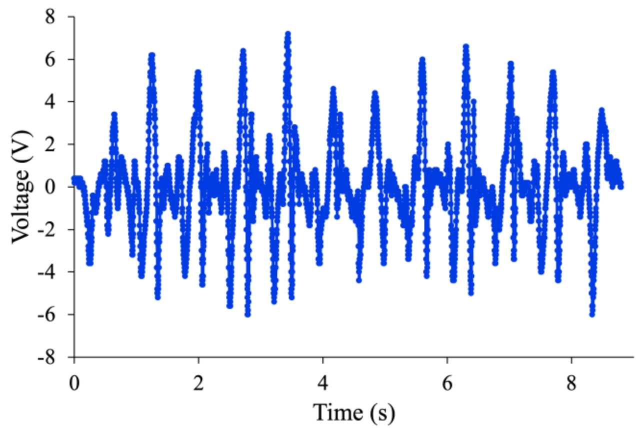

Figure 8. Voltage on the resistor induced by the patch at the front side of the knee during running.

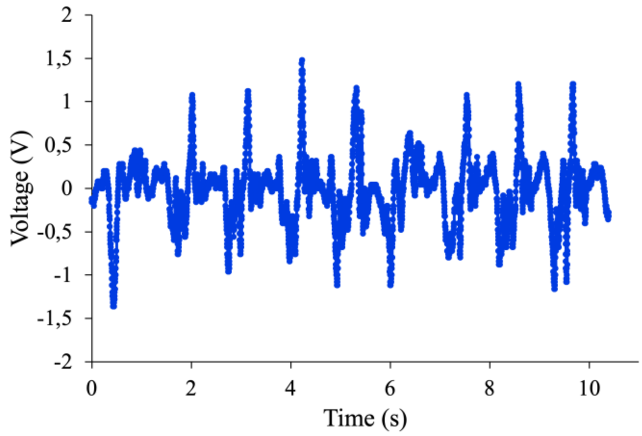

Figure 9. Voltage on the resistor induced by the patch at the back side of the knee during walking.

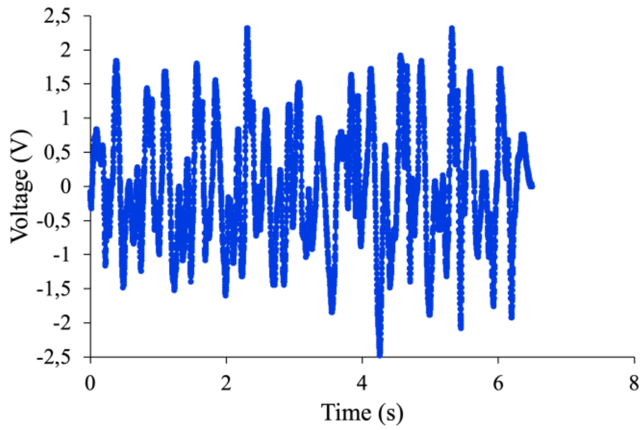

Figure 10. Voltage on the resistor induced by the patch at the back side of the knee during running.

As expected, the voltage amplitudes on the resistor is roughly half of that obtained in the open circuit tests. After determining the rms voltage in each experiment, the maximum instantaneous and rms power values are calculated and given in Table 2. The results show that an instantaneous power up to 98.5 μW and 123.4 μW can be obtained from the combination of the patch transducers during walking and running, respectively. The device utilizing two patch transducers simultaneously produces total rms output powers of 6.2 μW and 12 μW during the same activities.

Table 2. The summary of power values obtained on the resistor during walking and running.

Patch location	Activity	P_{max} (μW)	P_{rms} (μW)
Front side	Walking	93.8	5.9
	Running	110.3	10.2
Back side	Walking	4.7	0.3
	Running	13.1	1.8

The open circuit voltage amplitudes, instantaneous and rms powers achieved in the experiments are all higher compared to the previously reported patch piezoelectric energy harvesters developed for scavenging power from the knee joints. This clearly proves that the MEMS-based energy harvesting device with piezoelectric patch transducers presented in this work has a higher performance and suits better for power harvesting from the knees during walking and running. However, there are still some aspects of this device that can be further improved. In all the experiments, the plastic backplate was used as a protective layer to receive part of the stress as the knee bends. Although this secures the piezoelectric material against fractures, it also decreases the stress, and hence the induced voltage, on the patch transducer. In future implementations, the backplate can be completely eliminated by employing a thicker patch transducer that can absorb all the mechanical energy and produce higher voltages while withstanding high bending angles. This will possibly increase the user comfort as well. In parallel, the extension and contraction along the sides of the knee can also be exploited to generate power. In this respect, the device can be constructed by using additional piezoelectric transducers located on the left and right sides of the knee. When combined with a smart circuit that can handle phase differences, all the patch transducers can be connected in series to generate a large voltage, which can be more advantageous when producing a DC voltage for powering wearable electronic devices or charging batteries. Finally, a narrow, elastic and easily removable clothing can be designed for attaching the device instead of integrating it in a knee brace for a more comfortable user experience.

4. CONCLUSION

A MEMS-based energy harvesting device with piezoelectric patch transducers was developed to generate power from knee motion. Compared to similar devices previously reported in the literature, the novelty and advantage of the energy harvester presented here lie in the optimization and arrangement of the transducers exclusively for the knee dynamics, leading to enhanced power output. The device was designed to utilize two patch transducers with minimal footprint located around the bending sites of the knee to effectively harvest the mechanical energy during normal gait. Simulations were performed to calculate maximum theoretical voltages that can be obtained on the patches. The device was placed inside a knee brace worn by a volunteer subject, and tested under normal walking and running conditions. A maximum open circuit voltage of 14 V and 14.4 V was obtained from the patch at the front side of the knee during moderate walking and running at speeds around 3 km/h and 5 km/h, respectively. When a 470 kΩ load resistor was connected, the device was demonstrated to provide instantaneous power levels up to 98.5 μW and 123.4 μW during the same activities. Finally, the rms output power was calculated to be 6.2 μW when walking and 12 μW when running. These results are higher than previously reported similar patch piezoelectric energy harvesters developed for knee joints. Aspects of this work that can be further improved for even higher performance and more user comfort are discussed. The results achieved in this work demonstrate the feasibility of this device as an onboard power component for wearable electronic devices, and as a means to continuously recharge their batteries.

REFERENCES

[1]. Y. Kuang, Z. Yang, and M. Zhu, "Design and characterization of a piezoelectric knee-joint energy harvester with frequency up-conversion through magnetic plucking", Smart Mater. Struct., vol. 25, 085029, 2016.

[2]. E. Iranmanesh, A. Rasheed, W. Li, and K. Wang, "A wearable piezoelectric energy harvester rectified by a dual-gate thin-film transistor", IEEE Trans. Electron Devices, vol. 65, no 2, pp. 542-546, February 2018.

[3]. Y.M. Choi, M. G. Lee, and Y. Jeon, "Wearable biomechanical energy harvesting technologies", Energies, vol. 10, 1483, September 2017.

[4]. T. Starner, "Human-powered wearable computing", IBM Syst. J., vol. 35, no. 3-4, pp. 618-629, 1996

[5]. A. Cadei, A. Dionisi, E. Sardini, and M. Serpelloni, "Kinetic and thermal energy harvesters for implantable medical devices and biomedical autonomous sensors," Meas. Sci. Technol., vol. 25, 012003, 2014.

[6]. L. Moro and D. Benasciutti, "Harvested power and sensitivity analysis of vibrating shoe-mounted piezoelectric cantilevers", Smart Mater. Struct., vol. 19, 115011, 2010.

[7]. J. X. Shen, C. F. Wang, P. C. K. Luk, D. M. Miao, D. Shi, and C. Xu, "A shoe-equipped linear generator for energy harvesting", IEEE Trans. Ind. Appl., vol. 49, no. 2, pp. 990-996, March/April 2013.

[8]. Z. Whang, V. Leonov, P. Fiorini, and C. V. Hoof, "Realization of a wearable miniaturized thermoelectric generator for human body applications", Sens. Actuators A Phys., vol. 156, pp. 95-102, 2009.

[9]. L. Francioso, C. De Pascali, I. Farella, C. Martucci, P. Creti, and P. Siciliano, "Flexible thermoelectric generator for wearable biometric sensors", Proc. IEEE Sensors 2010 Conf., HI, USA, pp. 747-750, 2010.

[10]. S. E. Jo, M. K. Kim, M. S. Kim, and Y. J. Kim, "Flexible thermoelectric generator for human body heat harvesting", Electron. Lett., vol. 48, no. 16, pp. 1013-1015, August 2012.

[11]. J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, "Biomechanical energy harvesting: generating electricity during walking with minimal user effort", Science, 319, 807, 2008.

[12]. M. Pozzi and M. Zhu, "Plucked piezoelectric bimorphs for knee-joint energy harvesting: modelling and experimental validation", Smart Mater. Struct., vol. 20, 055007, 2011.

[13]. M. Pozzi and M. Zhu, "Characterization of a rotary piezoelectric energy harvester based on plucking excitation for knee-joint wearable applications", Smart Mater. Struct., vol. 21, 055004, 2012.

[14]. Y. Kuang and M. Zhu, "Characterization of a knee-joint energy harvester powering a wireless communication sensing node", Smart Mater. Struct., vol. 25, 055013, 2016.

[15]. Y. Kuang, T. Ruan, Z. J. Chew, and M. Zhu, "Energy harvesting during human walking to power a wireless sensor node", Sens. Actuators A Phys., vol. 254, pp. 69-77, 2017.

[16]. G. De Pasquale and A. Soma, "Energy harvesting from human motion with piezo fibers for the body

monitoring by MEMS sensors", Proc. Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP), Barcelona, Spain, 13672479, April 2013.

[17]. G. Bassani, A. Filippeschi, and E. Ruffaldi, "Human motion energy harvesting using a piezoelectric mfc patch", Proc. Annual International Conference on the IEEE Engineering in Medicine and Biology Society, Milan, Italy, pp. 5070-5073, August 2015.

[18]. A. Proto, K. Vlach, S. Conforto, V. Kasik, D. Bibbo, D. Vala, I. Bernabucci, M. Penhaker, and M. Schmid, "Using pvdf films as flexible piezoelectric generators for biomechanical energy harvesting", Clinician and Technology, vol. 47, pp. 5-10, 2017.

[19]. M. Kim and K. S. Yun, "Helical piezoelectric energy harvester and its application to energy harvesting garments", Micromachines, 8, 115, 2017.

[20]. R. Riemer and A. Shapiro, "Biomechanical energy harvesting from human motion: theory, state of the art, design guidelines, and future directions", J. Neuroeng. Rehabil., vol. 8:22, 2011.