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Charging device for wearable electromagnetic energy-harvesting textiles

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Abstract

The study aims to develop charging devices for wearable electromagnetic energy harvesting textiles (WEHT). Electromagnetic energy through human movement can be easily and naturally generated and is not significantly affected by environmental factors, however, the electric current generated by the electromagnetic method of human movement is difficult to efficiently charge. Three charging circuits for use with wearable electromagnetic energy-harvesting textiles were developed. The three types of charging circuits developed are rectifier, voltage doubler, and voltage quadrupler circuits. The performances of the developed circuits were evaluated in comparison with a normal storage circuit, in which the generated energy is stored immediately. The results show that storage energy was generated from the WEHT in all the developed circuits, and the charging efficiency improved as the simulated walking frequency increased. Energy generated from wearable electromagnetic energy harvesting textiles has the highest storage efficiency when charged with a rectifier circuit. The rectifying circuit method showed a charging rate twice that of a normal storage circuit. The charging speed of the rectifier circuit was faster to reach 3.7 V, the nominal maximum barrier voltage of the single-cell lithium-ion batteries used in portable devices, than the normal charging circuit. In the voltage multiplier circuit, the voltage drop generated in the circuit was large, so the charging efficiency was not superior to the normal circuit or rectifier circuit. In conclusion, it is most effective to use a rectifier circuit for charging portable electronic devices using the energy harvested by wearable electromagnetic energy harvesting textiles.

Keywords: Charging device, Rectifier, Voltage multiplier, Battery, Wearable energy harvesting textile

Introduction

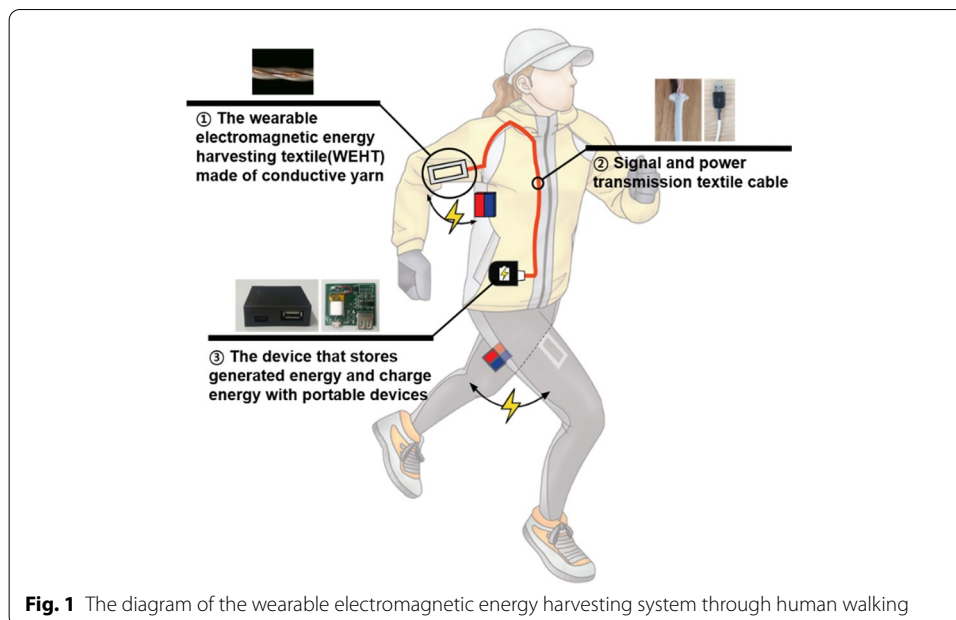
The population enjoying outdoor activities is increasing worldwide. As a consequence of this, the number of incidents leading to situations of distress caused by accidents, natural disasters, and other unfortunate events in outdoor areas is also increasing (Soulé et al. 2014). In remote and wilderness areas various items of special equipment related to life protection are needed (Vanpouille et al. 2017). In particular, if someone participating in outdoor activities possesses communication-related equipment, the likelihood of survival in the event of distress increases (Soulé et al. 2014). However, since communication signals are usually weak in remote areas, the energy required

for the use of communication equipment is significantly greater and batteries in portable communication devices are drained at a high rate. In addition, when temperatures are low, batteries discharge more quickly due to being outside of their optimal operational temperature range (Tampier et al. 2015). If a person in a remote location faces an emergency and their communication device batteries are exhausted, self-energy harvesting to recharge their devices could be lifesaving.

Walking is a natural human activity in outdoor environments, and is one of the most viable energy sources for sustainable self-energy harvesting. There have been many studies of self-energy harvesting using thermal, piezoelectric, triboelectric, photovoltaic, and electromagnetic energy produced by human motion (Ali et al. 2019; De Pasquale et al. 2013; Duffy and Carroll 2004; Halim and Park 2013; Halim et al. 2016, 2017; Hoffmann et al. 2013; Ishida et al. 2012; Jung et al. 2014; Kymissis et al. 1998; Li et al. 2017; Liu et al. 2014, 2015; Lou et al. 2019; Lu et al. 2020; Nia et al. 2017; Pillatsch et al. 2014; Saha et al. 2008, 2020; Wang et al. 2017a, b, c; Ylli et al. 2015; Yoshimura et al. 2011; Zhang et al. 2014; Zhao and You 2014; Zi et al. 2015).

Electromagnetic conduction is suitable as an energy harvesting method in outdoor environments because it is minimally affected by external environmental factors such as temperature, humidity, or friction. Accordingly, many studies have been conducted on harvesting electromagnetic energy produced by humans' walking. (Halim et al. 2013, 2016, 2017; Liu et al. 2014, 2015; Saha et al. 2008; Wang et al. 2017a, b, c; Ylli et al. 2015; Zhang et al. 2014). However, since the energy harvested from walking is an alternate current and the amount produced is small, it is important to develop a charging circuit that allows the produced energy to be effectively stored with the lowest possible level of wastage. Previous studies on electromagnetic energy harvester from walking were mainly about measuring the energy generated from the developed harvester and proving the possibility of energy harvesting. There has been no research on the development of circuits that increase the charging efficiency of the generated energy. The charging circuit should be designed to maximize the charging of small and irregular alternating current wave energy generated by human activities and to allow users to use energy quickly in emergency situations where electricity is required.

The purpose of this study is to develop charging devices that can work efficiently with minimal loss of the small amounts of energy generated through human walking. For this study, the wearable energy harvesting textile (WEHT) described in previous research (Lee and Roh 2019) was fabricated and used. The WEHT generates electromagnetic energy using a flexible conductive yarn coil and magnet. The charging device developed in this study completes the wearable electromagnetic energy harvesting system as shown in Fig. 1. For charging devices, three charging circuits, a rectifier circuit, voltage doubler, and voltage quadrupler were designed. The developed circuits were analyzed for charging efficiency compared to a normal charging circuit in which the generated energy is immediately directed to the battery.

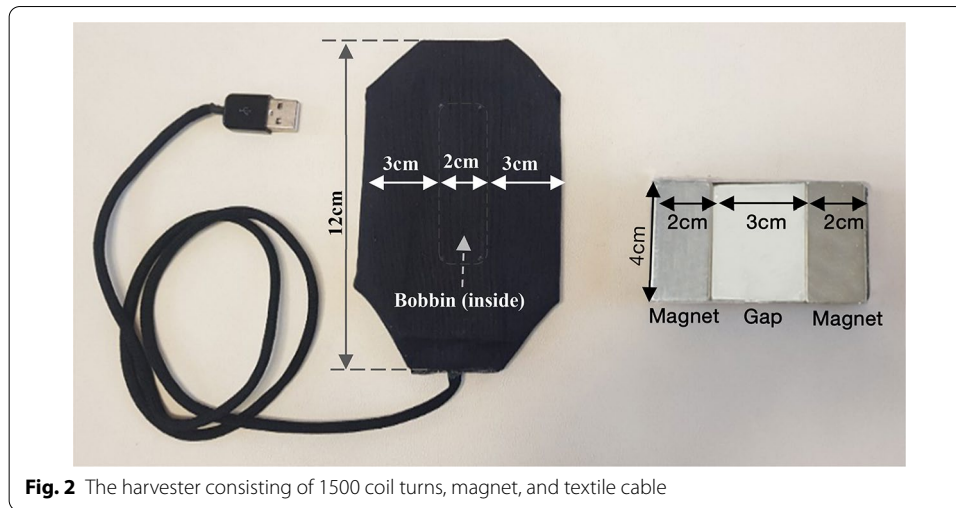


Methods

The harvester

For the harvester, a textile coil and two magnets were used. The electromagnetic energy generated from the WEHT increases when the number of turns of the coil increases, when the series connection is used, when the magnetic force is stronger, when the walking speed increases, and when the coil and magnet are positioned closer together. In our previous study (Lee and Roh 2019), we confirmed that the amount of electromagnetic energy generated from the WEHT increased linearly as the number of coils turns increased. Also, since the WEHT's textile coil used a multiplied conductive yarn, when the conductive strands in the yarn were connected in series, the amount of harvested energy was 1.74 times more than when in parallel. The average level of electromagnetic energy in the WEHT for two-magnet arrangements was 1.61 times higher than for a one-magnet arrangement. The energy generated by the WEHT increased linearly as the swing frequency increased.

In this study, the three-ply conductive yarn developed in the previous study was used (Lee and Roh 2019). The conductive yarn was wound on a flat bobbin with 1500 turns, and connected in series. The coil was 8 cm wide, 12 cm long, 0.5 cm thick, and 55.75 g in weight (Fig. 2). The 8 cm width of the coil is a size that does not exceed that of the arm of a typical male garment. The coil size was chosen to be as efficient as possible without spoiling the wearability and aesthetics of the garment (Lee et al. 2019). The coil was wrapped with fabric (100% polyester, woven fabric) for wearability and flexibility. The coil was connected to the energy charging device through a textile cable (Lee et al. 2018). The gap between magnets (NdFeB, width: 20 mm, height: 40 mm, depth: 10 mm, Gauss range 4000–4300, weight: 120 g) is 3 cm, the thickness of one side of the coil. The reason for the spacing between the magnets is that the WEHT has a structure that generates maximum energy when the flat magnets and

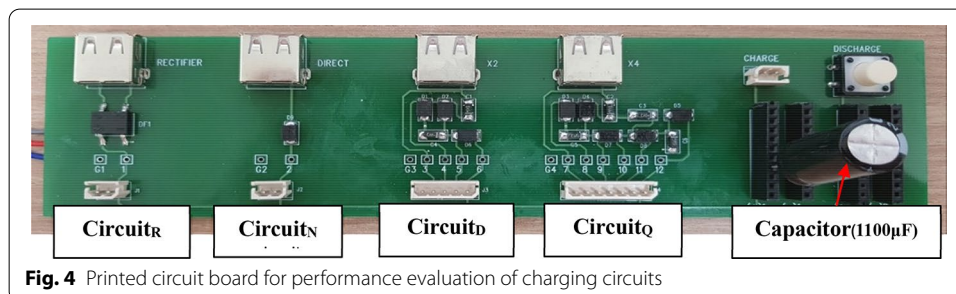
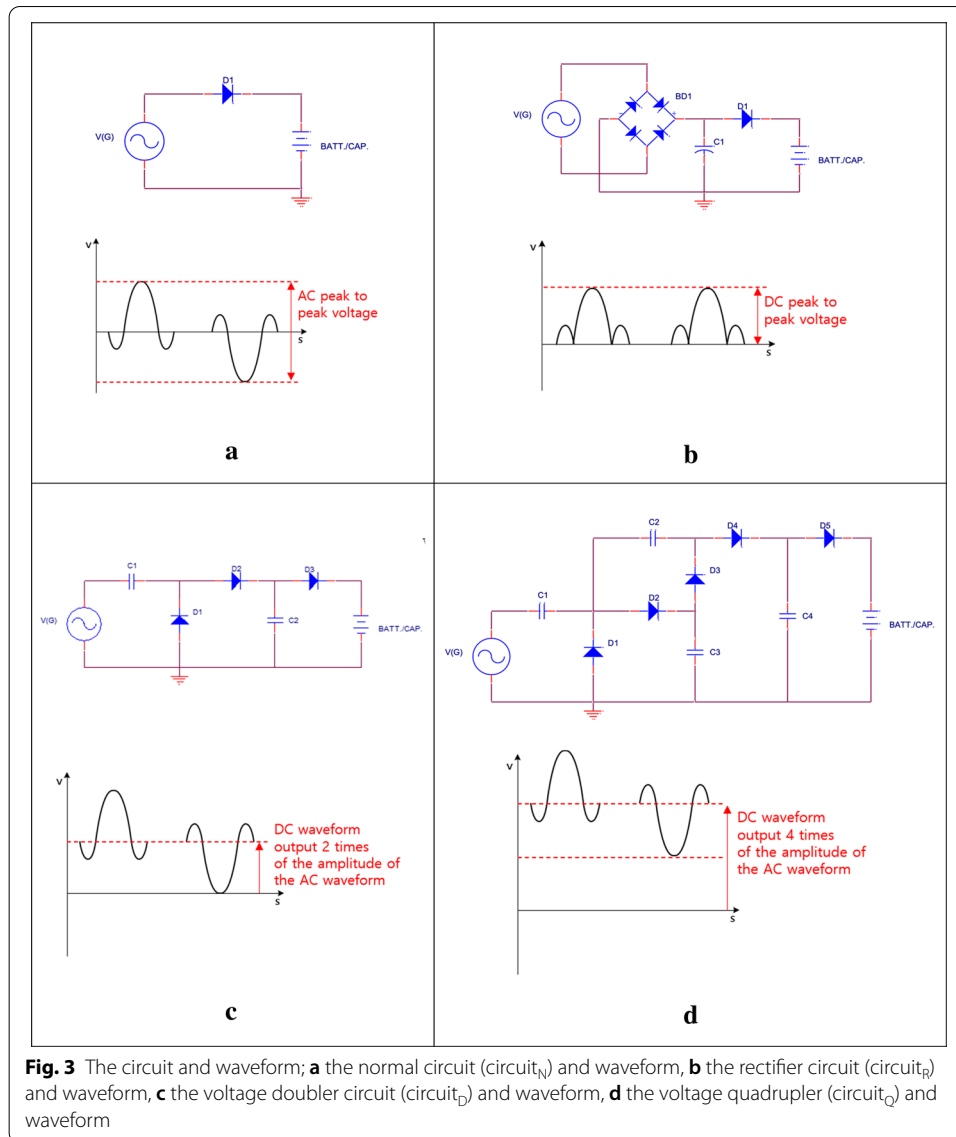


coils swing past each other (Lee and Roh 2019). The textile cable was made from conductive yarn and had excellent flexibility and wear resistance. To facilitate connection with devices to be charged, a USB type A connection was connected to the end of the textile cable.

Charging circuits

The electromagnetic energy generated through human walking is in the form of an alternating current (AC) waveform, and the amount of energy produced is very small. To increase the charging efficiency for electromagnetic energy generated through human walking, the negative voltage produced by the harvester should also be utilized. As the amount of total energy involved is so small, it is necessary to utilize as much of it as possible to produce a viable charging device.

In this study, three charging circuits were designed to increase the charging efficiency of the WEHT. The three circuits designed are the rectifier circuit (circuit_R, Fig. 3b), voltage doubler (circuit_D, Fig. 3c) and the voltage quadrupler (circuit_Q, Fig. 3d). The rectifier circuit converts AC, which periodically changes direction, into direct current (DC). In Fig. 3b, circuit_R is a full-wave rectifier circuit, and through the bridge diode, the negative polarity of the wave is converted to positive polarity. In circuit_R, the voltage generated through the coil is converted to an average voltage higher than the input. Figure 3c, d show the voltage multiplier circuit. A voltage multiplier circuit is an electrical circuit that converts AC electrical power from a lower voltage to a higher DC voltage, typically using a network of capacitors and diodes. The voltage multiplier circuit designed in this study was divided into a voltage doubler (circuit_D) and a voltage quadrupler (circuit_Q). Through circuit_D and circuit_Q, the DC voltage output becomes twice and four times the input voltage respectively. In order to compare the performance of the designed circuits, a normal circuit (circuit_N) was fabricated in which the energy generated from the WEHT is used to charge the battery directly. Circuit_N is a control circuit for comparison with the circuits designed



in this study (Fig. 3a). Circuit_N used only minimal diodes so that the voltage flowed directly to the battery, and no special function was added.

Preparing performance evaluation

The circuits were all made on printed circuit boards (PCBs) (Fig. 4). For performance evaluation of the circuits, a capacitor (1100 μF , 25 V) was used and the same swing instrument used in the previous study was used (Lee and Roh 2019) (Fig. 5). The distance between the coil and the magnet was maintained at 1 mm. The swing angle was set to 60° which is similar to the natural human arm swing angle (Lee et al. 2018). Swing frequency was controlled to 0.7 Hz for slow walking or stretching, 1.0 Hz for normal walking, 1.4 Hz for fast walking or jogging, and 2.0 Hz for a sprint (Cavagna et al. 1997; Holt et al. 1995). The voltage generated and charge produced by each circuit was measured using an oscilloscope [Tektronix TDS2012C (100 MHz, 2-Ch, 2 GS/s Digital Storage Oscilloscope)].

Results and discussion

Figure 6 shows the waveforms in which the energy generated from the WEHT is charged into the capacitor at four frequencies. In all four circuits, the higher the frequency, the faster and more energy was charged. Charging occurred even at low frequencies. Notably, circuit_R (Fig. 6b) showed the best overall charging rate compared to the others. Circuit_R has a higher rate of increase in the amount of energy charge at the slowest walking pace compared to the other circuits.

The voltage multiplier circuits (circuit_D, circuit_Q) showed lower charging efficiency than charging using circuit_N or circuit_R (Fig. 6c, d). Voltage drop is the decrease of electrical potential along the path of a current flowing in an electrical circuit (Jenneson 2003). Voltage drop occurs due to the diode used to construct the circuit. In the voltage multiplier circuit, because of the large number of diodes, the voltage drop is large, and the charging efficiency is reduced. For this reason, the overall charging amount of circuit_Q is lower than circuit_D. Although some voltage drop occurs in circuit_R, because the DC is converted from the AC of the generated energy, the increased charge amount is larger than the voltage drop amount.

To quantitatively evaluate the performance of each charging circuit method, the waveforms charged at 2.0 Hz rate were compared. Figure 7 shows the time to reach each level for each number of cells based on 1 cell lithium-ion battery (Max voltage: 4.2 V, Nominal

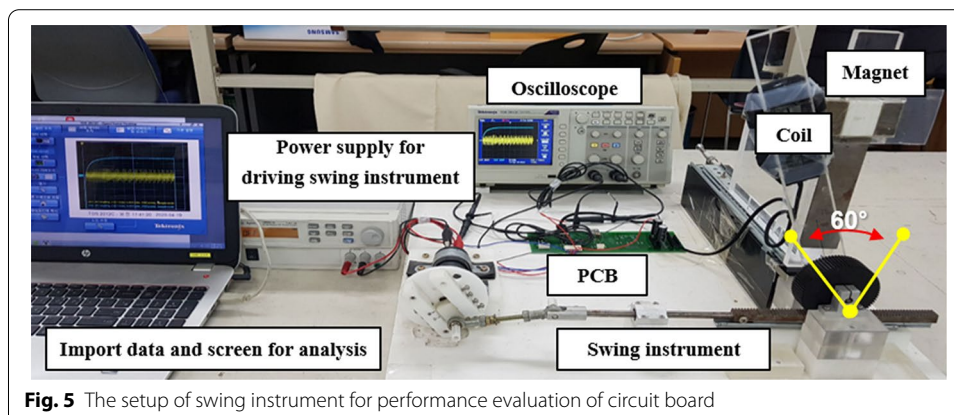
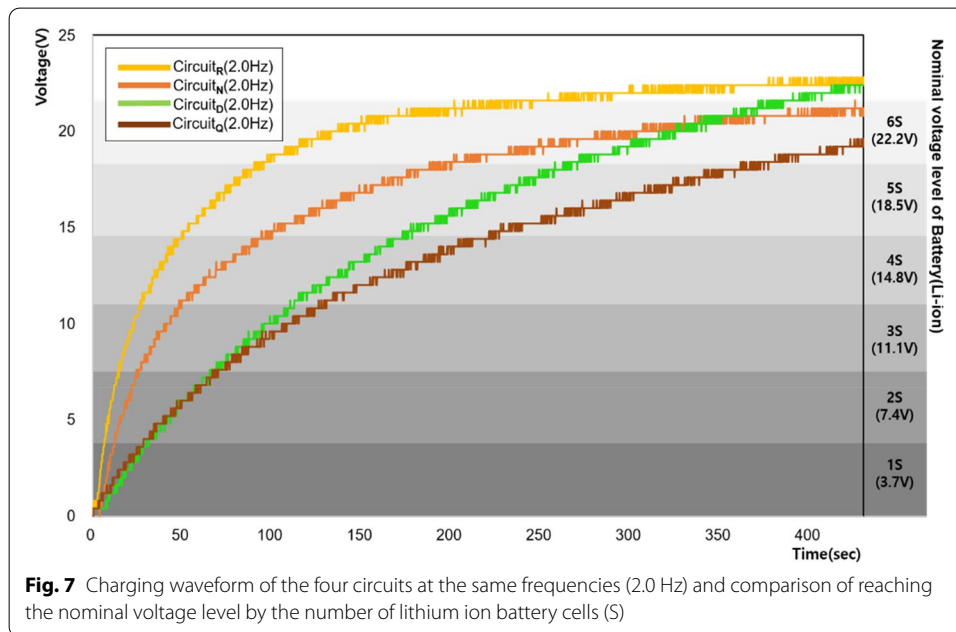
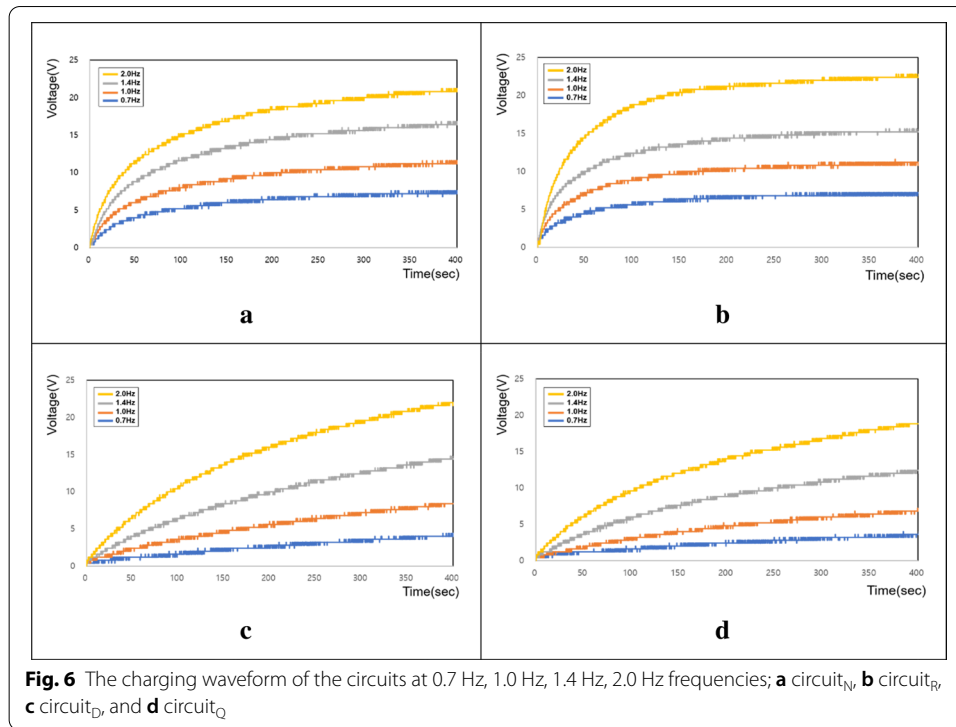


Fig. 5 The setup of swing instrument for performance evaluation of circuit board



voltage: 3.7 V). The charging rate of the circuit can be analyzed through the time to reach the nominal voltage level of each battery cell.

Lithium-ion batteries can be charged and reused, and the self-discharge rate is slower than other types of batteries. Lithium-ion batteries are used in a variety of ways, from smartphones (1 cell) to notebook batteries (6 cells), depending on the device type,

purpose of use, and capacity. A single cell is the most often used in portable electronic device batteries, including smartphones. For charging devices suitable for this study, considering the use as a portable device and wearability, the number of batteries used is one cell or two cells.

The amount charged through the developed circuits increased almost linearly until 3.7 V, which is the nominal voltage level of one cell. The time to reach 3.7 V charging was 6.4 s for circuit_R and 12.2 s for circuit_N. Circuit_R has a charging rate that is almost twice as fast as circuit_N. This means that when you need to charge a 1-cell battery suitable for portable devices, it is effective to select and use circuit_R, and the available energy is generated from 6.4 s. In the case of circuit_N, available energy is generated from 12.2 s.

Circuit_R was the fastest to reach the nominal voltage level for a six-cell battery (22.2 V). The charge amount of circuit_D was larger than that of circuit_N after 316 s. This means circuit_D has an advantage over circuit_N in situations where the device can charge for more than 316 s. At 414 s, the charge amount of circuit_D became the same as that of circuit_R. After 414 s, the charge amount of circuit_D will be greater than the charge amount of circuit_R. In an environment with a large capacity battery, and a harvesting period of 414 s or longer, circuit_D will be useful. Circuit_Q shows the smallest charge amount and the slowest charge speed at all cell levels, so it is judged that the voltage loss due to the diode is the largest.

In conclusion, circuit_R with its high charging efficiency is most suitable as a charging device to be used in our wearable energy harvesting system. If the rectifier circuit is connected to a single cell lithium battery in a portable device, someone urgently needing to charge their device, walking with a swing rate of 2.0 Hz frequency or more, would see battery charging begin after 6.4 s. The circuits developed in this study can be appropriately selected and used by the user according to the number of cells in the device and the user's exercise time.

Conclusions

The charging device were developed for wearable electromagnetic energy harvesting fabrics that can be connected to and used in portable devices. Rectifier and voltage multiplier circuits were used as a method to increase the charging efficiency, and three circuits were designed for charging devices. The charging performances of the developed circuits were analyzed and evaluated.

In conclusion, among the circuits developed in this study, the rectifier circuit has the best charging efficiency. The rectifier circuit showed charging efficiency twice as fast as the normal circuit in which generated energy is immediately charged. The rectifier circuit could be effective in emergency situations that require power quickly. The rectifier circuit is suitable for a highly wearable charging device to provide power to a portable device with a single cell lithium-ion battery, such as a smartphone. When it was necessary to harvest energy quickly to charge a battery, the voltage multiplier circuit was not suitable. The voltage multiplier circuit had more energy loss due to voltage drop than the normal circuit and the rectifier circuit.

Further studies on the optimal number of coils turn and magnetic strength of the energy generating device may lead to larger energy output and quicker and more efficient charging. The charging devices developed in this study can be used in various

wearable energy harvesting systems. The charging devices developed in this study can be used not only for wearable energy harvesting systems using electromagnetic transduction but also for energy harvesting systems using other methods of energy generation transduction.

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Authors' contributions

This manuscript was developed by HL and received guidance and analysis assistance from Professor JSR. Both authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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