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# Whole Body Human Power-Based Energy Harvesting using a Conductive Embroidered Cloth and a Power Aggregation Circuit

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***Abstract*— This paper proposes a whole body human power-based energy harvesting (HPBEH) scheme which aggregates the power from multiple HPBEH devices distributed on a special cloth embroidered with conductive threads. Each HPBEH devices is connected by using a special connector consisting of a tack and a clutch without one-to-one wiring. In a conventional HPBEH system, each device individually has its own HPBEH element. Power aggregation system using a multiple HPBEH devices can supply higher power than conventional EH systems to a power-hungry device. And each HPBEH devices has a flexible piezoelectric element (PE) placed in the whole body joints and sole. In the flexible PEs, the output voltage and the time when output reaches the peak are different. The experimental results demonstrate the feasibility of the power aggregation system in those case.**

## I. INTRODUCTION

A human power-based energy harvesting (HPBEH) [1], which uses energy sources such as joint motion or vertical displacement of mass centers, can supply the power to the wearable device permanently as long as a user is active. The power generated by a coin size HPBEH device is about 40 µW or less [2][3]. It is difficult to drive a wireless sensor node that frequently transmits data. In order to obtain more power generation amount, device upsizing is essential. For example, in [4], 1.7 mW power generation is achieved by using piezoelectric elements (PE) and exoskeleton frames attached to the knee joint. This device can transmit the sensor data at 0.5 second intervals while walking.

In conventional HPBEH systems, each device individually has its own HPBEH element [5]. Energy sources that can be scavenged around a small area/volume HPBEH device are insufficient to drive a power-hungry device. However, it may be driven by whole body energy aggregated from multiple HPBEH elements distributed across the clothing.

In this paper, we propose a scheme to aggregate the power from multiple flexible PEs. It can be applied to a whole body HPBEH system composed of asynchronous PE elements, i.e., output voltages of PEs are not in the same waveform and not synchronized. To connect multiple PEs distributed on whole body without one-to-one wiring, conductive-thread-embroidered fabric (CTEF) and tack-type connector [6] [7] are used in this work. As shown in Fig. 1, each flexible PE is placed in the whole-body joint and sole. In the proposed scheme, output power of all flexible PEs is aggregated in the storage terminal efficiently regardless of the phase and amplitude of the output voltage of each element.

When the PEs with different output voltage and phases are directly connected in parallel via the CTEF, part of the output is canceled out. It will lead to energy loss. To avoid this problem, we use a power aggregation scheme presented in [8]. In [8], the feasibility of power aggregation circuit was demonstrated by experiments that aggregate the output of multiple solar cells. Unlike those solar cells, in the flexible PEs arranged in the whole body joints, the output voltage and the time when output reaches the peak are different.

In the proposed system, the power is aggregated from each HPBEH device to the storage terminal using the whole body power network. Also, the storage terminal can supply the power to the wearable device distributed on the CTEF. The advantages of our proposal include: 1) the energy that can be generated in a whole body area can increase the maximum output of HPBEH system; 2) a cognitive system such as leveling the total amount of electricity generation and power demand may be realized; 3) the whole body power network constructed by CTEF has no risk of disconnection.

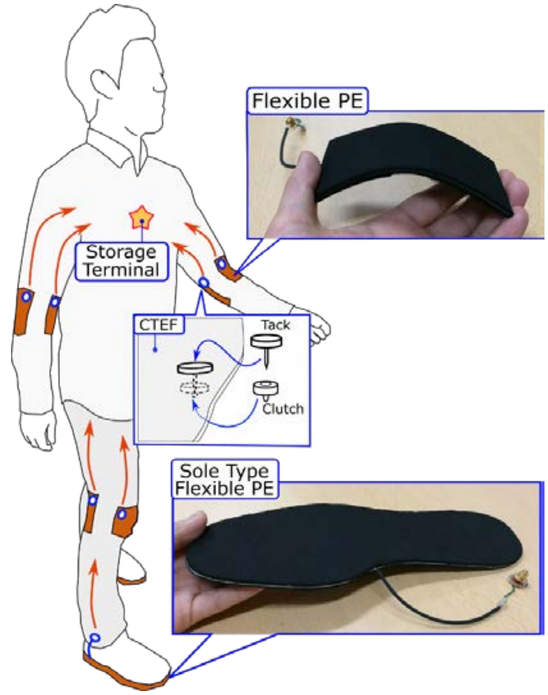

Figure 1. Concept of whole body HPBEH system by using CTEF and tack connector and the multiple flexible PEs.

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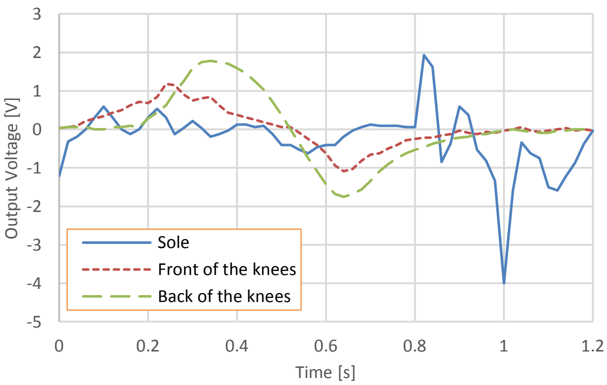


Figure 2. Output voltage of each flexible PE across one half of a gait cycle.

This paper presents the feasibility of the power aggregation system in the case of that the output voltage and the time when output reaches the peak are different. In the next section, power aggregation scheme and the circuit configuration are demonstrated. The experimental verification is presented in Section Ⅲ. Finally, we will conclude this paper in Section Ⅳ.

## II. CIRCUIT DIAGRAM OF WHOLE BODY HPBEH SYSTEM

In this paper, we developed a prototype of HPBEH system that covers under-the-knee region on one of the legs. A flexible PE is placed on the front of the knee, the back of the knee, and the sole as shown in Fig. 1. The output voltage of each flexible PE when the wearer walked one step is shown in Fig. 2. Each flexible PE was directly connected to an oscilloscope with an internal resistance of 1 MΩ and the voltage was measured. The wearer starts walking and foot departs from the ground at time $t$ = 0. The sole PE output shows a peak at landing, $t$ = 1 s. At this moment, PEs placed on the knee do not generate much power, because the knee is almost extended. Thus, the output voltage and the time when output reaches the peak are different.

To explain the necessity of the power aggregation scheme presented in [8], we consider the energy consumed by the load $R_L$ shown in Fig. 3. In Fig. 3, each flexible PE is connected in parallel via the CTEF and tack-type connector. $V_{sole}$, $V_{front}$, and $V_{back}$ denotes the output voltages of the flexible PEs placed on the sole, the front and the back of the knee, respectively.

The CTEF is a transmission path having a two-dimensional spread by sewing conductive threads on both sides of an electrically insulative (ordinary) cloth [6] [7]. A needle of tack type connector is pierced from the one side of the CTEF and fixed with a metallic clutch on the other side as shown in Fig. 3(a). In the tack type connector, a metallic needle is fixed and conducted by soldering to the surface of the double-sided copper clad board. Conductive thread on the top and the back side of the cloth respectively contact with the backside of the board and the clutch. If the back side conductive thread is grounded, the board surface can be designed as a ground.

By easily connecting PE to CTEF, available energy is lost. To show this problem, compare the energy available in Fig. 3(a) and (b) with the energy available in Fig. 3(c) that imitates the conventional HPBEH system. In Fig. 3(a), each flexible PE is directly connected to the CTEF by using tack-type connector. $V_A$ and $E_a$ are expressed as

$$V_A = \frac{R_L|V_{sole} + V_{front} + V_{back}|}{R_{in} + 3R_L}, \tag{1}$$

$$E_a = \int_0^t \frac{{V_A}^2}{R_L} dt. \tag{2}$$

$V_A$ denotes the voltage applied to $R_L$. And $E_a$ denotes the energy consumed by $R_L$. $R_{in}$ denotes the internal resistance of each flexible PE. In this paper, we assume that the internal resistance of each PE is same and that $R_L$ is so large as to be negligible for $R_{in}$ as shown in Eq. (3). The voltage drop due to the diode is not considered.

$$R_L \gg R_{in}. \tag{3}$$

From the above, Eq. (1) can be expressed as

$$V_A \cong \frac{|V_{sole} + V_{front} + V_{back}|}{3}. \tag{4}$$

In Fig. 3(b), each flexible PE is connected to the CTEF via a rectifying circuit. $V_B$ and $E_b$ are expressed as

$$V_B = \begin{cases} |V_{sole}| & (|V_{sole}| > |V_{front}|, |V_{back}|) \\ |V_{front}| & (|V_{front}| > |V_{sole}|, |V_{back}|) \\ |V_{back}| & (|V_{back}| > |V_{sole}|, |V_{front}|), \end{cases} \tag{5}$$

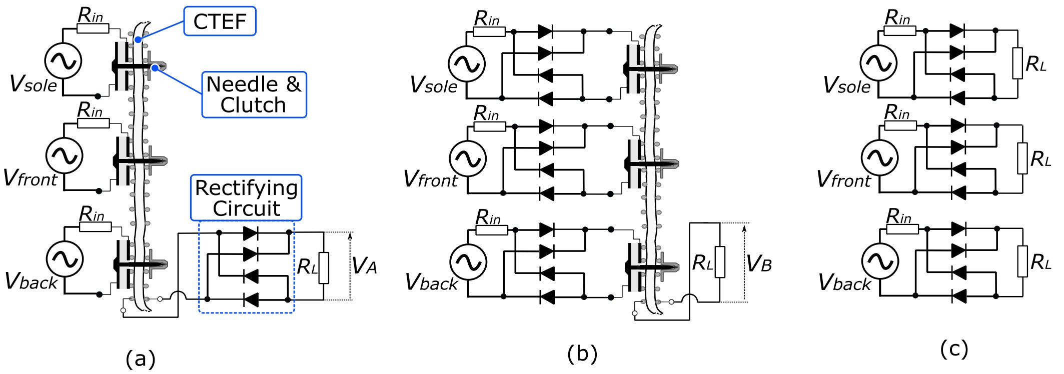


Figure 3. Each AC voltage source is (a) directly connected to the CTEF by using tack-type connector, (b) connected to the CTEF via a rectifying circuit, (c) electrically disconnected.

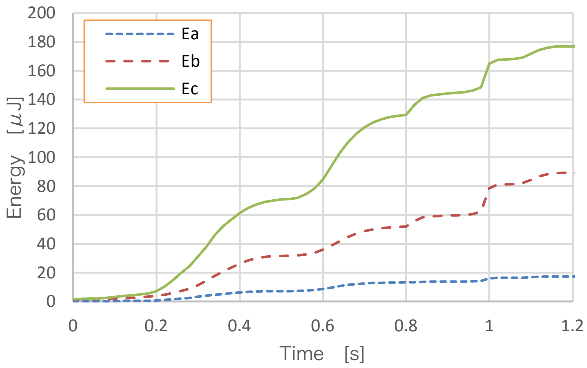


Figure 4. $E_a$, $E_b$, $E_c$ when each flexible PE outputs the voltage waveform shown in Fig. 2 and the value of $R_L$ is 1 MΩ.

$$E_b = \int_0^t \frac{{V_B}^2}{R_L} dt. \tag{6}$$

$V_B$ denotes the voltage applied to $R_L$. And $E_b$ denotes the energy consumed by $R_L$.

In Fig. 3(c), each flexible PE has a load $R_L$ and each flexible PE is electrically disconnected. Fig. 3(c) shows the conventional HPBEH scheme where each HPBEH device has its own HPBEH element. Let $E_c$ be the total energy consumed by each $R_L$, $E_c$ are expressed as

$$E_c = \int_0^t \frac{|V_{sole}|^2 + |V_{front}|^2 + |V_{back}|^2}{R_L} dt. \tag{7}$$

$E_a$, $E_b$, $E_c$ when each flexible PE outputs the voltage waveform shown in Fig. 2 and the value of $R_L$ is 1 MΩ are shown in Fig. 4. As shown in Eq. (2) and (4), when voltage amplitudes are small or voltage sources with different signs are mixed, $E_a$ decreases greatly. Thus, $E_a$ is the lowest in Fig. 4.

As shown in Eq. (5), the circuit shown in Fig. 3 (b) is the maximum value selection circuit. Thus, the problem of the circuit shown in Fig. 3(a) is solved. On the other hand, energy can be extracted only from the element with the highest voltage absolute value.

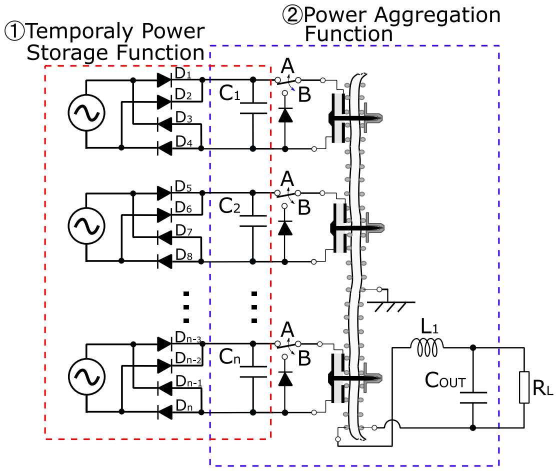


Figure 5. Schematic diagram of power aggregation circuit.

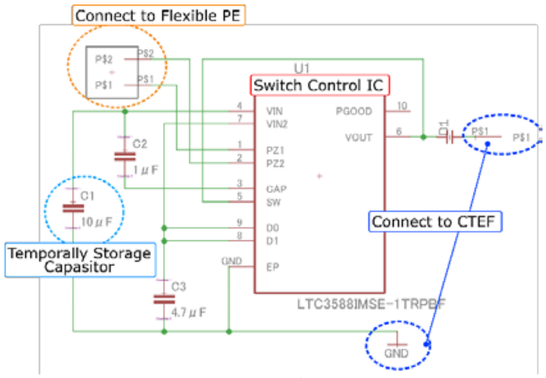


Figure 6. Circuit diagram of each HPBEH device

$E_c$ is the highest in Fig. 4. It shows that the usable energy of Fig. 3(a) and (b) is greatly reduced compared to the conventional HPBEH scheme as shown in Fig. 3(c). We use the power aggregation circuit presented in [8] to bring usable energy closer to $E_c$ in a system where the PEs are connected in parallel to CTEF.

Fig. 5 shows the circuit diagram of the whole body HPBEH system using the CTEF and power aggregation circuit. In the temporary power storage function (the switch is turned to B side), each AC source is electrically disconnected from the CTEF. In the current aggregation function (switch position A), energy moves from $C_n$ , which is the temporary storage of each HPBEH device, to the coil $L_1$. After the switch is returned to the B side, energy moves from $L_1$ to $C_{OUT}$ which is fixed in the storage terminal shown in Fig. 1.

Fig. 6 shows the circuit diagram of each HPBEH device. This device has the temporally storage capacitor, the flexible PE (Munekata Industrial Machinery Corporation [9]), and switch control IC (Linear Technology Corporation, LTC3588-1 [10]).

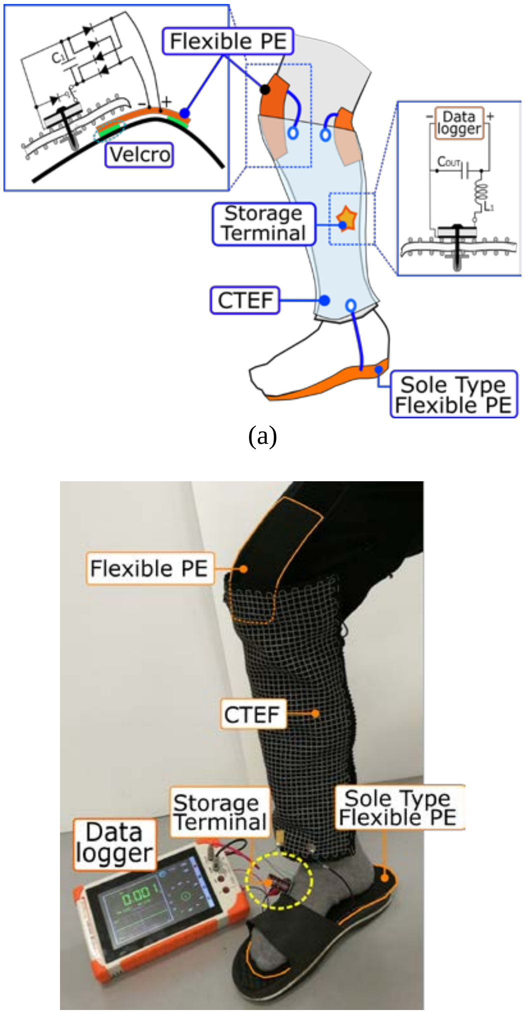
## III. EXPERIMENT

In this section, we measure and evaluate the charging speed for the number of the HPBEH device. The prototype device limited area to under-the-knee region on one of the legs. The measurement setup is shown in Fig. 7. And the prototype HPBEH device composed of a tack type connector, a flexible PE, and a switch control IC is shown in Fig. 8.

The storage terminal in Fig. 7 and 8 imitates the storage terminal shown in Fig. 1. By measuring the voltage applied across the capacitor $C_{OUT}$ of this storage terminal shown in Fig. 7 and 8, we evaluate how fast the storage terminal in the assumed system shown in Fig. 1 can be charged.

Each HPBEH device is connected to the CTEF with a tack type connector. The PEs placed on the front and back of the knee are fixed to the pants with the Velcro tape. And CTEF covers them.

The data logger measures the voltage of the capacitor ($C_{OUT}$: 47 μF) every 100 ms. When the wearer starts walking, charging to the $C_{OUT}$ starts. The voltages at five points from the charge start time to the end time is measured. Measurement was performed when connecting one device at each position, two devices at knee (front and back), and three devices.



(a)

(b)

Figure 7. (a) Schematic diagram of measurement setup. (b) Photo of the setup.

The average of the charge speed obtained from them is shown in Table Ⅰ. The sum of the power generation amounts when operating individually almost matches the power generation amount when three are operated at the same time. The charging speed of front and back of the knee is higher than the sum of front of the knee and back of the knee. This is considered to be a measurement error due to the variation in walking speed.

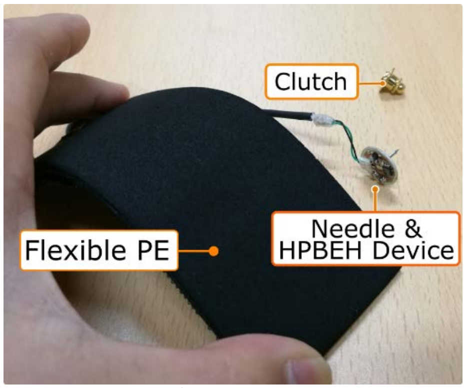


Figure 8. Photo of the prototype HPBEH device

TABLE I. THE AVERAGE CHARGING SPEED

| **Placement location of PE** | ***Charge Speed* [μW]** |
|---|---|
| Sole | 5.24 |
| Front of the knee | 2.19 |
| Back of the knee | 2.45 |
| Front and back of the knee | 5.02 |
| All positions | 9.79 |

## IV. CONCLUSION

We proposed a whole body HPBEH scheme which aggregates the power from multiple flexible PEs to storage terminal without one-to-one wiring by using tack-type connector and a fabric sheet embroidered with conductive threads. An efficient aggregation cannot be realized by directly connecting all PGEs to CTEF, because part of the output is canceled out when the PEs with different output voltage and phases are connected in parallel via the CTEF. The power aggregation circuit solved the above problem by the temporary power storage function and the power aggregation function.

The experimental result shows that the feasibility of the power aggregation system in the case of that the output voltage and the time when output reaches the peak are different.

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