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ABSTRACT

Body energy harvesting (BEH), especially for wearable devices, is an emerging and promising technology to improve the battery capacity and to avoid regular maintenance in terms of energy supply. A broad application of BEH increases sustainability and thus offers an advantage from an environmental point of view. We present a light weight BEH device for non-resonant arm and leg swing motions. The design was kept as simple and robust as possible and is based on an electrical generator. The generator is moved by an oscillating mass, which was previously simulated in a model, so that in this generator model, the kinetic energy is optimally transformed into electrical energy. Additionally, an ultra-low voltage power conditioning circuit, based on a step-up converter, was adapted to the BEH generator. The BEH generator and the power conditioning circuit were evaluated in a real test setup for arm and leg movements during walking and jogging with the BEH device worn on the wrist or ankle. An effective power of ~11.3 mW was generated. This provides a constant voltage to charge a battery or supercapacitor.

Over the last two decades, energy harvesting has become an established terminology for the conversion of chemical or kinetic energy into electrical energy. In particular, harvesting the mechanical energy from human motion has been comprehensively studied, as it can be used to prolong the restricted battery capacity in wearable electronic devices. Kinetic energy from heel strike,[1–3] center-of-gravity (COG) motion of the human body,[4–6] joint motion,[7,8] and arm or leg swing motion[9–12] can be used for conversion. Apart from thermoelectric and chemoelectric generators, the following principles are mainly used for harvesting energy from human motion: (1) various examples exist for piezoelectric energy harvesting devices that generate an electric charge when mechanical stress is applied to piezoelectric materials. This principle is typically used in shoe soles.[2,13] (2) Rotational BEH devices with piezoelectric cantilevers were also presented.[11] (3) Different designs were published for both electromagnetic linear systems[10,12,14] and electromagnetic rotational BEH devices.[8,9] (4) Furthermore, a few electrostatic BEH devices were presented.[7] Most portable systems deliver energy from body motions only in the micro-watt range, and hence, they are also referred to as a micro-energy harvester.[15] However, only a few power conditioning circuits have been designed to store as much as possible of the output power of the device into a capacitor or battery. Most of these power conditioning circuits were designed to convert high voltage peaks from piezoelectric generators to lower voltage.[16]

To address these limitations, we developed a BEH device, which maximizes the efficiency of the power conditioning process for low voltages. In our previous work, we developed BEH devices for upper and lower body motions to convert kinetic energy from a fluidic system applied in a prosthetic foot and upper limb motion with an electromagnetic linear generator and gyrating mass.[3,10] To further optimize the BEH device for upper body motions, we developed a BEH device to generate the greatest possible energy output while the design is as simple and robust as possible. We present a BEH device, shown in Fig. 1, for arm and leg swing motions and an ultra-low voltage power conditioning circuit to supply consumers, for example, wearable sensors, with DC voltage. The generator with a weight of 176 g consists of only four parts, the electrical generator, oscillating mass, and a two-piece housing.

Our research has shown that only very few BEH generators are commercially available. The vast majority were developed for

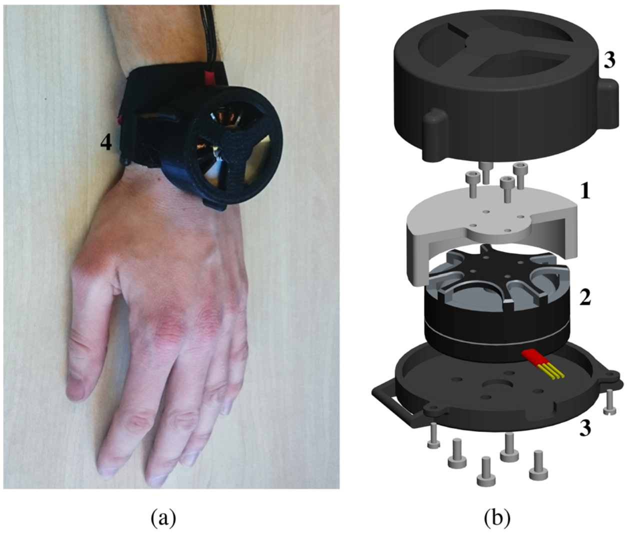

FIG. 1. (a) BEH device worn on the wrist and (b) an exploded view of the device. The oscillating mass (1) is connected to the rotor of the electrical generator (2). Both are protected by a two-piece housing (3). The device can be attached to the arm or leg with a wrist strap (4).

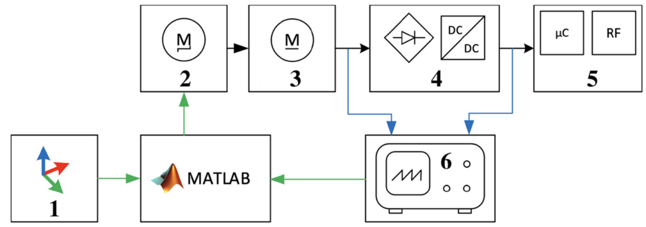

FIG. 2. Model-in-the-loop approach with gyroscope (1), stepper motor (2), generator (3), control unit (4), consumer (5), and oscilloscope (6) for the BEH device.

research purposes only and are not sold. For this reason, we decided to develop our own design, which should be as mechanically simple and robust as possible, as well as effective. Most available BEH devices are linear generators that require a higher resonant frequency than the relatively slow movements of the arms and legs during walking. We, however, chose a rotational, non-resonant system based on an electric motor as a generator. A generator is needed that produces relatively high voltages even with little movement, as indicated by the lowest possible K_V factor (revolutions per minute per volt). Generators with a low K_V factor need higher starting torques to move the generator and lead to the conversion of mechanical energy into electric energy, even at low speeds. Having compared different models of commercially available electrical motors that can be used as BEH generators, we have chosen the brushless motor Gimbal Turnigy HD 3508 (Constar Micromotor Ltd., Guangdong, China). This model offers a good compromise between a low K_V factor of 41 rpm V^{-1} and a reasonable starting torque. It is then only necessary to connect an oscillating mass to the rotor of the generator, which optimally transfers the body movement to rotational movements. The oscillating mass and the generator of the BEH device have to be protected by a housing, and finally, an effective power conditioning circuit for low voltages is needed.

Table I shows an overview of published BEH devices[2,9,12,14,17–20] compared to our previous work[10] and the proposed device.

For the developed BEH device, two simulations are conducted with MATLAB software R2018b (The MathWorks Inc., Natick, MA, USA). The first simulation is applied to calculate the expected voltage produced by the generator and solve the differential equations for optimization of the oscillating mass. Therefore, the accelerations are obtained from previous work.[10] In the second simulation, the energy and power output of the BEH device with the ultra-low power conditioning circuit is determined. A simulation of the electrical components is not possible because many suitable electrical components are highly integrated and have a multitude of operating states. Therefore, the use of a model-in-the-loop system is an effective solution. Thus, the oscillating mass is simulated and the remaining hardware components are part of the control loop. Figure 2 shows the model-in-the-loop approach for the ultra-low voltage power conditioning circuit. In order to provide acceleration sensor data that is as realistic as possible, the data need to be recorded directly on the human body during natural movements. To standardize the data acquisition for arm or leg swing movements during jogging or dancing, a sensor wristband is used to wirelessly collect the sensor data.

TABLE I. Comparison of the performance of published BEH devices.

References	Total weight (g)	Number of mechanical components	Size (mm)
Saha *et al.*[17]	-	7	Ø17 × 55
Chen and Hu[18]	-	> 10	65 × 32 × 24
Xie and Du[19]	50	> 10	Ø40
Jiang *et al.*[20]	-	> 10	Ø80
Samad *et al.*[14]	140	6	210 × 16
Fan *et al.*[2]	22.3	10	45 × 30 × 24
Our previous work[10]	146	> 10	-
Geisler *et al.*[12]	20	> 10	Ø14.8 × 52
Liu *et al.* [9]	-	8	Ø65 × 18
This work	176	4	Ø59 × 32

The system consists of a base station connected to a computer via Universal Serial Bus (USB) and a sensor module, which is attached to the body by a Velcro wrist strap and powered by a lithium-polymer battery. Acceleration data are collected via a gyroscopic acceleration sensor and then sent via WLAN utilizing User Datagram Protocol (UDP) to the base station where the data are forwarded via USB at ~175 Hz. The base station and the mobile sensor module are based on the ESP32 DevKitC (Espressif Systems, Shanghai, China).

A test setup is developed to compare the simulation results with experimentally measured data. Thereby, the arm movements are simulated to compare the root-mean-squared (rms) values for voltage, current, and power. For this purpose, an aluminum lever arm with the average length of a human arm (50 cm), an Arduino Uno single-board micro-controller, a laboratory power supply, an oscilloscope, and a servo motor CYS Standard-Servo S0650 (CYS Model Technology Co. Ltd., Guangdong, China) are used. The servo motor oscillates with the lever arm in a pendulum motion and the BEH device attached to its end, controlled by a micro-controller.

Afterward, the BEH device with the ultra-low voltage power conditioning circuit is excited with real arm and leg motions during walking and jogging, respectively, 2, 5, 7.5, and 10 km h^{-1}. Thereby, the voltage and current are measured with the mixed signal oscilloscope 6 series B MSO (Tektronix, Inc., Beaverton, OR, USA).

The first mathematical model is developed for the BEH device to calculate the expected voltage generated by the generator from the calculated speed. For this purpose, a mechanical equation of motion according to Fig. 3 is established to mathematically represent the torque of the oscillating mass as a result of external accelerations around the pivot point via arm movement. Thereby, g is equal to the acceleration due to gravity, φ describes the torsion angle of the oscillating mass to the rest position and the direction of movement, and the coordinate origin is placed in the pivot point DP of the oscillating mass. In addition, $a_x(t)$ and $a_y(t)$ represent the acceleration in x and y directions, M_L is the load torque, m_M describes the mass of the generator, m_{SM} and J_{SM0} are the mass and moment of inertia of the oscillating mass, J_{MF} is the moment of inertia of the rotating motor flange with respect to the origin, and SP represents the center of gravity. The equilibrium condition around the pivot point gives the following equation:

$$M_L + m_{SM} \times a_y(t) \times \sin(\varphi(t)) \times r_{SP} + m_{SM} \times g \times \sin(\varphi(t)) \times r_{SP} + J_{SM0} \times \ddot{\varphi}(t) + J_{MF0} \times \ddot{\varphi}(t) = m_{SM} \times a_x(t) \times \cos(\varphi(t)) \times r_{SP}. \quad (1)$$

The load torque is the sum of the starting torque of the generator M_R and the electrical torque M_{el}. Experimentally, the value 7.7×10^{-4} N m was determined for the starting torque M_R of the generator. Equation (2) yields the final equation of motion [Eq. (3)]. R_M corresponds to the electrical resistance of the generator, in this case 13.8 Ω,

$$M_{el} = k \times \dot{\varphi}(t), \quad whereby \quad k = \frac{60^2}{4 \times \pi^2 \times K_V^2 \times R_M}, \quad (2)$$

$$\ddot{\varphi}(t) = \frac{m_{SM} \times r_{SP}}{J_{SM0} + J_{MF0}}\left[a_x(t) \times \cos(\varphi(t)) - (a_y(t) + g) \times \sin(\varphi(t))\right] - \frac{M_R + k \times \dot{\varphi}(t)}{J_{SM0} + J_{MF0}}. \quad (3)$$

MATLAB is utilized to simulate the expected voltage, generated through the BEH device. The results for the rms voltage, current, and power are shown in Table II.

The second mathematical modeling is conducted to simulate the energy and power output of the BEH device including the ultra-low power conditioning circuit. The coordinate origin is located on the axis of rotation of the oscillating mass. The required input variables of the model are the acceleration in x and y directions as well as the angular acceleration around the z axis. Since the rotor can only turn around the z axis, angular accelerations around the x and y axes as well as the acceleration in the z direction have no influence. In addition, the angular velocity ω' and the angle of rotation ϕ' are required for the calculation. The resulting torques in x and y directions M_x and M_y are calculated according to the following equation with the externally applied forces F_x and F_y, the distance of the center of mass to the z axis r_m, the mass m, and the current angle of

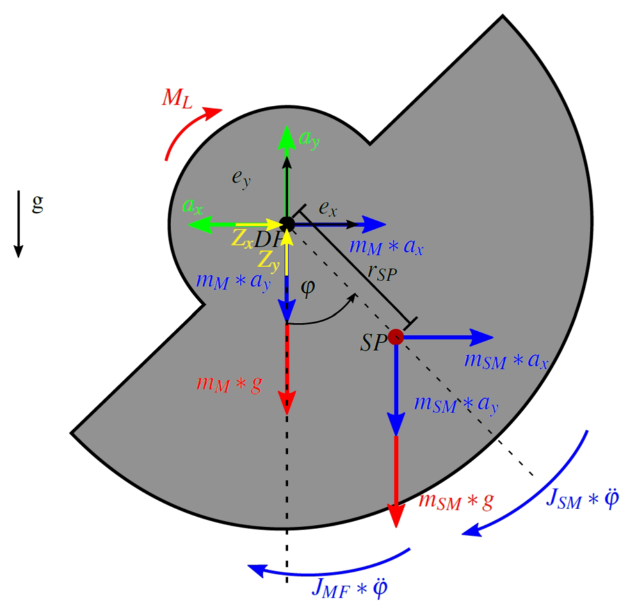

FIG. 3. Illustration of the oscillating mass of the BEH device. The constraining forces are shown in yellow, active forces and torques are depicted in red, inertial forces and torques are displayed in blue, and accelerations resulting from the arm movements are marked in green. All velocities and accelerations as well as angular rotation are functions of time.

TABLE II. MATLAB simulation results for the rms values for voltage, current, and power with a load resistance of 8.2 Ω, representing a connected biosensor.

Movement	V_{rms} (mV)	I_{rms} (mA)	P_{rms} (μW)
Walking	29.68	1.35	40.05
Jogging	62.05	2.82	174.99
Dancing	87.47	3.98	347.76

rotation ϕ,

$$M_x = F_x \times r_m \times \cos(\phi), \quad whereby \quad F_x = a_x \times m, \tag{4}$$

$$M_y = F_y \times r_m \times \sin(\phi), \quad whereby \quad F_y = a_y \times m. \tag{5}$$

Due to the moment of inertia of the oscillating mass J_z and the rotational acceleration α_z around the z axis, the torque M_z around the z axis is

$$M_z = J_z \times \alpha_z. \tag{6}$$

Afterward, the angular acceleration of the oscillating mass α_u can be determined as follows:

$$\alpha_u = \frac{M_x + M_y + M_z}{J_z}. \tag{7}$$

From the angular acceleration α_u and the fixed time step t, the new angular velocity ω and the new angle of rotation ϕ can then be calculated with the current angular velocity ω' and the current angle of rotation ϕ',

$$\omega = \omega' + \alpha_u \times t, \tag{8}$$

$$\phi = \phi' + \omega' \times t. \tag{9}$$

Table III shows the results for the second mathematical modeling.

In order to use as much energy as possible from the generator or to store it in a battery, a power conditioning circuit is required. This power conditioning circuit needs to be designed consistently with the electric characteristics of the generator and battery to achieve maximum power transfer and efficiency.[16] To store the alternating voltage from the generator in a battery, it must first be rectified. A commonly used circuit consists of a diode rectifier and an interface bucket capacitor, also referred to as a direct charging circuit. When the output voltage from the BEH generator is sinusoidal, as in our case, a half-wave rectifier circuit with center tap may be used. When supplied with a sinusoidal generator voltage V_G, the output DC voltage of this circuit V_{out} can be calculated with the forward voltage of the diodes V_F according to the following equation:

$$V_{out} = 2 \times \left(\sqrt{2} \times V_G - V_F\right). \tag{10}$$

Compared to a standard direct charging circuit, this circuit rectifies both half-waves of the sinusoidal output voltage. Due to the unavoidable voltage drop at the rectifier diodes, the resulting output voltage is lowered. The diodes conduct only when the input voltage V_G is higher than the output voltage V_{out} plus the forward voltage of the diodes V_F. Furthermore, the diodes conduct only for a very short time at a time and the voltage across the output capacitor fluctuates widely, resulting in a low efficiency. A simple rectifier circuit is therefore not suited for efficiently harvesting energy from our generator. For maximizing power transfer, a different approach by using switching converters is selected.

Several integrated circuits that are specifically designed for energy harvesting applications are currently available on the market.

TABLE III. Simulation results for the BEH device with the ultra-low power conditioning circuit.

Number	Energy output (mWs)	Power output (μW)
1	5.059	843
2	4.679	780
3	4.526	754

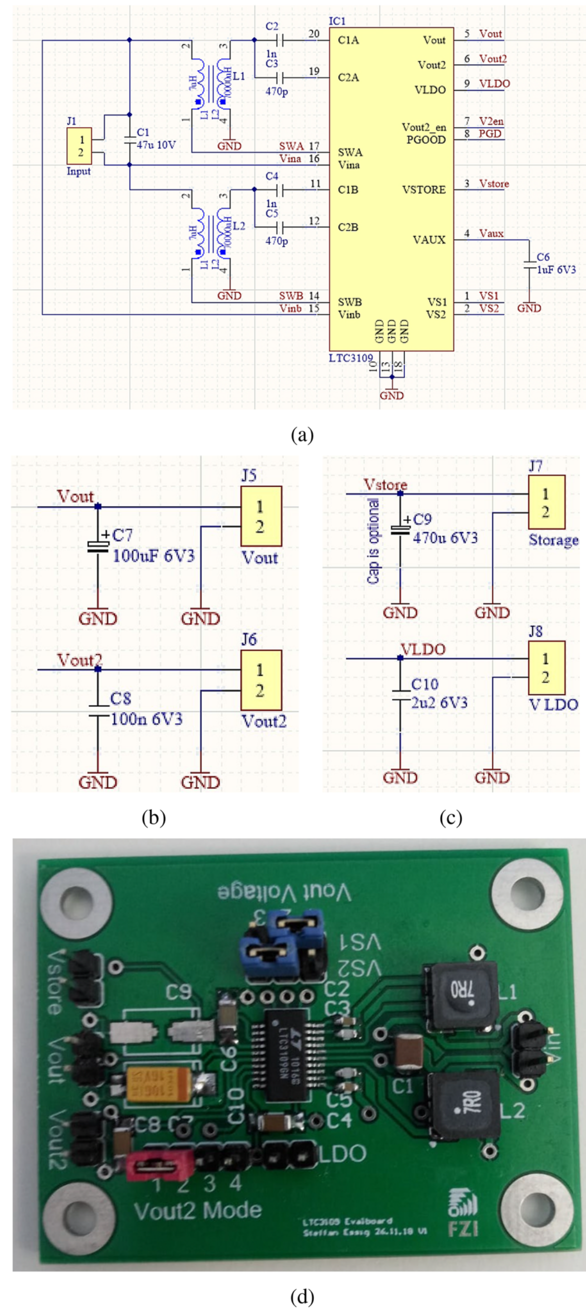

FIG. 4. (a) Circuit diagram for the ultra-low voltage power conditioning circuit. Once the input voltage is high enough, V_{out} will slowly charge the output capacitor to the selected voltage. (b) and (c) The behavior can be selected via the jumper. (d) shows the power condition circuit.

TABLE IV. Summary of the test setup results for the rms values for voltage, current, and power with a load resistance of 8.2 Ω.

Movement	V_{rms} (mV)	I_{rms} (mA)	P_{rms} (mW)
Walking	168	7.64	1.283

However, most of them were developed for industrial applications and require a higher starting voltage (>330 mV). By now, only a very few DC/DC step-up switching converters like the parts LTC3108 and LTC3109 (Analog Devices, Wilmington, MA, USA) were designed for harvesting energy from lower input voltages. According to their data sheet, the starting voltage is specified as 30 mV DC.[21] Unlike the LTC3108 converter, the input voltage of LTC3109 can be bipolar. Therefore, an ultra-low voltage power conditioning circuit was developed, see Fig. 4, which is based on the LTC3109 power converter. On the test board, the jumpers and screw holes take up most of the space. The actual electronics is only as small as the diameter of the generator. Compared to the standard circuit diagram from the data sheet, jumpers instead of solder bridges are used to set the output voltage between 2.35 and 5 V.[21] The behavior of the V_{out2} output can be adjusted via the V_{out2en} input. LTC3109 uses a P-channel MOSFET to turn V_{out2} on and off. When on, the output voltages V_{out} and V_{out2} are connected. The circuit also provides an output to view the state of charge of the output capacitor. When 92.5% of the set output voltage is reached, the output P_{GOOD} switches to a logic high level and below 90% P_{GOOD} switches back to a logic low level. This behavior of the output P_{GOOD} can be used in connection with the input V_{out2en} to switch a load on and off depending on the output voltage without further wiring of the board. The behavior of the circuit, respectively, of the output V_{out2} can be set via the jumper V_{out2} mode. It is crucial that all ceramic capacitors have X7R as the dielectric for low leakage current. The output of the function generator and the inputs of the oscilloscope are grounded, and the current transformers are not electrically isolated from the primary to the secondary side. The polarity of the measured currents or voltages must be checked after the measurement and adjusted if necessary.

A sinusoidal voltage with 37.1 mV rms (8 Hz) is applied as input voltage V_{in} for the step-up converter. The output voltage V_{out} is set to 3.3 V. A 470 μF capacitor is connected to the output V_{out} of the circuit. In addition, the V_{out2} output of the circuit is connected to a red LED (forward voltage 2.0 V) with a resistance of 2.2 kΩ. For the step-up converter circuit, an energy input of 2.96 mWS and an energy output of 0.198 mWs is determined. For an input voltage of 100 mV and by using transformers with a turn ratio of 1:100, the efficiency can reach up to 35%.[21] An experimental test setup is designed to experimentally simulate the arm movements of a human being and thereby verify the MATLAB simulation and the results according to Table II. Table IV shows the experimental results with a load resistance of 8.2 Ω, which represents the consumer. The BEH device reaches for walking movement an rms power of ~1.3 mW.

Finally, the BEH device was worn on the wrist or ankle of the body during walking motion and three different jogging speeds. The output voltage and current of both the BEH generator (V_1 and I_1) and the ultra-low voltage power conditioning circuit (V_2 and I_2) were determined according to Table V.

Figure 5 shows the results of the oscilloscope for fast jogging motions with the BEH device worn on the wrist.

The basic principle for the generator design is simple and thus robust because there are few moving parts, in total only four main parts, and there is no gearbox with frictional losses. For the generator, the brushless motor, which has in general very low wear, has to perform a bi-directional rotation. There is only minimal extra load on the bearings from the oscillating mass. Even with bi-directional rotation, this will not have a significant negative effect on the longevity of the motor. There are deviations between the simulation and experimental results for calculating the expected voltage produced by the generator and oscillating mass. This may be due to the following reasons: in the equation of motion, the starting torque is considered to be a constant applied torque, which means that the load torque, which counteracts the moment of inertia, is much higher than in reality. It was not taken into account that the motor becomes more light running after overcoming this starting torque. Furthermore, no second joint is incorporated for the experimental setup in the lever arm to simulate an elbow joint. Therefore, the simulation results are the minimum amount of energy produced by the BEH generator. The power conditioning circuit can also be adopted to higher input voltages than 500 mV by using transformers with a turn ratio of 1:50 or 1:20 instead of the previously installed transformers with a turn ratio of 1:100. Better simulation results can be achieved by outsourcing the code necessary for real-time calculations with control loop to a micro-controller

TABLE V. BEH device induced by real motions. Position 1 is before and 2 after the ultra-low voltage power conditioning circuit.

Movement: Speed (km h^{-1}) (position)	V_1 (V)	I_1 (A)	V_2 (V)	I_2 (mA)	P_2 (mW)
Walking: 2 (wrist)	0.68	0.11	1.75	1.75	3.06
Walking: 2 (ankle)	0.91	0.22	2.27	2.32	5.27
Jogging: 5 (wrist)	0.89	0.22	2.29	2.34	5.36
Jogging: 5 (ankle)	0.92	0.18	2.56	2.5	6.4
Jogging: 7.5 (wrist)	0.84	0.25	3.22	3.23	10.4
Jogging: 7.5 (ankle)	0.83	0.18	3.19	3.2	10.21
Jogging: 10 (wrist)	1.4	0.33	3.36	3.36	11.29
Jogging: 10 (ankle)	1.4	0.24	3.25	3.25	10.56

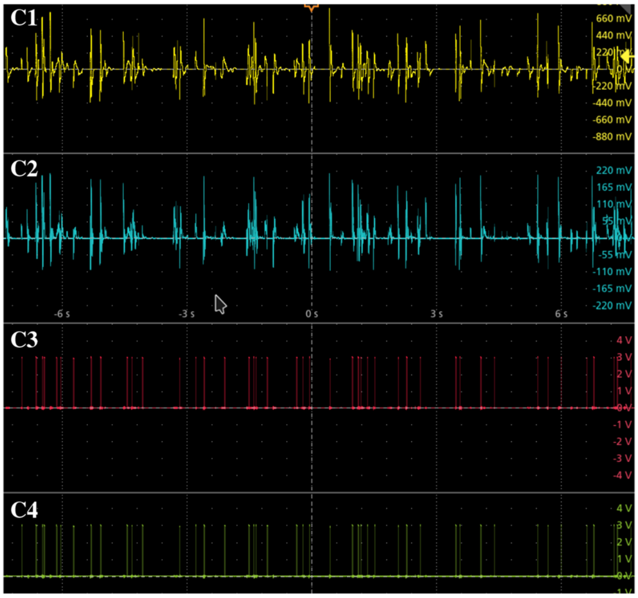

FIG. 5. Oscilloscope results for fast jogging motions. C1 and C2 represent, respectively, the alternating voltage and alternating current of the BEH generator, while C3 and C4 show, respectively, the direct voltage and direct current of the ultra-low voltage power conditioning circuit. C2 can be transferred with 1 mV mA^{-1} and C4 with 1 mV μA^{-1}.

instead of performing the calculations via MATLAB, due to a higher sampling rate. This allows the parameters to be set via MATLAB, but the actual control loop runs via a micro-controller that acquires the acceleration data, generates a new target torque, and applies the torque to the generator without much delay. In addition, torque control instead of speed control is an advantage, but this requires a redesign of the entire drive train, since the stepper motor control is unsuitable for fast and precise torque control. Although the achievable power outputs are currently still too low for a wide range of applications, this work nonetheless provides a foundation on which further simulations and developments can be based.

We developed a BEH device including a generator and an ultra-low voltage power conditioning circuit for arm and leg swinging motions. Thereby, the generator consists of only four parts and has a total weight of 176 g. Furthermore, we designed a test setup for the experimental evaluation and compared the results to the simulation. The expected voltage of the generator with a load resistance of 8.2 Ω, determined by a MATLAB simulation, results in a rms voltage between 30 and 87 mV for walking, jogging, and dancing movements. Furthermore, the BEH device yields a power output of ~11.3 mW during real arm jogging motions.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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