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A smart wearable device for capturing biomechanical energy from human knee motion

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Abstract—**Sustainable power supply is a challenge for portable and wearable electronic devices such as cell phones and headsets. To address this, researchers proposed capturing biomechanical energy from human motion to generate electricity. This paper proposed and developed a lightweight wearable device to capture the biomechanical energy from the human knee motion. To reduce the effect of inertial force on human gait, we developed a lightweight and compact transmission chain to convert the bidirectional rotation of the knee to a unidirectional rotation of the generator. Two input bevel gears with opposite one-way bearings on the same shaft are engaged with a single output bevel gear of the generator thereby only one input bevel gear is engaged for each input direction, achieving unidirectional output. In addition, to reduce velocity fluctuation and further minimize the effect of inertial force, a flywheel was fixed to the motor shaft via a gearbox. A prototype of the wearable device was developed and tested on a subject walking on a treadmill. Experimental results shows the flywheel enabled the harvester to achieve a continuous output while halving voltage fluctuations compared to a conventional harvester. The harvesters average power output can reach 0.11 W with minimal effects on the subject's walking gait.**

I. INTRODUCTION

Given the tight integration of electronic devices in modern society, the need for individuals to stay online throughout the day has become essential. This is further exasperated for individuals who relies on devices for their health being such as powered prosthetic users [1]. Current methods to power these devices relies on finite energy stored in batteries which limits its usability and the devices practicality. Instead, waste energy from human motion had been explored as a method to generate useful electrical energy on the go using wearable energy harvesters [2].

Compared to the other joints involved in walking, the abundance and high proportion of negative work at the knee joint had resulted in much interest in recent years [3]. Negative work refers to the dissipation or absorption of energy which in the context of the knee joint refers to the generation of a decelerating torque [4]. By using an energy harvesting device with smart material or electromagnetic generator [5] to provide this deceleration torque, useful energy may be extracted while reducing the effort from the user [3, 6].

Harvesting using smart materials involves the bending or rubbing of materials such as PZT [7], macro fibre composite (MFC) [8], and carbon nanotubes [9]. As the natural output of smart materials are relatively small [10], mechanisms were added to enhance the degree of bending over joints, such as with a slider crank mechanism [8]. To further increase power output to directly provide charge to electronic devices, electromagnetic generators are typically used instead [11]. However, due to the higher overall force involved with electromagnetic generators, effective strategies are needed to prevent hindering the user [3].

Cervera et al. [12] utilized an algorithm to determine the state of the gait and turn the harvest generator on or off depending on whether negative or positive work is done. However, this device rigidly connects the generator to the knee joint therefore the reflected inertial torque from the deceleration and acceleration of the generator during direction switching will need to be actively compensated by the user, increasing user effort. Furthermore, the generator output voltage would fluctuate significantly with knee angular velocity, resulting in an unstable power output. On the other hand, the knee brace energy harvester by Donelan et al. [13] utilized a one-way clutch to ensure only knee extension motion engages the generator, while allowing free knee flexion motion. This ensures the generator rotates in a single direction and eliminates inertial torque from directional changes. A similar one-way bearing approach was utilized by our cable driven knee energy harvester [14], but instead harvested during knee extension motion and relied on a variable radius drum for torque matching and avoid positive work.

Developing on this, Chen et al. [15] proposed a harvester which uses two one-way bearings mounted in opposite directions to convert the bidirectional motion of the knee to a unidirectional rotation of the generator. This allows harvesting to occur during both flexion and extension phases, increasing the potential power output. Similarly, Wu et al. [16] showed such mechanism can harvest energy while improving the metabolic cost of walking when compared to not harvesting. However, both these solution uses a double multi-stage gear

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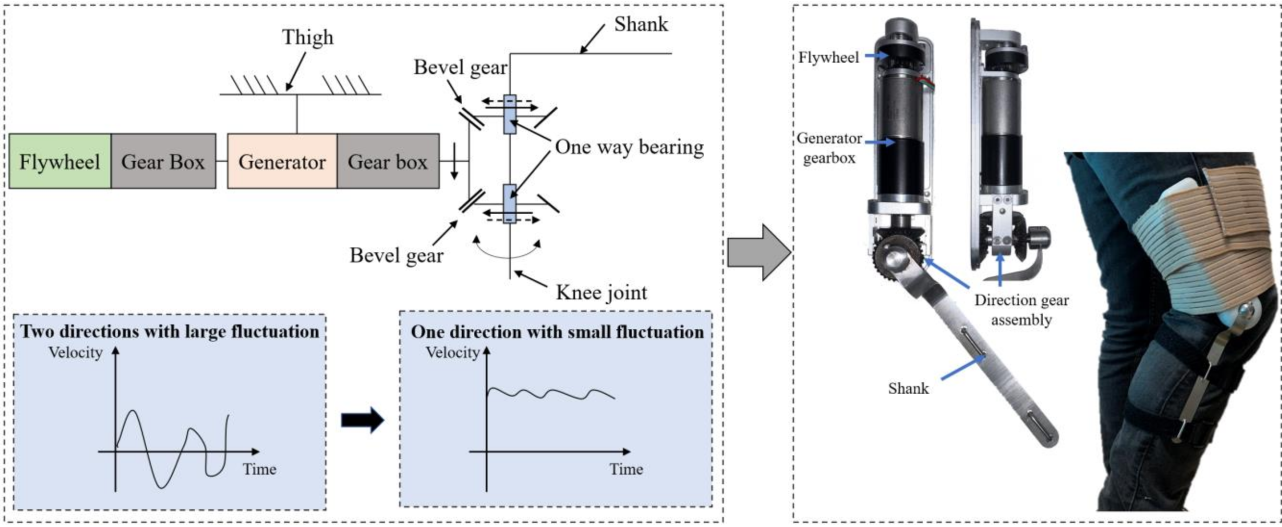

Fig. 1 (a) Schematic of the knee energy harvester and the desired outcome of the flywheel design (b) Harvester prototype layout and mounted on leg

transmission assembly to achieve rectification which increases complexity and weight while lowering efficiency.

While the rectification reduced inertial effects from directional changes, the harvesters output voltage and hence rotational velocity drops to zero for parts of the stance phase [4]. Therefore, a large input torque would be required to accelerate the generator during early swing flexion [17]. Considering the work in this period is positive, it may cause additional burden on the user. Additionally, the resulting voltage fluctuation would require a complex harvesting circuit with stored energy to maintain a constant output to charge mobile devices while putting an expected loading on the generator. Addressing these inefficiencies, this paper proposes a bidirectional knee mounted energy harvester with lightweight and compact rectification mechanism and flywheel mechanism. The main novelty of this harvester is twofold. Firstly, the simple rectifying mechanism uses only three bevel gears in a single stage configuration to convert the bidirectional knee motion to a unidirectional rotation of the generator, a mechanism that is more compact and efficient than the two-stage rectifier of previous harvesters. Secondly, a flywheel is integrated to the motor generator to increase its inertia thereby utilizing its momentum to enable the continuous rotation of the generator especially during the stance phase when the knees angular velocity is low. This momentum would reduce the output fluctuations over a gait, allowing a continuous and consistent power output for true on the go power delivery to devices while requiring a simpler and more efficient harvesting circuit. Further, the continuous rotation allows the positive work involved in early swing flexion to be avoided as the system would not engage until the knee reaches a certain angular velocity where negative work would be dominant, thereby increasing metabolic efficiency.

The layout of this paper is as follows. Section II describes the key workings of the harvester and details of the harvester prototype developed. Section III includes the modelling and simulation of the harvesting system. Section IV describes the experimental evaluation of the harvester system, including testbench and human subject testing. Section V finally concludes the paper.

TABLE I. SPECIFICATION OF PROTOTYPE

Parameter	Value
Weight	790 g
Generator model	Maxon EC-I 30, 539472, 30W
Generator speed constant	775 rpm/V
Generator torque constant	12.3 mNm/A
Generator terminal resistance	0.434 Ω
Generator moment of inertia	7.3 gcm^2
Generator gearbox ratio	132:1
Generator gearbox inertia	0.7 gcm^2
Flywheel gearbox ratio	1:1.57
Flywheel moment of inertia	240 gcm^2

II. DESIGN OF THE KNEE ENERGY HARVESTER

A. *Principle of transmission*

The schematic of the bidirectional energy harvester with flywheel mechanism shown in Fig. 1(a) outlines the working principle of the energy harvesting system. From the right, a bar link extending to the shank is used to transfer the effective knee torque to the single stage rectifying mechanism. This consists of a central shaft where two input bevel gears with opposite one-way bearings in its centre are mounted and are engaged to either side of a central output bevel gear on the generator gearbox output. As the shaft is rotated in one direction, one of the bevel gear locks while the other free spins, thereby rotating the output shaft in one direction. When the input shaft rotates in the other direction, the bevel gear previously locked disengages and the free spinning gear locks. As the input bevel gears are oppositely mounted, this allows the direction of torque transmission to remain the same on the output bevel gear, thereby achieving directional rectification.

The flywheel assembly is mounted to the back of the generator on the through shaft. A gearbox is placed between the flywheel and generator to tune the effective moment of inertia of the flywheel. While the flywheel keeps the generator in motion during low knee velocity phases, it contributes to a higher inertial torque when the input accelerates. Therefore, careful tuning is required to ensure the system torque is kept below the natural torque of the knee or additional effort will be required by the user [3].

B. Prototype

The prototype of the energy harvester is shown in Fig 1(b). The components on the central shaft including the three bevel gears, forming the direction gear assembly, are mounted to the thigh base assembly whereas the bar link is attached to the shank. This thin steel link can be twisted or bent except in the sagittal, allowing high flexibility of knee motion and prevent parasitic forces on the knee. The harvester is held using curved flexible polypropylene strips and elastic bands on the thigh, and Velcro bands on the shank, to ensure a comfortable yet strong mounting on the leg which prevents slipping during use while allowing adaptability to users of different height and size. A summary of the components are given in Table I.

III. Modelling of Harvester

A. Modelling of ideal harvester system

During the moments when the bevel gears are engaged, the angular velocity of the input is equal to the magnitude of the knee's angular velocity. However, this condition is only valid when torque is transferred through the bevel gears. In the case where the angular velocity of the driven bevel gear is higher than the driver, both bevel gears are disengaged, therefore

$$\dot{\theta}_o = |n_b \dot{\theta}_k| \ \ when \ \ \dot{\theta}_o = n_b \dot{\theta}_k \quad (1)$$

$$\tau_o = \begin{cases} 0 & when \ \ \dot{\theta}_o \geq n_b \dot{\theta}_k \\ \tau_k & when \ \ \dot{\theta}_o = n_b \dot{\theta}_k \end{cases} \quad (2)$$

where $\dot{\theta}_o$ is the angular velocity of the output of the generator flywheel assembly, n_b is the gear ratio of the bevel gears, $\dot{\theta}_k$ is the angular velocity of the knee, τ_k is the effective torque of the harvester on the knee joint, and τ_o is the torque at the output of the generator flywheel assembly. The output torque, τ_o, is dependent on two factors, the inertial torque, τ_i and the electromagnetic torque from the generation of electricity, τ_g, given by:

$$\tau_o = \tau_i + \tau_g = \left(J_{gb} + n_g^2(J_g + n_f^2 J_f)\right)\ddot{\theta}_o + n_b n_g K_t i \quad (3)$$

where J_{gb}, J_g, and J_f is the inertia of gearbox, generator, and flywheel respectively, n_g and n_f is the gear ratio of the generator and flywheel respectively, $\ddot{\theta}_o$ is the angular acceleration of the output, K_t is the generator torque constant, and i is the induced current. The frictional damping force is considered negligible based on the dominance of electrical damping. The induced current can be determined by the back electromotive force (V_{EMF}), which is given by:

$$V_{EMF} = \frac{n_b n_g \dot{\theta}_o}{K_v} = K_t n_b n_g \dot{\theta}_o \quad (4)$$

where K_v is the speed constant of the generator. The electrical circuit of the generator with a load resistor, R_L, is shown in Fig 2, where R_g is the internal resistance of the generator, and L_g is the inductance of the phase-to-phase inductance of the generator. Here, the load resistor is used to represent the output of the harvesting system. The inductance of the relatively

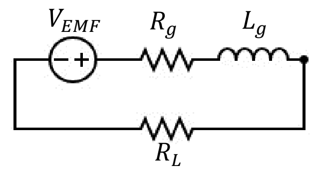

Fig. 2 Schematic of the knee energy harvester

small generators used in wearable harvesters are often negligible [16] and is therefore ignored to simplify the analysis. Therefore, based on the Kirchhoff's voltage law, the circuit voltage is given by:

$$V_{EMF} = (R_g + R_L)i \quad (5)$$

Combining equation (4) and the simplified (5), the output current of the electrical system is given by:

$$i = \frac{n_b n_g K_t \dot{\theta}_o}{R_g + R_L} \quad (6)$$

Applying (6) to (3), the dynamics of the ideal generator flywheel assembly is given by:

$$\tau_o = A\ddot{\theta}_o + B\dot{\theta}_o \quad (7)$$

$$A = \left(J_{gb} + n_g^2(J_g + n_f^2 J_f)\right); B = \frac{K_t^2 n_b^2 n_g^2}{R_g + R_L} \quad (8)$$

Furthermore, the power output of the generator at the load can be determined by

$$P_L = \frac{n_b^2 n_g^2 K_t^2 \dot{\theta}_o^{\,2} R_L}{(R_g + R_L)^2} \quad (9)$$

B. Simulation of harvesting system

The system dynamics is modelled by including a frictional damping component to (7), converting the dynamics to:

$$\tau_o = A\ddot{\theta}_o + (B + \mu)\dot{\theta}_o \quad (10)$$

where μ is the friction coefficient of the generator gear system which is arbitrarily estimated as $\mu = 0.1$. To simulate the system response, the knee kinematics of a healthy male subject was first determined using the VICON motion capture system, giving $\theta_k(t), \dot{\theta}_k(t)$ and $\ddot{\theta}_k(t)$. Solving the linear differential equation for generator output
angular velocity, the response of the system when left to free spin is determined by:

$$\dot{\theta}_o = C_2 r_2 e^{r_2 t} \ when \ \dot{\theta}_o > n_b \dot{\theta}_k \quad (11)$$

where $r_2 = -(B + \mu)/A$. C_2 is determined by the initial condition of the instance in which the generator begins to free spin. This is found numerically by finding the output shaft speed at time $\Delta t = 0.001\ s$. If the resulting speed is greater than the input speed $n_b \dot{\theta}_k$ indicating a free spinning condition, C_2 is determined at that instant and the response is applied until

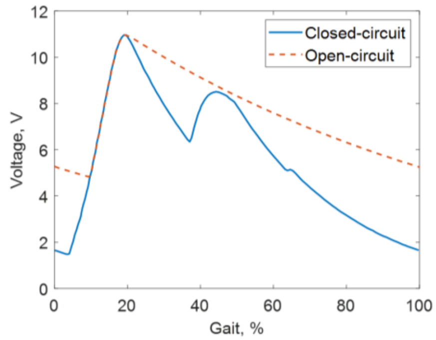

Fig. 3 Simulated harvester output voltage in open-circuit and closed-circuit mode with a 10 Ω load

a time in which the output shaft speed is lower than the input where (1) is applied.

Based on the specification of the prototype outlined in Table I, the resulting system output over a walking gait is shown in Fig. 3. In both open and closed-circuit mode, the generator and flywheel achieved the desired effect of remaining in motion throughout the gait cycle.

IV. Experiments

The evaluation of the harvester was conducted in three separate experiments. A testbench was first used to simulate the harvester over a walking gait to evaluate the torque and power output system. This was followed by on subject evaluations, first analysing the effectiveness of the flywheel in maintaining continuous motion compared to a conventional system. Then, a gait analysis was performed where the impact of harvesting and output power were evaluated.

A. *Testbench evaluation*

The testbench setup to evaluate the energy harvester is shown in Fig. 4. A large servo motor to the right is used to rotate the output shaft of the knee harvester following the gait trajectory as mentioned in Section III-B. To measure the harvester's system dynamics, a torque sensor (T27 Hollow Flange, Interface Co., USA) is placed between the servo motor and harvester. A PC running a custom program was used to control the servo motor and collect torque sensor information. To measure the electrical output of the harvester, an oscilloscope is connected to the output of a three-phase full bridge rectifying circuit.

Three scenarios were used to evaluate the system, including open loop, closed loop, and no generator. For each scenario, the servo motor performs 10 continuous gait cycles three separate times for a total of 30 gait cycles. The results were then separated into individual gaits, normalized, and averaged. For the open loop case, no electrical load is applied to the output of the rectifier whereas for the closed loop case, a 10 Ω load resistor is applied and the voltage over the load is measured. In the no generator case, the harvester is disconnected with only the torque sensor, servo motor, and the connecting shafts attached, allowing the inertial torque of the testbench setup over a gait cycle to be determined. Hence, by eliminating the testbench inertial torque from the torque

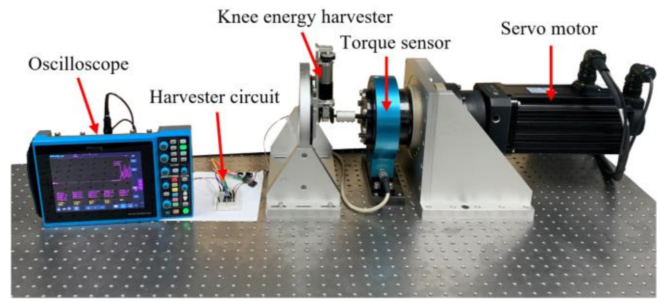

Fig. 4 Setup of the harvester testbench

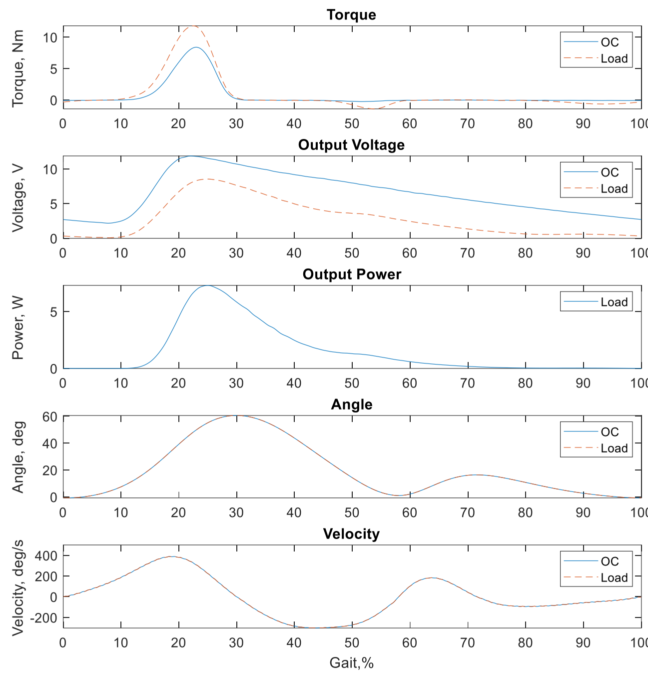

Fig. 5 Output of the harvesting system over a gait

profile of the open and closed loop cases, the torque of only the harvester can be found, as shown in Fig. 5.

Similar to the simulation result, peak generator reaction torque and peak voltage occurred at the swing flexion phase, with a maximum value of 11.8 Nm/8.4 Nm and 8.5V/11.9 V for the closed and open-circuit cases, respectively. For the closed-circuit case, this corresponds to a peak power output of 7.2 W and an average output of 1.5 W over a gait. Furthermore, like the simulation, only one peak is noticed during swing flexion with inertial rotating keeping the generator from engaging whereas two engagement is noticed with the closed-circuit case. However, while the generator stayed in motion throughout the gait in closed-circuit mode, the engagement during swing extension was less significant than the simulation which may have caused the voltage to reach a minimum of 0.1 V.

In order to efficiently harvest energy from human motion, the harvesting torque should be kept below the natural torque of the wearer [3]. This was achieved as the the peak reaction torque during harvesting was kept below the natural torque experienced at the knee over the swing flexion phase [4], suggesting the harvester would not require additional positive effort from the user to harvest energy.

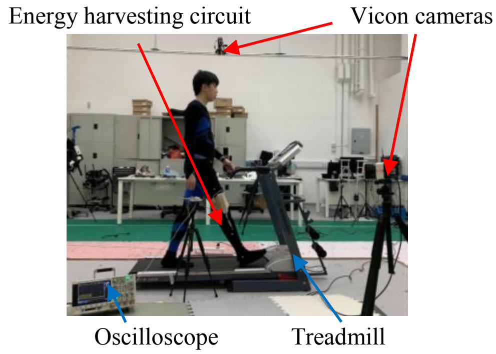

Fig. 6 Experimental setup for harvester evaluation

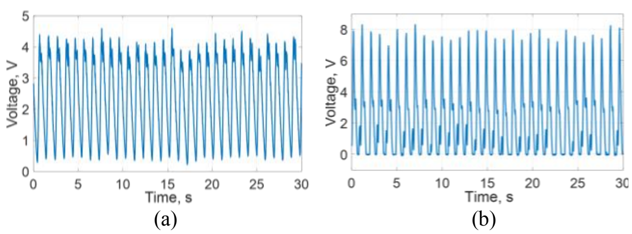

Fig. 7 Open-circuit voltage after rectification when walking at 6 km/h with (a) flywheel and (b) conventional harvester

B. *Flywheel effectiveness evaluation*

The effectiveness of the bidirectional energy harvester was evaluated on a human test subject (Male, 25 y/o, 72kg, 186 cm) with the setup shown in Fig. 6. The subject was tasked to walk on a treadmill at 6 km/h with the harvester attached on the knee joint and the harvest circuit in open-circuit mode. A full bridge rectifier using Schottky diodes was used to rectify the output from the generator and an oscilloscope was used to measure output the output voltage of the rectifier. The subject was asked to walk for two minutes, and only the gait of the last 30 seconds were used for analysis to allow the subject to acclimate to the walking condition. To demonstrate the flywheels effectiveness, this experiment was repeated with the flywheel removed, representing a conventional setup.

As shown in Fig 7, the target of maintaining continuous rotation of the generator throughout the gait cycle with the flywheel mechanism was demonstrated. The open-circuit voltage was kept above 0 V, with a minimum of over 0.22 V, indicating a non-zero rotational velocity of the generator. This is compared to a conventional harvester, where the voltage drops to zero for over 26% of the gait. Further, the voltage fluctuation of the proposed solution was half that of a conventional harvester with a peak-to-peak of about 4 V compared to about 8.2 V, and an average voltage of 2.34 V compared to 2.22 V with conventional. Therefore, compared to a conventional harvester, the flywheel was able to effectively regulate the voltage output of the harvester to ensure a positive output throughout the gait cycle while significantly reducing voltage fluctuations.

C. *Energy harvesting evaluation*

The variation of the walking gait in terms of stride rate, range of motion, and general variations to natural gait had shown to be associated with an increase in walking demand [18-20]. Therefore, to determine the effect the proposed harvester has on the walking gait, further evaluation is

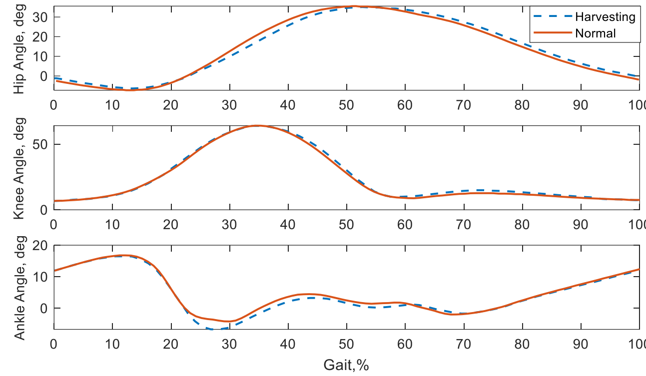

Fig. 8 Lower limb kinematics while walking at 4 km/h with and without the harvesting system

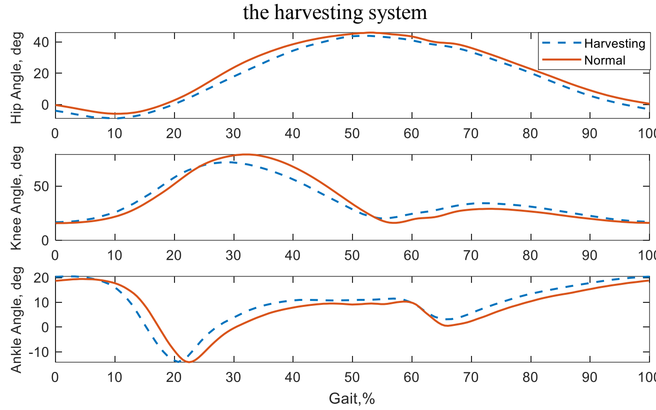

Fig. 9 Lower limb kinematics while walking at 6 km/h with and without the harvesting system

conducted with a motion capture system. The subject is tasked to walk with the harvester at 4 km/h and 6 km/h on a treadmill for 2 minutes and only the last 30 seconds is analysed to allow the subject to acclimate to the condition. An 18-camera Vicon motion capture system (VICON, Oxford, UK) and the built-in Plugin Gait model was used to measure the gait kinematics of the subject at the hip, knee, and ankle based on reflective markers placed on the lower limb of the subject. The kinematic data over the 30 seconds are first separated into individual gait cycled based on knee cycle indices, then normalized to percentage of gait cycle and averaged.

For each speed, the subject walked with and without the harvester, defined as *harvesting* and *normal* walking, respectively. A 10 Ω load resistor was connected to the output of the harvesting circuit and the voltage over this resistor is measured with an oscilloscope to determine the power output.

Comparing the joint angle profile when walking at 4 km/h in Fig. 8, the harvester caused only minor affects to the users' gait. The root mean square error (RMSE) between *harvesting* and *normal* was less than 1.7^{o} for all three joints, as shown in Fig. 10. Pearson's correlation coefficient for all three joint is above 0.993, suggesting high correlation between the *harvesting* and *normal* gaits. Furthermore, as outlined in Table II, only minor difference was noticed with the step frequency and range of motion. These observations occur as the harvesting circuit outputs an average power of 0.076 W and peak of 0.67 W.

Slightly greater influence from the harvester was noticed when walking at 6 km/h, though the overall difference remains small, as shown in Fig. 9. A shift in the knee and ankle profile to the left was noticed with *harvesting* compared to *normal*,

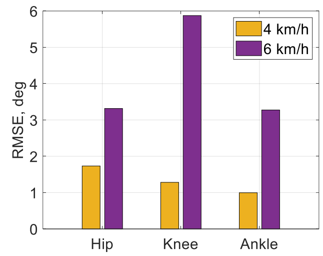

Fig. 10 Root mean square error between harvesting gait and normal gait

TABLE II. GAIT KINEMATICS AT 4 KM/H

Condition	Step frequency (Hz)	Range of motion (º)		
		Hip	***Knee***	***Ankle***
Load	0.839	41.0	56.7	23.3
Normal	0.836	42.5	57.1	21.1

TABLE III. GAIT KINEMATICS AT 6 KM/H

Condition	Step frequency (Hz)	Range of motion (º)		
		Hip	***Knee***	***Ankle***
Load	0.988	52.5	55.4	34.6
Normal	1.009	51.4	63.4	33.5

with an overall RMSE of 5.8º and 3.2º for the knee and ankle, respectively. Similarly, a slight upward shift of the hip profile during harvesting led to a RMSE of 3.3º. Despite this, the Pearson's coefficient remained high at 0.998, 0.973, and 0.938 for the hip, knee, and ankle, respectively. As shown in Table III, the step frequency remains relatively unchanged. Likewise, the difference in the range of motion of the hip and ankle remained small at 1.1º for both joints. A higher reduction in knee joint range of motion was noticed at 8º. Despite this, a higher power output was noticed with an average power of 0.11 W, and peak of 0.73 W.

Overall, the gait analysis identified that the energy harvester with flywheel integration had minimal impact on the gait of the subject. A higher walking speed showed slightly higher impact to the gait, though the overall impact remains small. In terms of power output, the 50% increase in walking speed increased average power output by 44% while peak power increased by just 9.5%. This may suggest a greater mismatch between the generators input and knee motion as velocity and hence torque increases. Therefore, to improve the effectiveness of the harvester at higher speeds, a more rigid mounting method may be required.

V. CONCLUSION

In this paper, a bidirectional knee energy harvester with a flywheel mechanism was proposed to effectively harvest energy and minimize the effect of the harvester on the walking gait while walking. This harvester implemented a compact single stage rectifying mechanism to convert the bidirectional rotation of the knee to a unidirectional rotation of the generator, allowing harvesting to occur during both flexion and extension moments. A flywheel mechanism was mounted to the generator to ensure continuous output while maintaining a more stable voltage with lower fluctuations. Testbench evaluation verified the reaction torque of the harvester was kept below the natural knee torque. Further evaluation of the harvester on a human test subject showed, compared to a conventional harvester, the flywheel enabled the proposed harvester to continuously spin for continuous voltage output while halving the fluctuation in output voltage. This was achieved while the gait analysis showed only minor effects on the gait by the harvester and no influence on step frequency was noticed. On the other hand, the harvester can output an average power of 0.11 W while walking at 6 km/h, sufficient to power mobile devices such as GPS trackers and smartwatch or stored to power mobile phones. To further improve the effectiveness of the harvester, optimization methods will be implemented to determine the ideal flywheel inertia, generator, and gearbox selection for a balance between output power and inertial torque, thereby increasing power with minimal impact on the user.

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