Development of an Energy Harvesting Backpack and Performance Evaluation

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***Abstract*—A biomechanical energy harvesting backpack that generates electrical energy during human walking is presented. This device differs from previous designs because it integrates motion from both lower limbs into a single mechanical drive train. The energy harvesting backpack produced an average of 15 W of electricity during walking at a speed of 1.2m/s. It was found that approximately one quarter of the total mechanical work harvested was from the negative work performed during walking. This technology could potentially be used to power portable biomedical devices.**

I. Introduction

In the past decade, society has become increasingly dependent on portable electronic devices [1]. These devices have almost exclusively been powered by batteries, but due to the limited energy per unit mass of batteries, the performance and duration of operation of these devices have been constrained. Substantial improvement to the performance or operating time of portable devices, while avoiding the unattractive solution of heavier batteries, requires an alternative to current battery technology [2]. Recent advances in the field of energy harvesting have led to the development of efficient and sustainable technologies that are capable of collecting mechanical energy produced by human motion. Such technologies present an alternative to the current electrical power supplied by either batteries or fuel cells.

Various devices have been developed to harvest energy from human motion through capturing kinetic energy from movement and converting it into electricity [3]. These existing devices can be grouped into three categories based on the principle used in their energy conversion: (a) Inertia-based harvesters, (b) Impact force-based harvesters, and (c) Motion-driven harvesters. The inertia-based harvesters use the inertia force of a proof mass; Impact force-based harvesters use the forces from a large moving mass (e.g. body weight) and motion-driven harvesters harness electricity from limb motion. The inertia-based harvesters designed by [4] generates the largest amount of power. This device used a suspended-load backpack, that captures the up-and-down motion of the carried load during walking to drive a rotary-magnetic generator. It produced approximately 7.4 W (electrical) from a 38 kg load during fast walking and approximately 0.5 W electrical at more modest loads and walking speeds. The two most popular impact force-based harvester designs capture the energy dissipated during heel collisions. One design used a magnetic rotary generator that generated 250mW [5] and the other used dielectric electro-active polymer that generated 800mW electrical [6].

The most promising energy harvesting method is the motion-driven harvester. By recognizing the human muscles are the origin of the mechanical work performed during human movement, this harvesting technology directly captures mechanical energy from lower limb motion during walking. The best motion driven harvester was designed by [7], [8], who developed a knee-mounted energy harvester with a brushless DC rotary magnetic generator for producing electricity. This harvester was designed to harvest energy from leg deceleration in each gait cycle with a control system regulating the timing of when power generation occurs. This mode of energy harvesting is similar to the regenerative braking found in hybrid cars. A pair of these harvesters generated 5W electricity during walking at a speed of 1.5m/s, during which 1W of metabolic power was required from the user to produce 1W of electrical power. The metabolic cost of this type of harvesting is much lower than traditional human power generation [9].

Of the aforementioned energy harvesting technologies, the suspended load backpack and knee-mounted energy harvester produced the largest amount of power (5-10W), making them suitable for powering portable devices with a higher power requirement. However, these technologies still have several limitations. The major limitation of the spring-loaded backpack is the requirement for a heavy load to produce desirable levels of power, which places a considerable burden on the user. Furthermore, the up-and-down oscillation of the mass may disrupt the user's gait pattern and walking stability. Similarly, the knee-mounted device [7], [8] is limited by the addition of its mass on the knee. Since the metabolic cost of carrying a given mass distally from the subjects center of mass is considerably greater than that of carrying it proximally [10]. Walking while wearing the knee device without power generation increases the energy expenditure by 20% when compared to walking without the device. Additionally, the extrusion of the device to the lateral sides of the knee could potentially hinder the movement, agility, and comfort of the user.

The requirement to produce useful amounts of electricity, while avoiding substantial load or user discomfort necessitates a new energy harvesting technology. In this paper, the feasibility of harnessing the energy of the entire lower limbs during walking is evaluated. A new lower-limb driven energy harvesting backpack prototype is introduced and it's

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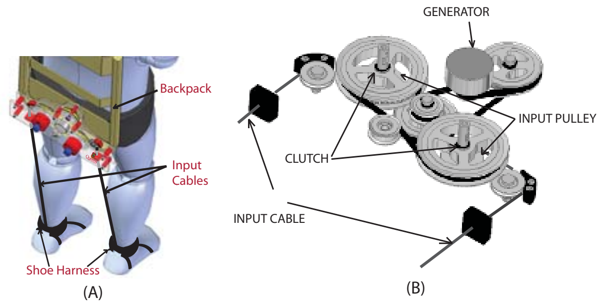

Fig. 1. (A) Energy harvesting backpack. (B) Components of the energy harvesting backpack.

performance and metabolic consequences are examined.

II. Energy Harvesting Backpack Modeling

Motion-driven energy harvesting backpacks harvest energy using the user's lower limb motion. This is accomplished by initially capturing the changing linear displacement between the backpack and the user's feet using two independent cables (Fig.1(a)).

To predict the amount of electrical power produced and the associated load exerted on the user, a model of the energy harvesting backpack was developed. The energy harvesting backpack has three main design parameters which are: the gear ratio, the generator, and the electrical load. These parameters allow for numerous different configurations of producing electrical power and mechanical resistance to the user. The mechanical resistance imposed on the user by the harvester is the summation of the resistive loads produced by the mechanical and electrical systems.

During walking, there is a relative cyclic movement between each foot and the trunk (Fig. 4(a)). This cyclic linear displacement serves as an ideal source of mechanical power input for the energy harvesting backpack. To capture this motion, the proposed harvester design uses cables attached to shoe harnesses. The cable velocity is the derivative of the cable length

$$V_c = \frac{\Delta S_c}{\Delta t} \tag{1}$$

where V_c is the cable velocity (m/s), S_c is the cable length (m), and t is time (s).

A unidirectional roller clutch mounted within the input pulley engages the gear train only when the cable is lengthening. The linear input velocity is then converted into rotational velocity through the input pulley and amplified through the gear train,

$$\omega_g = (V_c/r) \cdot r_t \tag{2}$$

where ω_g is the angular velocity of the generator, V_c is the input cable velocity, r is the radius of the input pulley, and r_t is the overall gear ratio of the drive train.

The line-to-line voltage produced by the generator is calculated as

$$E_g = \frac{\omega_g}{K_g} \cdot \sqrt{3} \tag{3}$$

where K_g is the electromotive force (EMF) constant (v/rpm) provided by the manufacturer. The EMF constant is dependent on the dimension of the motor winding, the number of winding turns, and the strength of the magnetic field of the generator. The three-phase voltage from the generator is rectified using a full-wave rectification circuit before it is applyed to an external load resistor.

The current is determined by equation

$$I_l = \frac{E_g - 2 \cdot E_d}{R_l + R_g} \tag{4}$$

where R_l is the electronic load, R_g is the generator internal resistance, and E_d is the forward voltage drop (V) of the rectifying diodes used in the full-wave rectification circuit.

When generating electrical power, the generator produces a reaction torque that acts on the gear train.

$$T_g = I_l \cdot K_t \tag{5}$$

where K_t is the torque constant ($N{\cdot}m/A$), and I_l is the current (A).

The reaction torque, T_p, that is applied at the input pulley is amplified by the gear train

$$T_p = T_g \cdot r_t \tag{6}$$

In addition to the reaction torque (T_p) acting on the input pulley, input torque T_a is required to accelerate or decelerate the gears and the generator rotor, which is calculated as

$$T_a = J_a \cdot \alpha_I \tag{7}$$

where J_a is the apparent inertia at the input pulley and α_I is the angular acceleration of the input pulley.

The total input torque T_i at the input pulley is the sum of the toque required to produce electricity and drive the mechanical components

$$T_i = (T_p + T_a)/\eta_t \tag{8}$$

where η_t is the overall mechanical efficiency in the gear train. This efficiency depends on the input cable speed and electrical load, which varies during different periods of the gait cycle.

With the total torque on the input pulley, the required force on the cable is calculated as

$$F_c = T_i/r_i \tag{9}$$

where r_i is the radius of the input pulley.

The electrical power harvested is calculated as

$$P_e = \frac{E_l^2}{R_l} \tag{10}$$

To generated the electrical power P_e, the input mechanical power for the harvester is

$$P_m = F_c \cdot V_c \tag{11}$$

The overall efficiency of the energy harvester is calculated as the ratio between the generated electrical power and the required input mechanical power

$$\eta = \frac{P_e}{P_m} \tag{12}$$

The overall efficiency can be experimentally determined by measuring the input mechanical power and the electrical power production.

The overall efficiency of the energy harvester can alternatively be expressed as a combination of electrical power generation efficiency and the gear train efficiency,

$$\eta = \eta_g \cdot \frac{R_l}{R_l + R_g} \tag{13}$$

With a known power generation efficiency and the overall efficiency determined from Eq.12, the gear train efficiency can be estimated from Eq.13.

III. Device Design

The motion-driven energy harvester is designed to be mounted at the base of a standard backpack frame (Arucsystems, USA). The total weight of the system is 6.68kg (2.27 kg - harvesting device and 4.41 kg - backpack frame). This energy harvester consists of four major sub-systems: a lower limb motion-harness system, a gear train, two cable retrieval mechanism, and a power generation and conditioning unit (Fig. 1). The lower limb motion-harness system consists of two individual 5-point foot harnesses (Nautilus Inc. USA) attached to the users' shoes and two corresponding cables. These nylon coated, stainless steel wire input cables, feed into the input pulleys that connect to the gear train.

The gear train increases the speed and reduces the torque from the inputted mechanical energy generated movement of the user's leg. This conversion is achieved through three stages, with an overall gear ratio of 18:1. The first stage with a gear ratio of 3:1, is made up of a three-pulley system. This stage combines and amplifies the motion from each leg. The second and third stages have gear ratios of 3:1 and 2:1, respectively. The current prototype uses belts instead of gears to reduce the noise from previously designs that used spur gears. A innovative feature of this gear train is its ability to integrate the motion from both of the user's legs so that the desired electrical power can be produced by a single generator unlike the knee-mounted harvester that employed multiple generators [8]. Consequently, this design reduces weight and cost without sacrificing the amount of energy harvested.

The cable retrieval mechanism serves two functions: retracting the cables after each power generation cycle, which occurs during the swing phase of the gait cycle, and eliminating cable slack to prevent tripping risks. The two cable retrieval mechanism uses a constant force spring to maintain a constant tension level in the cable. These springs were chosen to provide a fixed amount of force to retract the cables and overcome the friction in the gear train. A constant force spring is advantageous over standard tension and compression springs because it exerts constant force irrespective of the spring extension. This feature reduces the fluctuation and magnitude of the force, especially at the end of cable extension.

The power generation and conditioning unit includes a miniature generator (EC-powermax 30 200Watt, Maxon Motor, USA) and a power conditioning unit. Together convert the mechanical energy from movement of the user's leg into usable electricity. Currently, the generated electricity is dissipated in a power resistor and the power conditioning is done with a full-wave rectifier. The amount of electrical power being harvested is adjusted by varying the electrical load in the power conditioning unit. This provides another option for generating larger amounts of power without increasing gear ratio.

IV. Performance Evaluation

The performance of the energy harvesting backpack was evaluated through bench-top testing and human walking experiments.

A. Bench-Top Testing

The purpose of bench-top testing was to evaluate the accuracy of the proposed harvester model in predicting the amount of electrical power generated and the associated reaction force on the user. The input motion profile was generated with a motor (Maxon EC-Powermax 30, Maxon Motor, USA) with a 23:1 gear ratio that drove one cable of the harvester. The input angular velocity to the generator was measured by the generators' quadrature encoder. The encoder pulse signals were collected using the quadrature encoder input on the data acquisition (DAQ) card (NI PCIe6353, National Instruments, USA). Angular velocity from the generator was used to calculate the linear velocity of the input cable. The angular acceleration was also calculated to estimate the forces due to the inertia of the system. The DAQ card also measured the voltage across the load resistor with a known resistance (10Ω), which was used to calculate the current and the amount of electrical power generated. To measure the amount of mechanical power input to the harvester, the reaction force on the cable was measured by a load cell (ATI Industrial Automation, Apex, North Carolina) mounted on the cable. The gear train efficiency is not constant and it is dependent on the input cable speed and the electrical load applied to the harvester. Therefore, the mechanical efficiency map was established under a set of combinations of these two parameters using Eq.12 and Eq. 13. With the efficiency map, the required pulling force on the cable can be predicted based on the model presented in Section II. The accuracy of the model was determined by comparing the model predicted force with the measured cable force from the load cell.

B. Human Subject Testing

Human walking experiment was performed to determine the amount of electrical power that the energy harvesting backpack could produce during walking and evaluate the metabolic consequence of the harvester on the user.

1) Subjects: Five young, healthy adults volunteered to participate in this study (5 male, mean age 24 (SD 3.0), mean mass 76.1kg (SD 13.3)). To their knowledge, none of the subjects had any injuries, past or present, that affected their gait. All subjects gave their informed consent in accordance with the policies of Queens University's General Research Ethics Board.

2) Experimental procedure: Data collection was conducted at the Human Mobility Research Center of Hotel Dieu Hospital, Kingston. Each subject participated in seven walking activities. The walking activities were conducted at 1.2m/s on a split-belt force instrumented treadmill (AMTI Force-Sensing Tandem Treadmill) which measured ground reaction forces. Prior to the treadmill trials, the subjects were given a five to ten-minute acclimation period, after which their resting metabolic power (RMP) during quiet standing was measured. Metabolic costs were measured during four walking activities with a resistance of 14Ω: (1) Normal walking. The user walked without wearing the energy harvester. (2) Weight-only. The user walked while wearing the energy harvester without the foot harnesses attached. (3) Mechanical engagement. The user wore the energy harvester with the foot harnesses attached, but electrical power generation was turned off by leaving the circuit open. (4) Electrical engagement. The user wore the energy harvester and generated electricity. Each trial lasted ten minutes with a three-minute rest in between. To further determine the relationship between the amount of power generated to the load resistance, there additional walking trials were performed at different electrical loads (10Ω, 18Ω, 22Ω; one load per trial). The metabolic costs were not measured during these trials. Each trial lasted two minutes. A three-minute rest period followed each trial. The order of the trials randomized.

3) Metabolic measurements: To measure energetic consequences of the energy harvesting backpack on the user, the rate of oxygen consumption and carbon dioxide production were measured using open respirometry (K^4b^2, COSMED, Italy). Metabolic power was calculated for each trial using the equation from [11]. Metabolic data from the third quarter of each trial was analyzed to allow the subject to reach steady state, and to prevent end-effects. The net metabolic increase was calculated by subtracting the resting metabolic power from the metabolic power calculated during each trial.

4) Electrical and Mechanical power: The electrical voltage applied to the load was measured using a data acquisition card (NI DAQCard-6024E, National Instruments, USA) and a custom-made Matlab Simulink script. The sample rate was chosen as 600Hz. The instantaneous electrical power was calculated using Eq.10. The average electrical power produced by the harvesting backpack was determined by averaging the instantaneous electrical power of 10 steps in the middle of a trial.

The instantaneous input mechanical power to the harvester was calculated as the product of the force applied to the cable and the relative velocity between the foot harness and the input pulley. A load cell (Nano 25, ATI Industrial Automation, USA) was mounted between the foot harness and input cable on the user's right leg to measure the force on the cable. Force data was acquired using the same data acquisition card with a sample frequency of 600Hz. The force data was filtered using a 2nd order zero-lag Butterworth filter with a cut-off frequency of 30Hz. The relative velocity was determined by calculating the derivative of the relative cable length. The relative cable length was determined using reflective markers on the foot harness cable attachment points and one at the cable insertion points on the harvester. These markers were tracked using a six-camera motion capture system (Qualysis Oqus, Gothenburg, Sweden). The relative cable length was calculated as the distance between the foot harness marker and the input pulley marker on backpack. The mechanical power was only calculated when the cable is lengthening because mechanical energy only flows into the harvester from the user during the period the cable is pulled. The instantaneous mechanical power P_m was calculated using Eq.11. The average input mechanical power to the harvesting backpack was determined by averaging the instantaneous mechanical power over the same period as the average electrical power for each trial.

V. RESULTS

The results from bench-top testing is shown in Fig.2. From the measured cable linear velocity and acceleration (Fig.2 (A)-(B)), the proposed model was able to accurately predict the current I_l (Fig.2 (C)) and thus, the amount of electrical power generated. The model prediction of cable force is composed of force from electrical power generation and inertia force (Fig.2 (D)). The combination of these two components predicted the total force on the cable and matched the measured force. After 0.45s, the measured cable force reduced to approximately zero because the cable started to retract and thus, there was minimal cable tension between the driving motor and the input pulley. The harvester model predicted the power production and the cable force well.

TABLE I
SUMMARY OF MECHANICAL POWER AND ELECTRICAL POWER

		10 Ω	**14 Ω**	**18 Ω**	**22 Ω**	**Open**
Electrical Power	Mean	19.28	15.26	13.93	12.19	-
(W)	SD	2.68	3.16	1.51	1.78	-
Mechanical Power	Mean	49.73	39.34	38.39	36.68	33.37
(W)	SD	14.97	9.88	9.41	8.28	10.00
Efficiency (%)	Mean	48.4	42.4	38.1	34.4	-

n =5; SD: standard deviation

Human experimentation results demonstrated that the amount of power generated by the proposed energy harvesting backpack is much higher than the suspended-load backpack (7.4W) [3] and the knee-mounted generator (5W) [8]. The amounts of electrical power generated under different electrical load are listed in Table I. It is evident that the developed energy harvesting backpack was capable of generating a large amount of electricity, from 12W under a load of 22Ω to 19W under a load of 10Ω. The voltage waveforms under different electrical loads resistances exhibited a similar magnitude, and

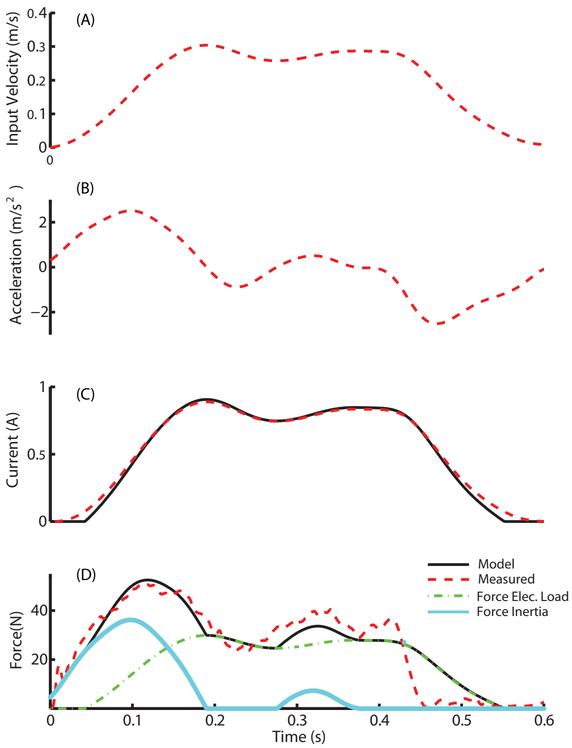

Fig. 2. Results from bench-top testing. (A) Input angular velocity to the generator. (B) Angular acceleration. (C) Measured and predicted current. (D) Measured and predicted cable force. Total predicted cable force is a sum of the force for power generation and the force for driving the inertia.

the difference in power production was mostly due to the difference in current (Fig. 3). The overall efficiency of power generation decreases as the load resistance increases with the maximum efficiency of 48.4% at a load of 10Ω.

During a gait cycle, the input cable lengthens during the swing phase and retracts during stance phase (4(A)). Electricity was generated by the leg motion when the cable velocity was positive(4(B)). The associated force resisted the lower limb motion during swing phase with a maximum magnitude of 100 N (4(C)). There is a two-burst pattern in the electrical power because of input from both legs. The electrical power exhibited a small lag to the input mechanical power due to delay in the gear train motion.

Table II shows the gross metabolic and net metabolic power during different activities: Normal walking, weighted walking, mechanical engagement, and electrical engagement. The metabolic cost of normal walking is similar to the results in literature [9]. The cost of carrying the additional weight of the harvester is 18 W. The net metabolic cost of generating 15W electricity is approximately 172 W. With an overall harvester efficiency of 42%, the mechanical power requirement is 39W (Table I.) This yielded a muscle efficiency of 23%, which is slightly smaller than the maximum muscle efficiency

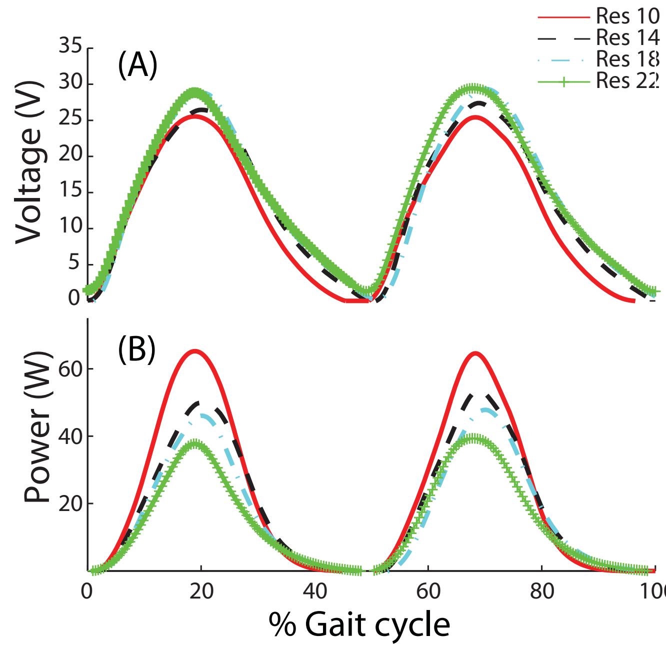

Fig. 3. Instantaneous voltage and power under different load resistances (10Ω to 22Ω) over one gait cycle.

of 25% in mechanical power production [12]. This indicated that the majority of the power generation was from muscle performing positive work. Interestingly under the mechanical engagement condition where no electricity was generated, the mechanical power requirement is 33 W with a net metabolic cost of 103 W. If all the mechanical work is performed by positive muscle work, the metabolic cost should have been 132W. Therefore, there must be a portion of mechanical work was performed by the muscles that was negative. Considering that the efficiency of muscles performing positive work is 20% and performing negative work is -120%. The following equation helped to find the amount of negative mechanical work, P_{neg} performed by the muscles

$$(33 - P_{neg}) \cdot 4 - \frac{P_{neg}}{1.2} = 103W \tag{14}$$

From Eq. 14, we found that the negative work,P_{neg}, is about a quarter of the total mechanical work, *i.e.*, 9 W. Comparing the metabolic results between the mechanical engagement and electrical engagement, we found that there was significant metabolic cost attributed to the the mechanical power required for generating electricity. This indicates that the harvester with current electrical loads imposed a mechanical resistance that exceeded the capability of the lower limb muscle, resulting in lower muscle efficiency and higher metabolic cost of walking.

VI. Conclusion

The results of this study show that the proposed energy harvesting backpack was able to produce a larger amount electrical energy than previous energy-harvesting designs. It was shown that the motion of both lower limbs can be integrated

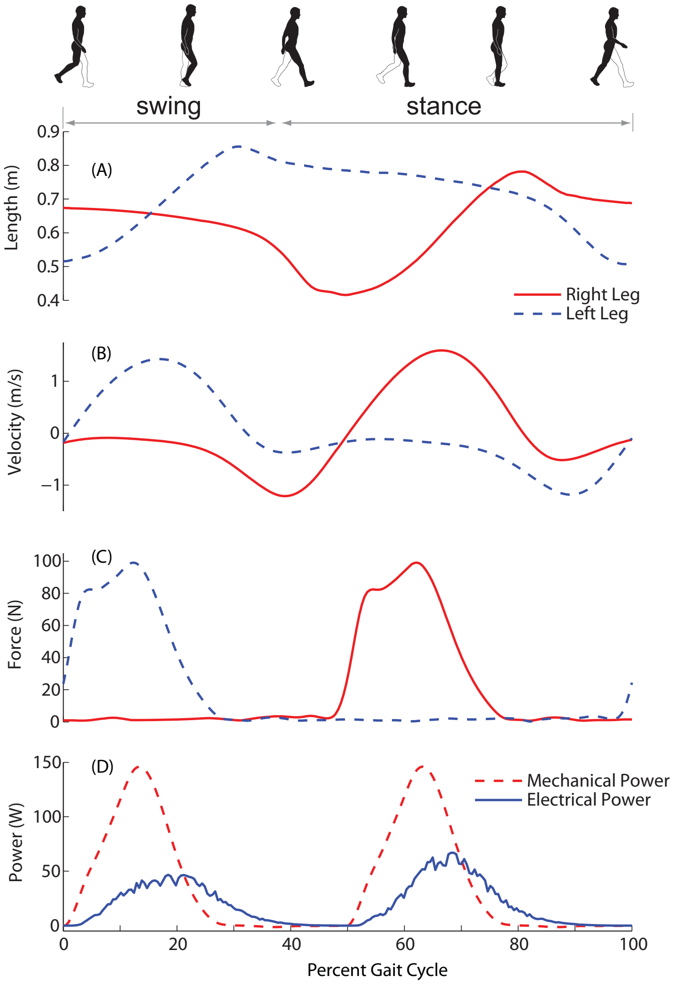

Fig. 4. Experimental results during human walking trial from a representative subject. (A) Measured cable length changes during one gait cycle. (B) Computed cable velocity. (C) Measured force on the cable. (D) Measured Mechanical power and electrical power.

TABLE II
SUMMARY OF METABOLIC DATA.

		Quiet standing	**Normal walking**	**Weighted walking**	**Mechanical engagement**	**Electrical engagement**
Gross Power	Mean	113	298	316	419	487
(W)	SD	22	27	33	34	51
Net Power	Mean	-	185	203	306	374
(W)	SD	-	13	26	30	46

n =5; SD: standard deviation; net power was calculated by deducting cost of quiet standing

into one drive train, reducing the complexity of the system. A portion of the mechanical work used for power generation came from the muscles performing negative work. Further work will focus on improving the mechanical efficiency of the energy harvester, and developing a control system that selectively engages the energy harvesting.

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