Decreasing the cost of energy harvesting through load profile matching

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1 Motivation

As more energy harvesting devices are being developed to fulfill the demand for portable power, more emphasis is being placed on their effects on the user. An ideal device would be capable of producing a significant amount of electricity (≈10W) during the user's normal daily activities, without negatively affecting the user's biomechanics or energetics. To achieve this goal, the device must be able to harvest energy during specific periods of the gait cycle, such that its negative effects are minimized.

2 State of the Art

We developed a novel lower limb-driven energy harvester (Fig:1) that captures the motions from both of the user's lower limbs into a single power generation unit [1]. This device harvests energy during the terminal swing phase of gait. During swing phase, the knee flexor muscles perform negative work to decelerate knee extension. The load applied by the harvester assists this knee deceleration, which serves a similar function as the generative braking of the knee harvester [2]. While harvesting energy, the lower limb-driven harvester has been shown to decrease the metabolic cost of walking relative to that of walking with the weight of the harvester [1]. This indicates that the harvester is both able to produce electricity and assist in walking.

The load provided by the harvester is made up of two components: the load due to the mechanical system (e.g. friction and inertia) and that due to the electrical systems (e.g. electrical power production). Because the harvester currently only uses a simple constant resistance bank, the mechanical load related to the electrical system is proportional to the input velocity. This means that the load felt by the user is directly related to the user's kinematics (e.g. a fast leg swing would relate to a large load). Therefore, if there were an undesirable load, the user would be forced to change their kinematics, which could lead to an increased metabolic cost of walking [3, 4]. Assuming that a proper loading profile would follow the net knee power, a loading profile that follows the knee velocity would not be ideal, because the knee velocity and net power are not perfectly aligned. Currently, exoskeletons have been designed to assist human walking by providing moments about different joints during specific phases of the gait cycle. The timing of this assistance has been found to be critical in terms of effectively decreasing the metabolic cost of walking [5]. Implementing dynamic load control for the lower limb-driven energy harvester should allow for the proper negative work assistance to be applied to the user and thus reduce the cost of walking.

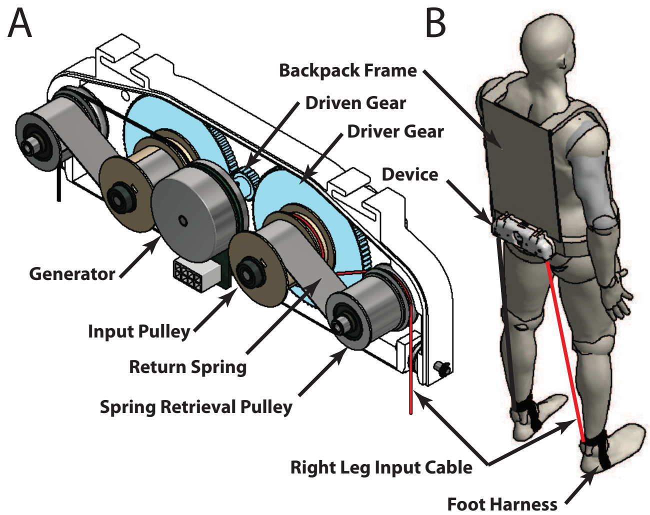

Figure 1: Lower-limb driven energy harvester (A) Schematic of device components. **(B)** Schematic view of the device worn by the user. The lower limbs pull the cables during the swing phase of a walking cycle and the out-of-phase motion of the two limbs makes the integration of the two limb motion into a single generation unit possible.

3 Approach

To provide proper assistance to the user, as well as increase electrical power output, a dynamic electrical load will be incorporated into the lower limb-driven energy harvester. This will be achieved through the implementation of an adapted end stage Boost converter-based current controller. This device rectifies the three-phase AC output of an energy harvesters generator prior to feeding it into a standard layout Boost converter topology. The current drawn from the rectified voltage is controlled by a closed loop PI control scheme. Unlike in conventional Boost topologies, which maintain a constant output voltage, the goal of this current controller is to follow a desired load profile by varying the output voltage. This controller will adjust the load profile to kinematic changes in the user's gait cycle (e.g. walking speed).

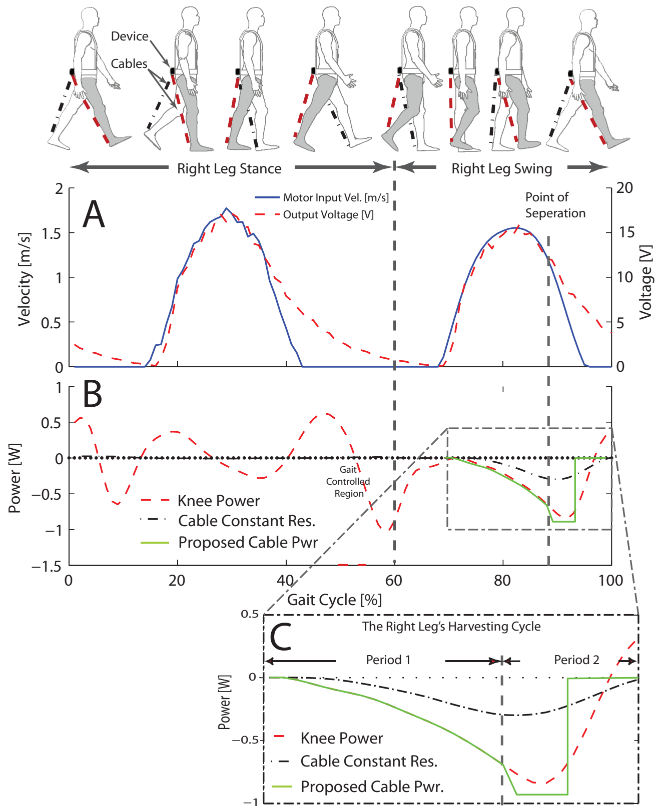

Figure 2: Timing of power generation during walking (A) The input motion from both legs into the harvester [m/s] (blue)and the output voltage from the generator [V](dashed red), during a gait cycle. **(B)** The right leg's net knee power [W/kg] (dashed red), cable power from constant resistance [W/kg] (dashed black) and theoretical cable power from a proposed profile (green), during a gait cycle. **(C)** Enlarged view of the right leg's harvesting region from (B)

The load profile (Fig.2) will consist of two different periods. The goal of the first period is to provide proper assistance to the user. The load profile during this period is composed of two parameters, the shape and the level of assistance (0-100%). The shape will be determined by matching the harvester cable power profile to the net knee power, found though inverse dynamics (Fig. 2.C). The level of assistance will be defined as the ratio between the amount of work performed by the harvester and the net knee joint work, both performed during the first period. By altering the level of assistance the proper profile will be determined. It is hypothesized that this profile will decreases muscle activation and will lead to a decrease in metabolic cost.

The second period begins when the input motion to the harvester is decoupled from the generator. This occurs when the built-in unidirectional roller clutch decouples the driving shaft of each leg from the generator. This occurs when the generator is rotating faster than it is being driven by the input motion. At this point, the generator motion is being dampened by both the electrical load and the mechanical losses (e.g. that due to friction). During this period, the electrical load will be increased, causing either recoupling to occur or, if the swing phase has ended, complete dampening of the generator rotation. The aim of this period is to decrease the losses related to friction and in turn increase electrical power production. With the input being decoupled from the generator, the user will no longer feel the loading related to electrical power production.

Human treadmill walking experiments will be conducted to compare the biomechanical and energetic effects of the proposed dynamic load profile to that of both harvesting using a constant electrical resistance (constant resistive bank) and normal walking. This effect will be determined through comparing the metabolic power (K4b2, COSMED, Italy), kinematics (Oqus, Qualisys, Sweden), kinetics (Ground reaction forces measured using an AMTI Force-Sensing Tandem Treadmill, (AMTI Inc., MA)), and electromyography (Trigno Wireless EMG, Delsys, USA) measurements between the conditions. The electromyography signals will be compared between condition to determine if muscle activation was decrease. The device performance will be determined by comparing the electrical output and mechanical power input between the conditions.

4 Best Possible Outcome

The best possible outcome of this study would be to identify a load profile that is related to a smaller total cost of harvest (TCOH) in comparison to the constant resistance, where TCOH is the ratio between the metabolic power increase from normal walking without carrying the harvester to the amount of electrical power produced. We will exam how a specific load profile alters the knee flexor and extensor muscle activation through analyzing EMG measurements. The insights gained from this study could provide a better understanding of the interaction and energy flow between energy harvesters and their users.

References

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