Biomechanical Energy Harvesting System with Optimal Cost-of-Harvesting Tracking Algorithm

Ze'ev Rubinshtein, Mor Mordechai Peretz
Power Electronics Laboratory
Department of Electrical and Computer Engineering
Ben-Gurion University of the Negev
Beer-Sheva, Israel
zeevrub@ee.bgu.ac.il ; morp@ee.bgu.ac.il

Raziel Riemer
Department of Industrial Engineering and Management
Ben-Gurion University of the Negev
Beer-Sheva, Israel
rriemer@bgu.ac.il

***Abstract*— This paper presents an innovative biomechanical energy harvesting system based on the regenerative braking concept applied to the human natural motion. To determine optimal braking profile previous studies used an off-line procedure based on constant external load to determine the optimal braking profile. The new concept of this study continuously optimizes the maximum amount of energy that can be extracted during human motion while minimizing the subject's effort (metabolic rate). This is achieved by an energy harvesting system equipped with a programmable braking profile and a unique power extraction algorithm, which adaptively changes the braking profile to obtain the optimal ratio of energy to effort. These are facilitated by a BLDC generator that is connected to boost converter. A digital current programmed control of the boost converter enables an adaptive torque variation according to bio (measure of effort) and electrical feedbacks. This study focuses on the human knee joint as the energy source since the most of this joint work during level walking is negative (muscles are acting as brakes). Since this work is preliminary and more oriented to the novel concept of adaptive profile and optimal power extraction, the operation of the energy harvester is demonstrated on a full-scale laboratory prototype based on a walking emulator. The results exhibit ultimate power extraction capabilities as well as adaptation to the walking pattern.**

I. INTRODUCTION

With the increasing use of portable electronics, there is a growing demand for portable, preferably renewable, sources of power. An emerging technology is biomechanical energy harvesting [1], [2]. This technology uses human natural motion, e.g. walking, to generate energy. The motivation of this approach stems from the fact that the average energy density of food is 35-100 times higher than batteries. Moreover, during one day of activity a person uses approximately 10.7MJ [3] of energy. To store this amount of energy using batteries, a bank of approximately 20Kg is required.

During human single step, the legs' muscles perform both positive work to generate forward motion and negative work to absorb the kinetic energy and stabilize the motion. Similar to the concept of regenerative braking in electric vehicles [2], the negative work can be extracted using an electric generator that replaces some of the braking that the muscles are required to do and by that, reduces the muscles' effort while generating electricity. In this context, the knee joint stands out of all the other body joints with the highest negative work of approximately 33J per step for both knees for 80Kg subject walking on a plane surface at normal speed (~1Hz) [3].

The common terminology to quantify the efficiency of harvesting is by the Cost of Harvesting (COH) [1], which is defined as the ratio between the difference in the metabolic energy with and without harvesting (*Δmetabolic energy*) and the difference of extracted electrical energy with and without harvesting (*Δelectrical energy*), that is:

$$COH = \frac{\Delta\, metabolic\ energy}{\Delta\, electrical\ energy} \quad (1)$$

The goal of efficient harvesting is to reduce the COH as much as possible. This is done by maximizing the electrical power harvested out of negative work while the metabolic power is reduced. Naturally, if the extracted energy exceeds the amount of negative work available, the motion is forced to a halt, and the subject has to perform extra (positive) work to resume motion. Therefore, at all conditions the braking torque applied to the joint must be smaller than the joint muscle natural torque (i.e. torque perform by the knee during walking with no device). Furthermore, matching the braking torque to the natural joint torque does not yield the best results [3]. In this case all the human motion is controlled by the device while the muscles are not active, which is not feasible for able-bodied humans (i.e. without disability). The subject of applied torque profile that yields the best COH results is still an open-subject in the biomechanical community and is beyond the scope of this study.

Previous studies on biomechanical harvesters have reported power output range of up to approximately 8W [1]-[6]. There, systems were designed to achieve maximum energy at a given level of effort. A true regenerative system that extracts and stores the energy as well as optimizes the COH has not been reported hitherto.

The objective of this study is to introduce a biomechanical energy harvesting system that applies regenerative braking with COH minimization algorithms to maximize the production of electrical power with minimal interference to human subject effort and motion. This is achieved by an algorithm that controls the harvesting system and adjusts the torques profile to achieve the best COH at a given set of conditions. This is required since the optimal braking torque

978-1-4799-2325-0/14/$31.00 ©2014 IEEE

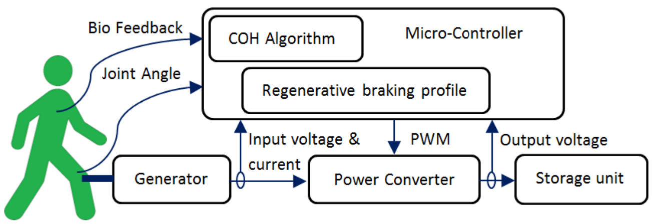

Fig. 1 closed-loop biomechanical energy harvesting system

that will produce the lowest COH varies from one subject to another, type of surface, motion pace and more.

The closed-loop harvesting system is conceptually illustrated in Fig. 1. It consists of a generator to convert motion into electricity, a boost converter that operates in a current programmed mode to achieve the desired torque pattern while extracting energy, and a storage unit (battery plus charger). An additional feedback loop is added to track the optimal COH point at all times. The performance of the introduced system, to-date, is examined using a walking emulator (Fig. 2) and the information of the COH is synthesized into the system.

II. Knee Joint As A Power Source

In human walking, the knee joint performs a periodic motion where a single step is defined as a period. Fig. 3 [3] illustrates a typical knee joint activity during a period, for the values of (top to bottom, Fig. 3): angle (zero represents a straight leg position), velocity, torque, and power. The period is separated into 4 sections according to flexion and extension of the knee (J1 through J4). As can be observed from Fig. 3, by calculating the instantaneous product of the applied torque on the joint and the velocity, areas of negative work can be identified, these are marked as K1, K3, K4. As a result, the knee joint can be considered as a low frequency pulsating power source (~1Hz) with relatively low angular speed (<5 rad/sec).

Direct measurement of knee joint torque is not feasible and methods for estimating the knee muscle torque require equipment that is complex and hard to fit on the knee. Therefore, an alternative approach based on the information of the joint angle and rotation velocity is taken to identify the regions J1 to J4. The joint rotation velocity can be extracted by taking the derivative of the angle. In this way, only one sensor of the joint angle is required. This approach is based on the observation that each section of negative work ends at zero velocity and different joint angle for each section [7]. Using this information an algorithm that identifies the particular portion of the step has been developed.

A simplistic algorithm for identification of J1 to J4 is realized by detecting the velocity zero crossing instance (e.g. transition from negative slope to a positive one), and capturing the angle value at this instance. The maximum angle value of all zero crossing points would correspond to beginning of section J4. Since the angle value of J4 is significantly higher than in the other sections, the identification of J4 is simplified and is obtained by comparison against the angle median value rather than a maximum search. Once J4 is identified, the other

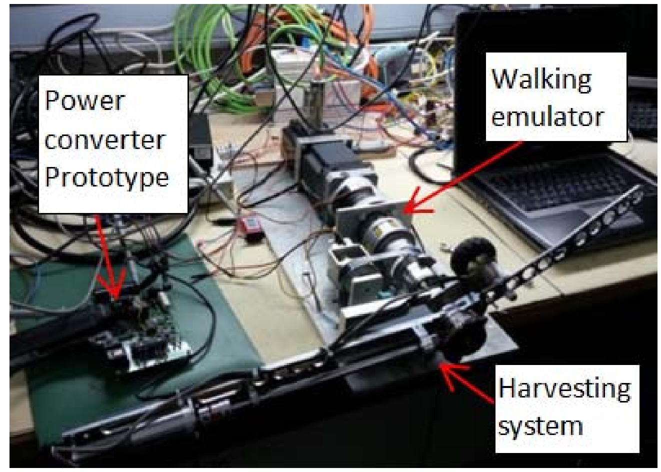

Fig. 2 experimental setup with walking emulator and biomechanical energy harvesting system

sections are easily obtained by the zero crossing detection, given a periodic walking pattern.

Since the walking profile may vary, a refinement of the detection procedure is facilitated by an adaptive algorithm in which the system is "learning" the walking profile of the subject. This adaptive process is explained in more detail by the flowchart of Fig. 4. At system boot, a straight leg and a starting point at J1 section are assumed as well as an initial joint angle median. In the first periods (several walking steps) the system does not perform harvesting and is dedicated for "learning" the walking pattern of the subject. The process of joint angle median refinement is iterative and is updated every period. It can also be seen from Fig. 3 that only a portion of the sections J1, J3 and J4 have negative work. Therefore, to avoid inducing torque on the subject at false location, once a region that contains negative work is detected (e.g. J4), the system monitors the rectified generator voltage (which is proportional to the rotation speed in a synchronous brushless machine) and triggers the harvesting command when it has reached a programmable threshold, relative to the maximum voltage. This ratio has been selected from experimental joint

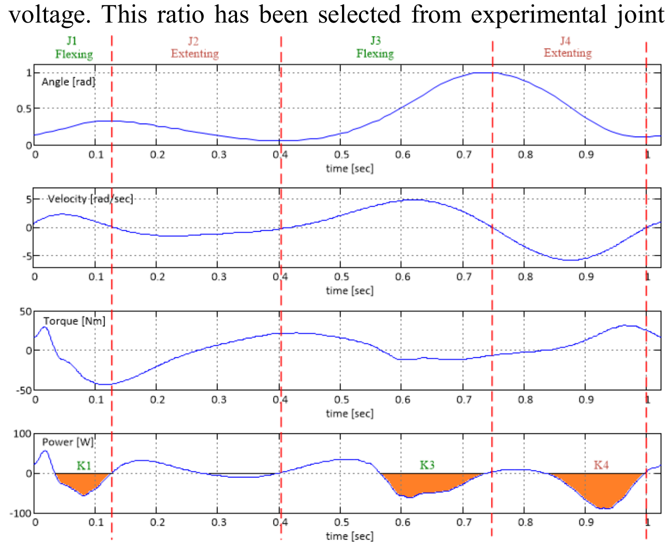

Fig. 3 Sample of knee joint activity during single step

data mining by a trial and error procedure which has been found suitable to accommodate the power stage practical limits while maintaining smooth walking pattern. The angle median and the voltage threshold values are updated every period with the detection of J4.

III. HARVESTING SYSTEM

The electro-mechanical system used in this study (Fig. 2) consists of a walking emulator (to be replaced by a knee brace for human subjects experiments), configured to emulate knee motion and assembled such that knee motion drives a gear train through a unidirectional clutch, transmitting only knee flexion motion to a brushless DC (BLDC) generator [6]. The 3 phase BLDC generator is followed by synchronous rectifier for low power loss. To facilitate a desired braking profile on the BLDC generator, an average current controlled boost converter is employed. This is enabled by the linear relationship between the BLDC generator current and the induced resistive torque [8]. Current source behavior is vital since the generator output voltage and the required resistive torque are not directly linked. The harvested power is then transferred to energy bank, and an off-shelf Li-Ion battery charger is used as the load of the power harvester.

The system is self-contained as the energy bank serves as a semi-constant power source for the power stage controller, peripherals and the battery charger. The energy bank is over-voltage protected by a damp resistor in parallel to the output capacitor that absorbs excess energy in cases that the consumed power is lower than the harvested one.

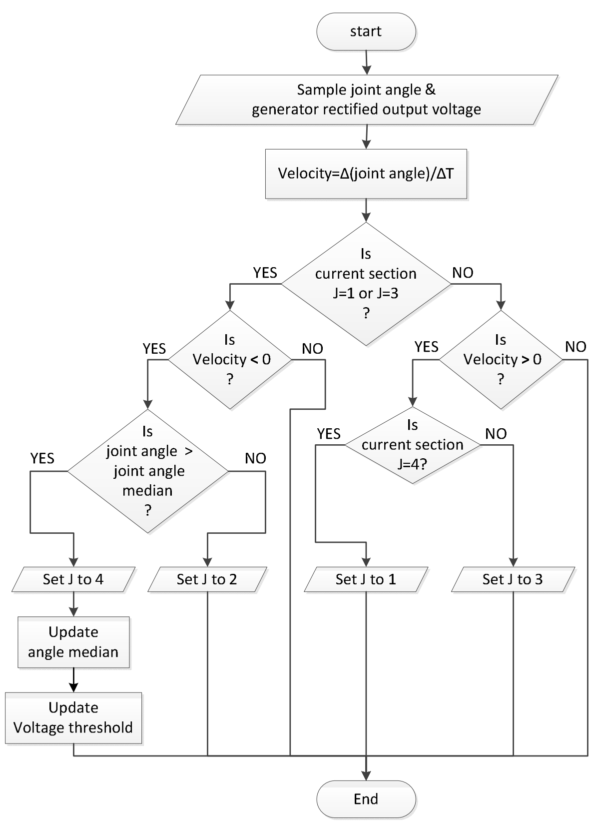

Fig. 4 closed-loop biomechanical energy harvesting system

The power harvesting system is digitally controlled. The controller consists of two modes: wake-up and free-run. In the wake-up mode the system doesn't actively harvest energy, the BLDC generator voltage breaches the rectifier diodes and charges the output energy bank with minimal amount of energy. This energy used to power up the microcontroller. In the first three walking steps, the microcontroller works in low-power mode while learning the subject walking profile.

The free-run stage has two modes of operation: harvesting and no-harvesting. The no-harvesting mode is similar to wake-up phase, the power stage is set in sleep mode and the microcontroller is programmed to wake up every 8.25ms and sample the knee joint angle to keep track on the key parameters (angles, speed and knee position in step period) while looking for areas of negative work.

Once a negative work area has been detected, the system shifts to harvest mode. Here, all system resources are activated, the generator Hall Effect sensors are turned on and the rectifier operation is set for synchronous switching. Average current mode operation forces the boost average inductor current to follow a specified braking profile (REF_{K_i}) that is constructed, in this study, from two arrays named base ($BASE_{K_i}$) and delta ($DELTA_{K_i}$), for each negative working area (K_i). The base array contains an initial generic current profile that allows energy to be harvested from a subject without affecting the user's natural motion. This array is loaded to the reference profile during system boot.

$$REF_{K_i}(n) = BASE_{K_i}(n), \tag{2}$$

where *n* is array cell index and *i* is index of K-ith section.

To allow on-line adjustment of the braking profile, i.e. current shape, the current reference to the boost controller (REF_{K_i}) is constructed by summation of the base and the delta arrays. That is,

$$REF_{K_i}(n) = REF_{K_i}(n) \pm DELTA_{K_i}(n). \tag{3}$$

As opposed to the base array which is fixed, the delta array can be updated on-the-fly. As a result, a flexible current reference of any shape and magnitude may be applied on the subject for evaluation and further optimization of the harvesting. It should be noted however, that to-date, the issue of the optimal harvesting profile is still an open issue in the biomechanical community. Therefore, the emphasis in this work was on varying the gain of the generic base profile, rather than realizing various braking profiles.

Following the current profile, the harvested energy is transferred to energy bank (capacitor C). The sizing of C is obtained such that an entire step of maximum harvested energy ($E_{in_{max}}$) can be stored for later use in predefined voltage swing $\{V_{min}, V_{max}\}$ by:

$$C = 2E_{in_{max}}/(V_{max}^2 - V_{min}^2) \tag{4}$$

It should be noted that a boost converter has a practical voltage gain limitation of 7-8, therefore the upper voltage bound of the energy bank sets the converter minimum operating voltage. Since the region detection procedure already monitors the generator voltage (for harvesting on negative work regions), the minimum operating voltage serves as the minimum threshold to trigger harvesting.

Since the information of the input voltage and current are readily available and are required for the COH minimization routine, the controller calculates the amount of harvested energy over a single step as follows:

$$E_{in_{step}} = \sum_n V_{in}(n) I_{in}(n) \Delta T \qquad (5)$$

where ΔT is the time between samples, V_{in} and I_{in} are the input voltage and current to the boost converter, respectively.

IV. OPTIMAL COH TRACKING ALGORITHM

In theory harvesting small amount of available negative energy should reduce the metabolic rate, in comparison to a case of carrying the harvesting device but not harvesting. On the other hand, harvesting more than the available negative energy would increase the metabolic rate. Furthermore, even in the case that exactly all the negative energy is harvested, then the metabolic rate would increase. In such case, the device will perform all the joint control and the human must not resist the forced action, i.e. not apply his knee muscles at all. Therefore, reasonable conjecture is that there exists some level of support (harvesting during negative phase) that will be optimal. However this optimal level has not been established yet.

Following these arguments, a conjecture made in this study is that a global minimum exists for the COH function of (1) and the object of the algorithm is to converge into this target point. The COH minimum location or value may vary from one harvesting profile to another, but it always exists. There might be a case that a braking pattern yield higher extracted energy than another (lower COH), however, this issue is still an open subject and is beyond the scope of this study.

To facilitate easier realization of the COH tracking algorithm, and without losing generality, this study redefines the COH function of (1) so that the differences of metabolic energy ($\Delta metabolic\ energy$) and electrical energy ($\Delta electrical\ energy$) is between the present and previous harvesting states. By doing so, well-known maximum power point tracking (MPPT) algorithms can be adopted and implemented with readily available information.

The algorithm that is selected to track the optimal COH is a modification of the well-known Hill-Climbing concept [9]. Upon arrival of new metabolic rate data, the controller calculates the difference of present and previous received metabolic energy; the difference of present average harvested energy between predefined several last steps (*N*) using (5) and the average of harvested energy of previous algorithm activation. If the COH result is negative, the harvested energy is smaller than the optimal one and the reference current profile is increased. If the COH is positive, the harvested energy is higher than the optimal amount and the reference is decreased (Fig. 5).

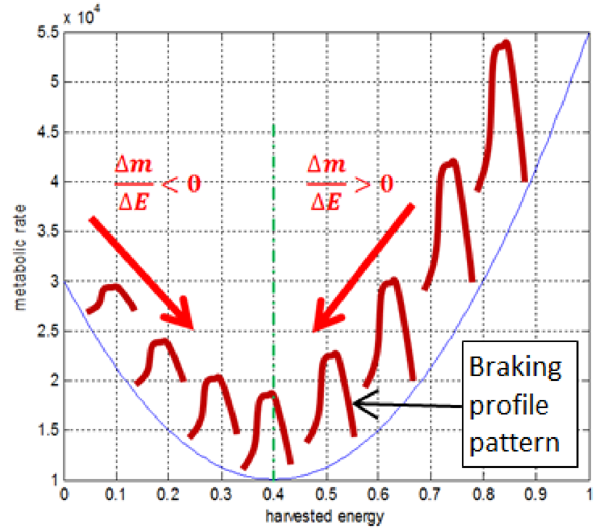

Fig. 5 metabolic rate curve as a function of normalized harvested energy power biomechanical energy harvesting system

V. EXPERIMENTAL SETUP AND RESULTS

To test the proposed system and the optimal COH tracking algorithm in isolated environment a knee emulator has been constructed (Fig. 2). The knee emulator is a system based on custom-made mechanical design that integrates the exact construction of the real knee brace and generator, and is controlled using off-shelf servo motor (Emerson Control Techniques). To mimic the knee joint motion, the joint angles of a single step have been programmed into the servo motor controller, as a look-up table. To reduce rotation speed, increase location resolution and output torque, a 10:1 gear train is included in the mechanical structure. The experimental data of the emulator controller and the power stage has been viewed and recorded by oscilloscope and MATLAB. Since the device is not tested on human subjects, the metabolic rate data has been synthesized by a MATLAB script where the metabolic energy curve was created as parabola function of averaged electrical harvested energy ($E_{in_{av}}$). The microcontroller transmits (through serial communication) to the PC the value of $E_{in_{av}}$ and receives back the appropriate metabolic energy.

To test the power harvesting and the control algorithm capabilities, different load profiles have been examined. One case of braking by a constant torque (constant current) is shown in Fig. 6. Results of the optimal COH tracking algorithm are depicted in Fig. 7, which shows that the optimal point has been reached and the system oscillates around it as expected.

VI. CONCLUSIONS

An energy harvesting system with optimal energy harvesting tracking algorithm has been presented. Experiments showed that the power harvester features adequate dynamic response with zero steady-state error. The optimal COH tracking algorithm has been demonstrated to successfully detect the negative work areas and harvest the optimal amount of energy.

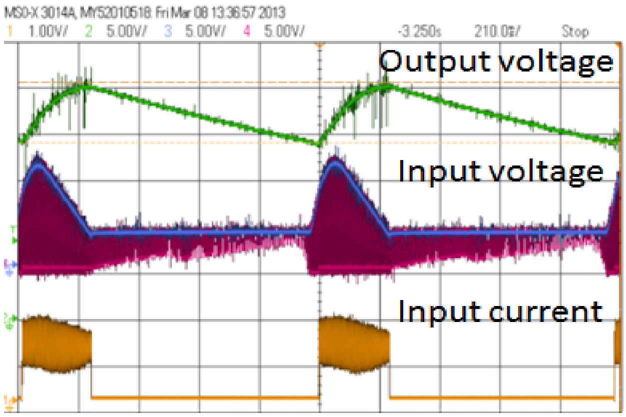

Fig. 6 Exemplary experimental results of the power harvester during regenerative braking action

The concept of regenerative braking, commonly used in electric or hybrid vehicles, has been adapted in this study to channel part of the negative energy invested by a human subject during walking, into electricity. Ultimately, this can potentially reduce the metabolic effort of the subject during walking.

In contrary to vehicle braking, where the braking action is triggered by the user (by pressing the brake pedal), a biomechanical harvester must be capable of detecting regions of negative work, and apply the proper torque on the system such that energy is extracted and, at the same time, without interference to the natural motion. To this end, an adaptive algorithm that "learns" the walking pattern and estimates the harvesting profile has been developed.

The braking-harvesting action is facilitated in this work by the torque applied on the knee joint. This is realized by a current-controlled boost converter that acts as a programmable load to a generator. In this context, a current sourcing behavior is essential for proper operation since the torque of a synchronous machine is directly linked to its terminals' current.

To generalize the harvester solution onto any subject, walking profile, or duration, an optimal energy harvesting procedure has been developed. Based on a bio-feedback from the user, the controller continuously optimizes the negative work detection procedure and the harvesting profile such that the per-period Cost of Harvesting is minimized.

The converter configuration, control, and the tracking algorithm establish an infrastructure for future advanced research of braking torque shapes on the optimal amount of harvested energy and its effect on human subjects. Although demonstrated on a knee joint harvesting device with metabolic rate as human state parameter, the proposed approach can be applied to other joints and different human state parameters with some adjustments.

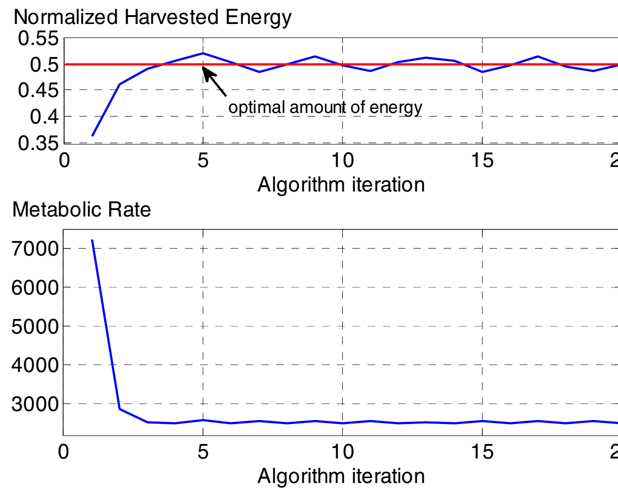

Fig. 7 Normalized harvested energy (upper graph) and metabolic rate (lower graph) as functions of COH optimal algorithm iterations

References

[1] J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, "Biomechanical energy harvesting: generating electricity during walking with minimal user effort," Science, vol. 319, no. 5864, pp. 807-810, 2008.

[2] P. Niu, P. Chapman, R. Riemer, and X. Zhang, "Evaluation of motions and actuation methods for biomechanical energy harvesting," IEEE 35th Annual Power Electronics Specialists Conference, 2004. PESC 2004. vol. 3, pp.2100-2106, 2004.

[3] R. Riemer and A. Shapiro, "Biomechanical energy harvesting from human motion: theory, state of the art, design guidelines, and future directions," J. of Neuroengineering and Rehabilitation, vol. 8, no. 22, doi:10.1186/1743-0003-8-22, Apr. 2011.

[4] L. C. Rome, L. Flynn, E. M. Goldman, and T. D. Yoo, "Generating electricity while walking with loads," Science, vol. 309, no. 5741, pp. 1725-1728, 2005.

[5] Q. Li, V. Naing, and J. M. Donelan, "Development of a biomechanical energy harvester," J. of Neuroengineering and Rehabilitation, vol. 6, no. 22, doi:10.1186/1743-0003-6-22, Jun. 2009.

[6] R. Riemer, A. Shapiro, and S. Azar, "Optimal gear and generator selection for a knee biomechanical energy harvester", 1st International Conference on Applied Bionics and Biomechanics, Venice, Italy, 2010.

[7] S. Mizrachi and R. Riemer, "Biomechanical energy harvesting: control and evaluation of device efficiency", ICR 2013, Tel Aviv, Israel, 2013.

[8] J. F. Gieras and M. Wing, Permanent Magnet motor technology, 2nd ed., New York: Marcel Dekker, 2002.

[9] T. Esram and P. L. Chapman, "comparison of photovoltaic array maximum power point tracking techniques," IEEE Transactions on Energy Conversion, vol. 22, no. 2, Jun. 2007.