A Brief Review on Human-Powered Lower-Limb Exoskeletons

Saurav Dhand[a], Ashish Singla[a*], Gurvinder S. Virk[b]

[a] Department of Mechanical Engineering, Thapar University, Patiala-147001, India

[b] Robotics and the Built Environment, University of Gävle & KTH Royal Institute of Technology, SWEDEN

* Corresponding author: ashish.singla@thapar.edu

Abstract- Most current commercially available exoskeletons use rechargeable Li-Ion batteries, which require frequent charging to meet the operational needs. The battery charging is a serious bottleneck, when the person, wearing the exoskeleton, needs to go for trip outdoors or for extended excursions such as trekking. To reduce the reliance on battery power, more reliable and alternative energy sources are required. In this respect, human-powered products (HPPs) are emerging as useful emergency electric power sources, when regular power supplies are unavailable. Being economical and environment friendly, these devices can also act as a boon for under-developed countries, since batteries are expensive and the mains power supply can be unreliable. The energy generation in these devices is broadly based on five methods—piezoelectric, vibrations, radio frequency (RF), electrostatic and electromagnetic, and each method produces different amount of electrical energy. These methods are reviewed here; the first four methods produce relatively small amounts of energy, which is inadequate to charge the battery of assistive exoskeletons. Therefore, the focus here is on electromagnetic devices and how this can be used to power assistive exoskeletons. Some human-powered products are also reviewed and the paper compares conventional and alternate methods to charge lower-limb exoskeletons used for assisting elderly persons.

Index Terms- Alternate energy source, lower-limb exoskeletons, human power, Human Powered Products, Human Powered Generators (HPGs).

I. INTRODUCTION

With advances in technology and modernization of equipment, there has been a continuous demand for more portable electronic devices. More stress is continually given to reductions in size and power consumption. Sometimes, advances in both size and power consumption are achieved by adopting assumptions such as restricting use case scenarios, limiting performances, etc. Most modern electronic devices require rechargeable batteries as the power source. For continuous operation, the batteries need to be charged frequently or replaced periodically to ensure the operational performances can be maintained. Replacing the battery after each use is not a viable option. As mobility of portable devices is restricted by the battery size, longer mobility can be assured using high capacity rechargeable batteries. It is found that increase in battery capacity leads to increases in overall weight of the system. Therefore, the battery capacity can be increased to a certain extent, beyond which the dynamics of the device, housing the battery as the energy source, will be disturbed. Sometimes, batteries are discharged when you need them the most and the mains electricity network access is also sometime not reliable especially in developing countries or in rural areas.

For a person with difficulties in personal mobility needed for normal daily living activities due to issues with the lower body, a long-term assistive device can be used. The assistance is mostly required for independent motions such as standing, performing sit-to-stand transfers and walking. Commonly used equipment to aid such mobility tasks comprise a walking stick (metallic/wooden), tripod and quadruped frames, crutches, walking frames, rollators, and wheel-chairs. All these conventional methods are not very reliable and sometimes fail to give the required assistance needed to maintain independence. For example stair-climbing is a serious problem which cannot be solved by using wheel-chairs. In recent years, there is a significant increase in the development of power assistive devices, such as mobility exoskeletons powered by electrical motors, which are used to provide the required assistance in lower-body motions such as walking as well as in load augmentation. The method for supplying power to these exoskeletons is usually via rechargeable batteries which are charged regularly as needed by direct connection to AC/DC mains supply; this can limit the use of exoskeletons to stay within close proximity to a recharging point due to the normally low battery sizes used to reduce weight. Therefore, an alternate method for low-powered exoskeletons is needed; this is the main focus of this paper. Human power is considered as an alternative energy source for powering the battery that supplies power to lower-limb mobility exoskeletons. Here we consider the concept of human power from upper-limb motions of the body and if it can be used for charging purposes. Thus, exoskeleton wearers can roam freely without worrying about how electricity sources can be found for charging the exoskeleton's battery.

This paper comprises of the following sections. Part II provides an overview of key current mobility exoskeletons and how they may be usefully classified. The powering methods adopted in these exoskeletons are also discussed. Part III describes various HPPs, how the methods can be classified as well as some examples of these devices available commercially. Literature surveys are presented for both cases, and the paper sends with some conclusions on how future assistive exoskeletons may be realized using HPP technologies.

II. EXOSKELETONS AND THEIR POWERING METHODS

Exoskeletons integrate humans with robotic machines to allow the human to perform a variety of tasks. For lower body exoskeletons such assistive devices are used for load augmentation or gait assistance or persons as shown in Fig. 1. Load augmentation is used here to mean the enhancement of an able-bodied person to carry heavy loads for long periods. Therefore these types of exoskeletons are used for military applications or by manual workers to carry heavy loads.

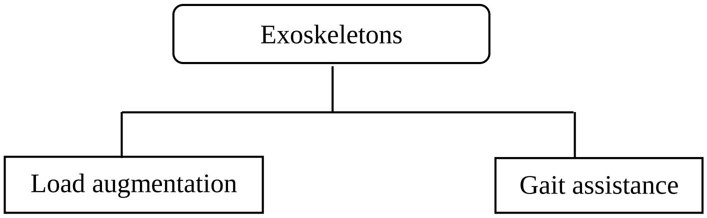

Fig. 1: Broad classification of lower-body exoskeletons

On the other hand, exoskeletons are also used for gait assistance for able and disabled persons to enable them to perform various mobility tasks for normal daily living activities independently. Clearly, such body fitting exoskeletons have advantages over conventional wheel chairs [1]. The exoskeleton wearer can anywhere without needed help from others. Table 1 categorizes different types of exoskeletons according to the purpose they have made for.

Before 1960, exoskeletons only appeared in science fiction movies and in some of the early patents. In late 1960s, United States and former Yugoslavia started research in this field simultaneously. The focus of the groups in United State was to develop exoskeletons for augmentation of the able-bodied persons to assist in military operations, whereas the work in Yugoslavia focused on development of active orthosis devices for rehabilitation of disabled persons [9]. Later, many authors developed different concepts of exoskeletons and the area continues to evolve [2].

Some exoskeletons from both load-augmentation and gait assistance sectors are discussed below:

A. *Exoskeletons for load-carrying augmentation*

1. ***Berkeley Lower Extremity EXoskeleton (BLEEX):*** This exoskeleton was one of the outcomes of the DARPA program named Exoskeletons for Human Performance Augmentation (EHPA). It carries its power source in form of a battery to drive the actuators at different joints as shown in Fig. 2. BLEEX comprises of seven degrees of freedom (DOFs), where three DOFs being at the hip joint, one at the knee and 3 at the ankle.
   Due to the high number of DOFs with powerful drives, the power consumption high. Approximately 1.3kW of power is consumed by the hydraulic actuators, various electronics and control systems [3, 4]. Therefore, it falls under the category of high-powered portable exoskeletons using rechargeable batteries, which can be charged using direct AC power supply.
2. ***Sarcos:*** The DARPA program also funded the work on making a full body exoskeleton named Sarcos shown in Fig. 3. Unlike BLEEX's linear hydraulic actuators,

Table 1: Different types of exoskeletons

To augment abilities of able-bodied humans		**To assist able and disabled persons and patients**	
Exo model	**Developer**	**Exo model**	**Developer**
BLEEX [3,4]	DARPA exoskeleton programs	Hybrid Assistive Leg-3 [6]	Univ of Tsukuba, Japan
Sarcos [5]	DARPA exoskeleton programs	Power Assist Suits [7]	Kanagawa Inst of Technology, Japan
MIT exoskeleton [5]	MIT, USA	RoboKnee [8]	Yobotics, USA
Enabling Technologies [5]	DARPA exoskeleton programs	CHRIS [10]	Hiroshima University, Japan

Fig. 2: BLEEX

Sarcos has rotary hydraulic actuators. This exoskeleton is more efficient than BLEEX [5]; it has a walking speed of 1.6 m/s while carrying around 70kg of load.

Fig. 3: Sarcos

3. ***MIT exoskeleton:*** This has a total of 6 DOFs, providing motion at the hip, knee and ankle joints as shown in Fig4. It can produce torques of 130, 50 and 90 Nm at these joints respectively [5].

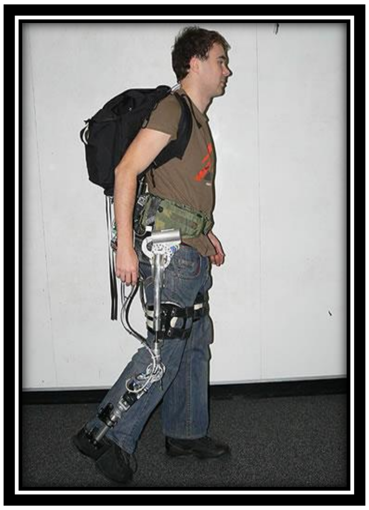

Fig. 4: MIT exoskeleton

B. Non-portable exoskeletons

1. ***Hybrid Assistive Leg (HAL-3):*** This is a Japanese exoskeleton designed by Cyberdyne set up by University of Tsukuba, Japan. It weighs around 21kg and is shown in Fig.5. The main motive behind the creation of this exoskeleton is for rehabilitation of disabled persons. HAL-3 can operate continuously for 160 minutes [6] and due to the number of sensors, the power requirement is high. It therefore falls under the category of high power exoskeletons. HAL-3 augments joint torques at the hip, knee, and ankle with 100V AC supply.

Fig. 5: HAL-3

2. ***Power assist suits:*** This exoskeleton shown in Fig.6, is made by Kanagawa Institute of Technology, Japan to provide help for a nurse caring for a patient or disabled person. The power assist suit has pneumatic actuators and the weight is ≈13.4kg [7]. It has various pressure sensors, a mini-computer, solenoid valves, one compressed air storage tank for its operation.

Fig. 6: Power assist suit

3. ***RoboKnee:*** This has been developed by Yobotics, USA to provide assistance to knees joint for climbing stairs or in simple walking in case of disabled person [8]. Very little information is available about RoboKnee in the literature.

Fig. 7: CHRIS

4. ***Cybernetic Human-Robot Interface System (CHRIS):*** CHRIS has been developed by Hiroshima University, Japan. The probabilistic neural network (PNN) in it detects the human's intentions and generates the control commands [10]. A 24V battery has been employed to drive two 150W permanent magnet, gear motors. It weighs more than 70 kg and requires high electrical energy to operate.

From the above classification of some key exoskeleton robots, it is clear that most of the load-carrying augmentation exoskeletons require high power. Therefore, these exoskeletons are powered using direct AC/DC power supplies. Low-power exoskeletons, that can be powered using alternate sources of power such as via human power, are presented in this paper.

Fig. 8: HAL-3

III. HUMAN POWERED PRODUCTS

There has been a continuous demand for small, environmentally friendly, electricity generating renewable energy sources. These sources are not dependent on conventional fossil fuels to produce electric current, but on alternative renewable energy sources such as wind energy, photovoltaic energy, micro hydro-power, tidal energy, human power, etc. A lot of research has been conducted in mathematical and computer modeling, feasibility studies and implementation of alternate energy sources [11–14]. Solar cells have dominated the commercial markets as an alternate source of renewable energy [15, 16], however their operation is susceptible to weather conditions which limits their reliability. The power output from all these renewable energy sources is either very high (kW in the case of wind energy) or very low (mW in case of piezoelectric). Moreover, there are various losses associated with storage of the generated electrical current. Many storage mediums are available for storing the energy depending upon the power produced [17–20]. Each source, be it Li-ion or Ni-MH batteries, mechanical flywheels or supercapacitors, can be used in any application subject to purpose and performance requirements of the energy storage as discussed in Table 3. In order to achieve maximum storage capacity and low losses, various multi-objective optimization techniques have been formulated by researchers. The focus of this work is to extend the use case scenarios of exoskeletons to remote areas which are deprived of mains electricity for recharging. For this purpose, the use of human power as an alternate source of energy is explored here. The human power can be exploited using various human powered products like hand cranking, rocking on a chair, walking, pedaling, etc.

With human powered-products, a wide range of energy outputs can be obtained but the most important is the suitability of HPPs to the assistive exoskeleton application under generate consideration. In the literature, HPPs are defined as *active human powered* and *passive human-powered*. Products are said to be actively-powered, when the sole intention of the person is to the electricity, for example hand cranking [21–24], and pedaling [25], whereas, in the case of passively-powered products, electrical energy is obtained as a by-product, when the person is executing some daily tasks like, walking, rocking on a chair.

Most HPPs are based on three major principles, namely:

1. ***Electrostatic****:* In electrostatic generators, the relative movement between electrically-isolated, charged capacitor plates is utilized to generate electrical energy. The energy can be harvested by doing work against the electrostatic forces between the plates. The variation in plate distance limits the voltage produced by these sources in a certain range. Research has been carried out to optimize the power output from electrostatic sources; e.g. Roundy [26] proposed two optimized models for electrostatic generators, which are the *in-plane gap closing* and *out-of-plane gap closing* for maximum power outputs. Another concept proposed by Sterken [27, 28], is based on three conditions, namely: (a) *maximizing the change in capacitance*, (b) *changing the damping ratio*, (c) *maximization of the polarizing voltage*, for maximum power output. The main problems with electrostatic generators are the initial charging of the capacitor as well as the power output being low.
2. ***Electromagnetic****:* These generators use the concept of electromagnetic induction, arising due to relative motion of a conductor in a changing magnetic flux. Most of the high power output alternators are based on electromagnetic sources of powering. A number of hand-crank generators, working on the electromagnetic principle, are reported in the literature having a power range of 50-70W.

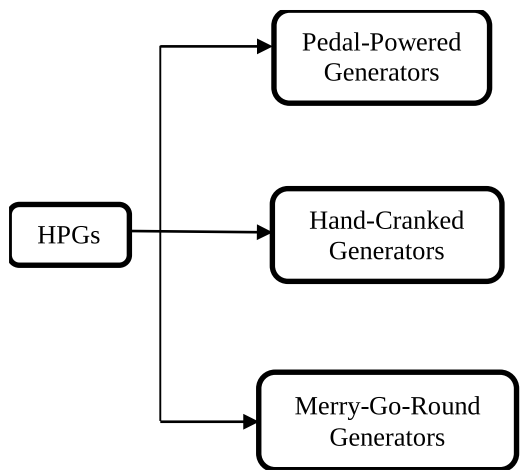

Fig. 9: Classification of human powered generators

3. ***Piezoelectric****:* These generators are based on the piezoelectric effect, where generation of electric current is by mechanically stressing active materials. Snyder [29–31] used this concept in a car wheel to power a tyre pressure sensor where wheel vibrations during driving are used to power the generator and abnormal tyre pressure is sensed using a suitable pressure sensor. A detailed mathematical model of a piezoelectric generator is presented by Roundy and Wright [32]. In their work, they have derived a relationship between input acceleration and the tip displacement of a cantilever beam. Further, the stress has been calculated, that generates the electric field in layers of a piezoelectric material.

Table 4: Comparison of different human powered generators[33]

Device	Power range (W)	Total capital cost (US $)	Unitary capital cost ($/W)
Bicycle	100–150	75–500	0.25–2.00
Hand-crank	50–100	50–500	1.00–3.00
MGRs	100–600	500–2400	2.00–4.00

As the torque requirements at the hip and knee joints of lower-limb exoskeletons are significant, and torque is directly proportional to power, high-powered motors are required. From the three HPG methods discussed, we will focus on electromagnetism because the other two methods result in the generation of relatively low electric power (of the order of microwatts). HPPs based on electromagnetic sources are able to generate sufficient power for driving lower-limb exoskeletons.

Human powered products are classified into three categories—*pedal-powered generators*, *hand-crank generators* and *merry-go-round generators* as shown in Fig. 9. Details of these generators are given next.

1. ***Pedal-powered generators**:* The idea behind these generators is to use the pedal work for the production of electrical energy using an alternator. With the help of pedaling, the mechanical energy is converted to rotational energy and stored in a flywheel which is connected to the alternator shaft, with belts, gears or chains to produce electricity. The average power output from these kinds of generators is approximately 120W. A commercially available indoor bike, developed by NEERG as shown in Fig. 10.

Fig. 10: NEERG indoor bike [37]

Tiwari et al. [34] demonstrated that while using a bicycle ergometer that with a pedaling rate of 50 rpm, 60 W of power output can be generated (see Fig.11). Another human powered bicycle concept, for powering appliances at a fitness club, is proposed by Strzelecki et al. [35]. The output power from this generator is capable of powering various appliances like a lighting system, a television, a radio, etc. Therefore the human exercising power in any gym can be utilized in many constructive ways rather than being simply wasted.

Fig. 11: Laboratory model of cycling generator [34]

2. ***Hand-cranking generators**:* The working principle of hand-cranking generators is the same as that of pedal powered generators, i.e. to convert the mechanical energy into electrical energy. The difference is that the mechanical energy input method comes from the hand cranking rather than via pedaling as shown in Fig.12. Many concepts of hand-cranking generators using shaking, gearless systems using pulling, etc, have been developed. Use of a portable charkha [36] is one example of hand-cranking generators, which can be used in rural areas as an alternate energy option. Hand-cranking generators can be used as mobile phone chargers and such manual mobile phone chargers exist while travelling and when there is power outages. According to Windstream Power [37], commercial hand-cranking generators can produces an average continuous power of 50 W with a comfortable hand cranking speed of around 50-60 rpm which are easy to set up via belts/gears.

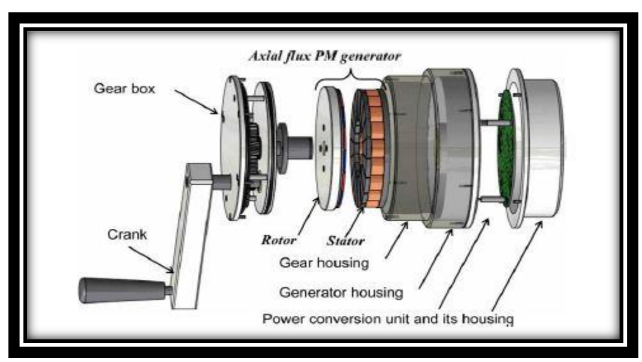

Fig. 12: Exploded view of a hand-cranking generator [23]

3. *Merry-Go-Round (MGRs) Generators:* As described in Table 4, MGRs can produce output power in the range of 100-600 W depending upon the size of the alternator and generator units. The principle behind MGRs consists of harnessing the human power of children playing on merry-go-rounds in

schools or playgrounds as shown in Fig. 8. Therefore, the energy conversion process can be very much enjoyable.

Fig. 13: Children playing on a merry-go-round [38]

With the help of a cylinder containing compressed air, significant power output can be obtained using MGRs and other playground rides such as see-saws. In these types of generators, the power is developed by doing work against the compressed air. The only limitation of compressed air powered generators is their low efficiency. However, the overall system is bulky as compared to pedal-powered and hand-cranking generators.

CONCLUSIONS

The paper has introduced the concept of providing human effort generated electrical energy to charge assistive exoskeletons. It has been observed that hand cranking generators are suitable as a portable energy source option for charging lower-limb mobility exoskeletons. It is clear that pedaling involves rotation of a crank using the lower limbs which is not a viable option for persons needing assistance for mobility tasks. Therefore, despite having greater potential for power output than hand-cranking generators, pedal powered generators could be viable for charging upper body exoskeletons for assisting reaching and manipulation tasks. Similarly the third case, namely merry-go-round generators are not appropriate for use as portable human energy harvesting devices due their bulky size even though they can easily generate 100-300 W power. Experimental aspects of designing and deploying assistive exoskeletons which are charged via human energy harvesting devices is being explored by the authors in their on-going research activities.

REFERENCES

[1] B. S. Rupal, A. Singla, and G. S. Virk, "Lower limb Exoskeletons: A Brief Review", Conference on Mechanical Engineering and Technology (COMET-2016), IIT (BHU), Varanasi, India, 2016.

[2] G. Singh, A. Singla, and G. S. Virk, "Modeling and Simulation of a Passive Lower-body Mechanism for Rehabilitation", Conference on Mechanical Engineering and Technology (COMET-2016), IIT (BHU), Varanasi, India, 2016.

[3] H. Kazerooni and R. Steger, "The Berkeley Lower Extremity Exoskeleton," Journal of Dynamic Systems, Measurement, and Control, vol. 128(1), pp. 14-25, 2006.

[4] A. B. Zoss, H. Kazerooni, and A. Chu, "Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)," IEEE/ASME Transactions on Mechatronics, vol. 11(2), pp. 128–138, 2006.

[5] M. Cenciarini and A. M. Dollar, "Biomechanical Considerations in the Design of Lower Limb Exoskeletons," IEEE International Conference on Rehabilitation Robotics (ICoRR), pp.1-6, 2011.

[6] H. Kawamoto, S. Lee, S. Kanbe, and Y. Sankai, "Power Assist Method for HAL-3 using EMG-based Feedback Controller," IEEE International Conference on Systems, Man and Cybernetics, Vol. 2, pp. 1648-1653, 2003.

[7] K. Yamamoto, K. Hyodo, M. Ishii, and T. Matsuo, "Development of Power Assisting Suit for Assisting Nurse Labor," JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, vol. 45(3), pp. 703–711, 2002.

[8] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The RoboKnee: An Exoskeleton for Enhancing Strength and Endurance During Walking," Proceedings in IEEE International Conference on Robotics and Automation, vol. 3, pp. 2430–2435, 2004.

[9] Aaron M. Dollar and Hugh Herr, "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art", IEEE Transactions On Robotics, vol. 24(1), pp. 144-158, 2008.

[10] K. Shima, R. Eguchi, K. Shiba and T. Tsuji, "CHRIS: Cybernetic Human-Robot Interface Systems," Proceedings of International Symposium on Robotics, vol. 38, 2005.

[11] R. Ramakumar, H. J. Allison, and W. L. Hughes, "Prospects for Tapping Solar Energy on a Large Scale," Solar Energy, vol. 16 (2), pp. 107–115, 1974.

[12] S. Hozumi, "Development of Hybrid Solar Systems using Solar Thermal, Photovoltaics, and Wind Energy," International Journal of Solar Energy, vol. 4(5), pp. 257–280, 1986.

[13] Ramakumar and W. L. Hughes, "Renewable Energy Sources and Rural Development in Developing Countries," Special Issue on Energy Related Studies, IEEE Transaction Education, vol. 24 (3), pp. 242–251, 1981.

[14] P. Tu, S. M. Hock, R. W. Thresher, and T. J. McCoy, "Potential of Hybrid Wind Energy Systems for Utility System Applications," American Society Mechanical Engineers, Solar Energy Division (Publication) SED, vol. 12, pp. 5, 1992.

[15] J. B. Lee, Z. Chen, M. G. Allen, A. Rohatgi, and R. Arya, "A High Voltage Solar Cell Array as an Electrostatic MEMS Power Supply," Proceedings in IEEE Workshop Micro Electro Mechanical Systems, pp. 331–336, 1994.

[16] K. Sangani, "Power Solar-The Sun in your Pocket," Engineering and Technology, vol. 2 (8), pp. 36–38, 2007.

[17] C. M. Colson and M. H. Nehrir, "Evaluating the Benefits of a Hybrid Solid Oxide Fuel Cell combined Heat and Power Plant for Energy Sustainability and Emissions

Avoidance," IEEE Transactions on Energy Conversion, vol. 26, (1), pp. 140–148, 2011.

[18] A. Roy, S. B. Kedare, and S. Bandyopadhyay, "Optimum sizing of Wind-Battery Systems incorporating Resource uncertainty," Applied Energy, vol. 87 (8), pp. 2712–2727, 2010.

[19] P. F. Ribeiro, B. K. Johnson, M. L. Crow, A. Arsoy, and Y. Liu, "Energy Storage Systems for Advanced Power Applications," Proceedings of the IEEE, vol. 89 (12), pp. 1744–1756, 2001.

[20] Electricity Energy Storage Technology Options, A white Paper primer on Applications, Costs, and Benefits EPRI Publication 1020676.

[21] H. Louie, K. Peng, E. Hoffstetter, S. J. Szablya, "Design and Testing of a Small Human-Powered Generator for Developing Rural Communities," North American Power Symposium (NAPS), pp. 1-8, 2010.

[22] J. Lee, D. Koo, S. Moon and C. Han, "Design of an Axial Flux Permanent Magnet Generator for a Portable Hand Crank Generating System," IEEE Transaction on Magnetics, Vol. 48 (11), 2012.

[23] D. Bang, S. Ani, H. Polinder, J. Lee, S. Moon and D. Koo, "Design of Portable Axial Flux Permanent Magnet Machines for Human Power Generation," IEEE Transactions on Magnetics, vol. 48 (11), pp. 2977-2980, 2012.

[24] L. Wu, A. Zachas, R. G. Harley and T. G. Habetler, "Design of Portable Hand Crank Generating System to Power Remote Off-Grid Communities," IEEE Power engineering society conference and exposition in Africa, vol. 48 (11), pp. 1-8, 2007.

[25] Y. Rao, S. Cheng and D. P. Arnold, "An Energy Harvesting System for Passively Generating Power from Human Activities," Journal of Micromechanics And Microengineering, vol. 23 (11), 2013.

[26] S. J. Roundy, "Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion," Dissertation, University of California, Berkeley, 2003.

[27] T. Sterken, K. Baert, R. Puers, and G. Borghs, "Power Extraction from Ambient Vibration," SeSens 2001. Dutch Technology Foundation STW, 2001.

[28] T. Sterken, P. Fiorini, K. Baert, G. Borghs and R. Puers, "Novel Design and Fabrication of a MEMS Electrostatic Vibration Scavenger," Power MEMS Conference, pp 18–21, 2004.

[29] D. S. Snyder, "Vibrating Transducer Power Supply for Use in Abnormal Tire Condition Warning Systems," U.S. Patent 4384382, 1983.

[30] D. S. Snyder, "Piezoelectric Reed Power Supply for Use in Abnormal Tire Condition Warning Systems," U.S. Patent 4510484, 1985.

[31] H. A. Sodano, G. Park, D.J. Leo, and D.J. Inman, "Use of Piezoelectric Energy Harvesting Devices for Charging Batteries," Proceedings in Smart Structures and Materials: Smart Sensor Technology and Measurement Systems of the SPIE 5050, pp. 101–108, 2003.

[32] S. Roundy and P. Wright, "A Piezoelectric Vibration Based Generator for Wireless Electronics," Smart Materials and Structures, vol. 13, pp. 1131–1142, 2004.

[33] A. R. Mechtenberg, K. Borchers, E. W. Miyingo, F. Hormasji, A. Hariharan, J. V. Makanda and M. K. Musaazi, "Human power (HP) as a Viable Electricity Portfolio Option Below 20 W/Capita," Energy for Sustainable Development, vol. 16, pp. 125–145, 2012.

[34] P. S. Tiwari, L. P. Gite, M. M. Pandey and A. K. Shrivastava, "Pedal Power for Occupational Activities: Effect of Power Output and Pedaling Rate on Physiological Responses," International Journal of Industrial Ergonomics, vol. 41 (3), pp. 261–267, 2011.

[35] R. Strzelecki, M. Jarnut and G. Benysek, "Exercise Bike Powered Electric Generator for Fitness Club Appliances," European Conference on Power Electronics and Applications, pp. 1-8, 2007.

[36] M. Tariq, K. Shamsi and T. Akhtar, "A Portable Manual Charkha Based Power Generation System for Rural Areas," ISESCO Journal of Science and Technology, vol.9 (16), pp. 89-93, 2013.

[37] www.windstreampower.com/humanpower/hpgmk3.html

[38] S. R. Pandian, "A Human Power Conversion System Based on Children's Play," IEEE International Symposium On Technology and Society, pp. 54-61, 2004.