A Hula-Hoop Inspired Human-Powered Electric Generator and Estimation of Conversion Efficiency based on Quantitative Assessment of Metabolic Energy Expenditure

Yoon-Ho Lim[1], Jeong-Jin Yeo[1], Mun-Ho Ryu[2] and Yoon-Seok Yang[2]

[1] Department of Healthcare Engineering, Chonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
[2] Division of Biomedical Engineering, Chonbuk National University, 567 Baekje-daero, deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea
Luhfriend1@nate.com, yeojjin85@gmail.com, {mhryu, ysyang}@jbnu.ac.kr

Abstract. Conventional self-electric generators are usually based on pedaling or rotary crank motion, which requires intensive work of lower or upper limb muscle. They are sometimes very useful, however, it is hard to keep these motions for a long time in order to obtain substantial amount of electric energy. In this study, we developed a large-sized human powered electric generator motivated by the hula-hoop motion for higher output enabled by bearable handling. The effectiveness of the developed human powered generator was estimated by measuring output electric energy and metabolic energy expenditure of operating human subjects. The calculated conversion efficiency of metabolic to electric power was 1.18% no less than other human powered generator. More importantly, the results also showed that the developed generator could be driven more than 5 min consistently without any muscular fatigue and was able to produce 700 mW average output electricity. which verified the feasibility of the technology. Ongoing study is focusing on improving its output by augmenting more electromagnetic conversion units and reducing frictional loss. Further research will test its first application as an indoor and outdoor lighting appliance.

Keywords: Human-powered generator, large electricity, whole-body movement, metabolic assessment

1 Introduction

Conventional human-powered self-electric generators hey are very useful for some occasions like emergency. However, it is difficult to obtain large electricity by using them. Since they normally adopt crank or pedaling dynamos, which require constant muscular activities of upper or lower limb, a long durational monotonous operation tends to cause quick muscle fatigue.

There have been a lot of research efforts to develop technology which can harvest human energy [1-2]. Most of them are concerned with the conversion efficiency at resonance condition or finding viable ambient source in human movements and its surroundings [3-4].

This study aims to develop a practical human-powered generator which can produce substantial amount of electric energy from strong longitudinal electromagnetic coupling and whole-body driving structure inspired by a hula-hoop motion for long durational operation with less fatigue in limb muscles. Moreover, we measured a metabolic energy expenditure to estimate the calorie consumption while operating the generator, which can yields the exercise load required to drive the generator and the conversion efficiency.

2 Materials and Methods

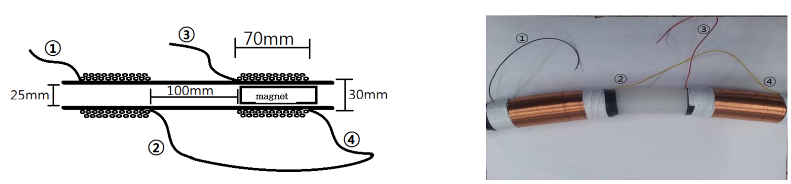
2.1 Human-powered generator inspired by hula-hoop

A human-powered generator was implemented in a ordinary hula-hoop by winding solenoids on outer surface of the poly-vinyl- chloride (PVC) pipe and putting a strong neodymium magnet inside so that it could produce electric power when the magnet is circling round in the pipe. In general, the energy conversion efficiency of generator using kinetic sources depends on the degree of electromagnetic coupling [5-6].

Among many configurations, the longitudinal formation provides the strongest coupling magnitude by allowing high concentration of magnetic flux to cross the coils [7]. More importantly, it can be easily realized by using a pipe body of the hula-hoop. The diameter of the hoop is 1000 mm and the outer and inner diameter of the pipe is 30 mm and 25 mm, respectively. The magnet has 100 mm length and 20 mm diameter. The total weight of the generator including coil winding and moving magnet is 1500 g.

The winding and wiring patterns of solenoid coils shown in Fig. 1 are related to the length of the magnet in order to increase the output by matching opposite phases of the induced voltages in separate solenoids [5].

A pair of solenoids has 70 mm winding region and 100 mm spatial gap in the middle. There are 2 pairs of solenoids along the hoop.



(a) (b)

Fig. 1. (a) schematic diagram, (b) The electromagnetic configuration of the hula-hoop generator.

2.2 Measurement of metabolic energy expenditure while operating the developed generator.

The generated electric power was measured by using a NI USB-6009 DAQ (National Instruments, USA) and LabView (National Instruments, USA) as shown in

Fig. 2. One 62 Ω resistor was connected at the output terminal as a load resistance which matched the internal resistance of the generator. In order to estimate the human metabolic energy required to steer the developed generator and the overall efficiency of human-powered electricity generation, we measured the metabolic energy expenditure while operating the generator by using a Quark CPET (COSMED, Italy), cardiopulmonary exercise test equipment based on breath-by-breath gas exchange analysis as shown in Fig. 3. The generating hoop was suspended to a ceiling by a 4-way rope to make the steering motion more convenient and efficient.

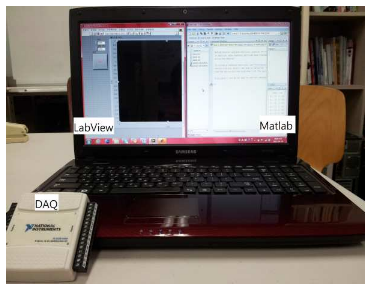


Fig. 2. The data acquisition device and software to measure the generator output.

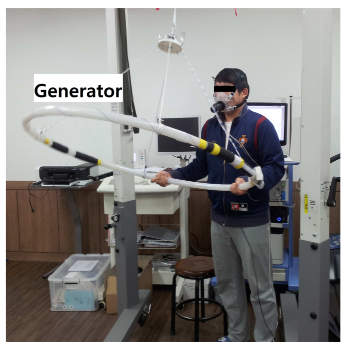


Fig. 3. The experimental setup for metabolic assessment of exercise load required to steer the hula-hoop generator.

All Four young male subjects (age: 24.5±3 year, height: 172±5 cm, and weight: 68.8±9 kg) participated in the experiment and they had no illness or disability. They were instructed to steer the generator so that the magnet could keep the circling motion after it began to travel along the pipe.

Table 1 shows the procedure for measuring resting and exercise metabolism. For consistent measurement, any extra activities which could affect the measurement such as conversation and stretching were prohibited for resting period.

Table 1. Experimental procedure for measurement of metabolism

Resting metabolic Rate	Exercise metabolic rate	Resting	Exercise metabolic rate	Resting	Exercise metabolic rate
5 min.	5 min.	5 min.	5 min.	5 min.	5 min.

3 Results and Discussions

Table 2 shows the output power of the developed hula-hoop generator with the corresponding metabolic energy expenditure assessed by subtracting the resting metabolic rate from the exercise metabolic rate for all 4 participants.

Table 2. Assessment of metabolic energy expenditure and the generated electric power

No.	Age (yr.)	Height (cm)	Weight (kg)	Resting metabolic rate (Kcal/min)	Metabolic energy expenditure (Kcal/min)	Generated electric power (W/min)	Overall efficiency (%)
1	28	170	70	2.03	2.97	53.25	0.43
					1.90	29.06	0.36
					1.90	53.84	0.64
2	26	167	78	2.16	2.02	45.86	0.54
					1.78	51.32	0.69
					1.46	52.42	0.93
3	20	175	62	2.08	1.10	46.42	1.01
					1.00	49.46	1.18
					1.07	49.30	1.10
4	24	176	65	2.26	2.70	50.05	0.44
					2.72	47.95	0.42
					2.55	49.70	0.46

The measured data showed maximum peak-to-peak voltage of 40 V, maximum output power of 900 mW, and average output power of 700 mW which are considerable amount of generated electricity.

The assessed metabolism also revealed that the exercise load required to steer the developed generator is similar to the load for activities like light gymnastic exercise or cycling. This relatively low energy requirement could be attributed to two facts. Firstly, since all the participant added periodic accelerations to the circling magnet inside the generator by steering the hula-hoop generator rhythmically differently from other continuously rotational dynamo devices. Secondly, they controlled the hula-hoop generator with their whole-body movement not with specific limb muscles, and consequently, none of them reported muscle fatigue during any of experimental period. Therefore, it was verified that we could acquire considerable amount of electricity from hula-hoop generator owing to its substantially large output and possible use of long durational steering.

Table 2 also shows the overall efficiency of human-powered generation, which was obtained by calculating the ratio of the generated electric power to the energy expenditure using the relation, 1 cal = 4.2 J.
It should be more proper to use overall efficiency rather than to use only the mechanic-to-electric conversion efficiency of the generator itself because the feasibility of human-powered electric generator greatly depends on the effectiveness of the driving method.

In fact, there are several factors in each phase of energy conversion affecting the overall efficiency as shown in Fig. 4. In general, about 45 % of the total metabolism is used in skeletal muscle for body movement [7-8]. Still, it is hard to tell how much of them is converted to body movement and how much of the kinetic energy in the body movement is effectively transferred to the steering of the hula-hoop generator since they vary with the different muscle physiology and motion dynamics of each individual. The maximum overall efficiency was estimated to be 1.18 % and this could be improved if the participant had been more accustomed to the steering of the generator as mentioned above.

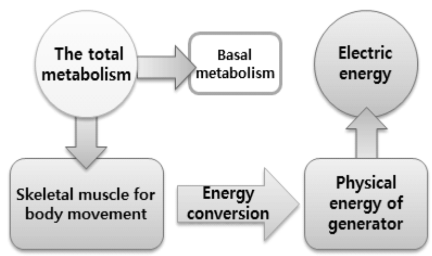


Fig. 4. The overall conversion efficiency from metabolic energy expenditure to electricity generation.

Table 3 shows the metabolic energy expenditure of common exercise activities in daily lives for comparison with that of the developed human-powered generator.

Table 3. metabolic energy expenditure of common exercise activities

Physical activities	Average energy expenditure (Kcal/h)	
Light fitness	90	
Slow gymnastics exercise	120	
Light gymnastic exercise	210	
Cycling	180～300	
Running	800～1000	
Steering of the hula-hoop generator	Participant 1	259
	Participant 2	235
	Participant 3	188
	Participant 4	294

The voltage output was clipped at ±20 V because of the measuring range of the data acquisition hardware (-10 V ~ +20 V) and in fact there were many occasions when the generator output exceeded the 40 V peak-to-peak examined by oscilloscope, we can be sure that the actual power will be a bit larger than measured.

Furthermore, there were 2 pairs of solenoid windings on the hoop and there were room for at least 4 more pairs of solenoids. This implies that it is possible to improve the output more than 3 times than now, that is, 2.1 W.

4 Conclusions

We designed and implemented a human-powered generator which could provide large electricity by using and measured a human metabolic energy expenditure needed to operate it. The experimental results verified its feasibility by confirming its substantial output performance and effectiveness for long durational use owing to the periodic acceleration with rhythmic steering.

Ongoing research focus is to find more effective driving methods which will greatly improve the overall efficiency of the human-powered electric generator.
Further study will include a miniaturization of the proposed generator and integration of electronics for power conditioning and storage for portable applications.

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