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An analysis of the energy flow and energy potential from human energy harvesting with a focus on walking

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Abstract: This paper aims to determine the limitations for electrical energy generation from harvesting mechanical work during walking. The assessment was considered from the point of chemical energy ingested in food, through the development of mechanical work, to the conversion into useful electrical energy from the perspective of the conversion efficiencies. An average person was considered, with four mechanical to electrical energy conversion technologies assessed. It was found that for an individual walking on level ground a potential of up to 5 J/step of electrical energy is available. Stair use impacts this, where stair ascent decreased and descent increased the potential. It was concluded that, although the energy outputs are small, they scale with the number of people, where an estimated potential of 900 MWh/day is calculated in the UK. Harvesting even a fraction of this available potential would appear worthwhile, however, it is unclear if this potential can be practically utilised.

Subjects: Novel Technologies; Renewable Energy

Keywords: human energy harvesting; energy flow efficiency; footfall harvesting; human energy

1. Introduction

The search for alternative forms of energy has increased in recent years in a bid to stem the use of fossil fuels for meeting our energy demands. One such source of energy that has recently gained attention in the media is human energy harvesting, whereby the mechanical work developed by an

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PUBLIC INTEREST STATEMENT

It has become clear in recent years that the way in which society produces the energy we use in everyday life needs to change. The aim of this paper was to examine the potential for electrical energy generation from people. The idea is to make use of energy expended by people in everyday life as they walk around their environment. This energy can be harvested by devices that convert it into electrical energy that can be stored or used for powering electrical loads. Although there has been interest in these technologies, with a number now commercially available, the amount of energy that could be generated from this source of energy is not well understood and is addressed in this paper.

individual is used as a means of generating electrical energy. It seems apparent that the potential power outputs from such technology will represent a widespread, diverse but low power source of energy, due to the diffuse distribution of people and the limitations on the mechanical work that can be developed by an individual. Several companies, such as Pavegen©, Innowattech and sustainable dance club (SDC), have developed devices to harvest energy from human walking through floor integrated energy harvesting devices. Claims such as "a typical installation of tiles with sufficient footfall will provide enough energy to power lighting for over 12 hours" (Pavegen, 2013) have been made, however, no verification of such claims are presented. Indeed the ambiguous nature of such claims makes an assessment very difficult. As such the focus of this paper is on the assessment of the flow of energy through the process of energy generation from the point of chemical energy ingested in food to the production of useful electrical energy. This will be used to determine the fundamental limitations to the energy potential available from footfall energy harvesting devices.

The paper is split into two sections; the first considers energy in people and the second is concerned with the conversion of mechanical work into useful electrical energy. The process of energy flow through the supply chain is examined, starting with the ingestion of food and an examination of the process of developing mechanical work. It is recognised that the user/device interface determines the mechanical energy input into the energy harvesting system. This mechanical work is then converted into useful electrical energy by the energy harvesting system. Various technologies can be implemented to achieve this, with a range of efficiencies and expected generated energy outputs for each of these technologies to be determined. The flow of energy will be examined through considering the conversion efficiency of each step, from the ingestion of food energy to the expected useful electrical energy output to determine a fundamental limit to the available energy potential from a single footstep.

2. Categorisation of energy harvesting sources

In determining the harvesting efficiency it was necessary to consider the various types of energy harvesting. Converting the mechanical work carried out by the human body into useful electrical energy was considered to be carried out by the harvesting device and electrical system. The process of energy harvesting requires a device to harvest energy expended by the human body. This can be carried out in many ways, but care is required while analysing the various approaches.

Harvesting devices were split into three categories based on the type of energy source that is being exploited. It is important to consider the work carried out on the device by the user and hence the user/device interface needs to be assessed. The three categories are outlined as follows:

(1) *Parasitic*: A device that acts to harvest energy from a user's actions, without having a significant impact on the user. The action is one which the user would normally carry out during their everyday life (e.g. footfall harvesting while walking).
(2) *Direct purpose*: The device requires specific action from the user, with the express goal of providing energy to achieve a desired outcome (e.g. Hand crank on a torch).
(3) *Recreational*: These aim to utilise a users desire to exercise/play, allowing for energy to be harvested from this (e.g. Energy generating cycling machine in a gym).

There are a number of general points that can be made about these sources. A general rule that applies to all sources of human power is that they will require the user to expend energy for it to be harvested. In general parasitic devices will only take a small amount of energy from each person per action as harvesting too much energy would be detrimental to the individual or the activity in which they are engaged. In contrast direct purpose and recreational devices are designed with the aim of utilising actions specifically and consciously carried out to generate energy, allowing considerably more of the expended energy to be harvested, through acceptance by the individual that there will be a significant impact on them. In the case of walking, the source is considered to be parasitic in nature and is the focus of this paper.

3. Flow of energy in people

3.1. Energy input

The energy required by humans to carry out the processes necessary for survival is provided by the chemical energy contained within the food we consume. The energy available for carrying out these functions is known as the metabolisable energy (ME) and is the energy available after faecal, urinary and gaseous losses have been accounted for in the digestion of the gross energy content of food (Tontisirin, MacLean, & Warwick, 2003). The average ME available for adults in the UK is 10.9 MJ/day for men and 8.7 MJ/day for women (SACN, 2011), giving an average of 9.8 MJ/day.

3.2. Energy use

This ME is used to carry out all of the processes required by the human body. The largest component of energy expenditure (EE) is usually the basal metabolic rate (BMR), which is considered to account for the vital functions required for life (Geissler & Powers, 2010). The contribution of BMR to total EE varies greatly between individuals depending on gender, body size, body composition and age (FAO, WHO, & UNU, 2004). This is expected to account for 45–70% (FAO, WHO, & UNU, 2004) or 60–75% in developed nations (Geissler & Powers, 2010), with an average value of 65% to be assumed. The EE needed to carry out the BMR requirements of an adult can be estimated using Table 1. Another source of energy use is the body's response to thermogenic stimuli such as consuming food or the body's response to temperature and is assumed to account for roughly 10% of daily EE (FAO, WHO, & UNU, 2004). The remaining energy is assumed to be available for physical activity, and is thus assumed to be 25% of daily EE.

When carrying out physical activities the human body expends additional power, this can be measured in the units of metabolic equivalent (METs), where the value for a given activity represents the power expended to carry out an activity as a multiple of the BMR, with values for some everyday activities given in Table 2. This METs value is a useful metric in determining the total power expended during a given activity.

Based on a daily ME of 9.8 MJ/day, 2.45 MJ/day (0.68 kWh/day) of energy is available for physical activity in an individual. This is similar to values in the literature of 3.35 MJ/day (Gilmore, 2008) and 1.98 MJ/day (Louie, Peng, Hoffstetter, & Szablya, 2010), with the discrepancies being a result of

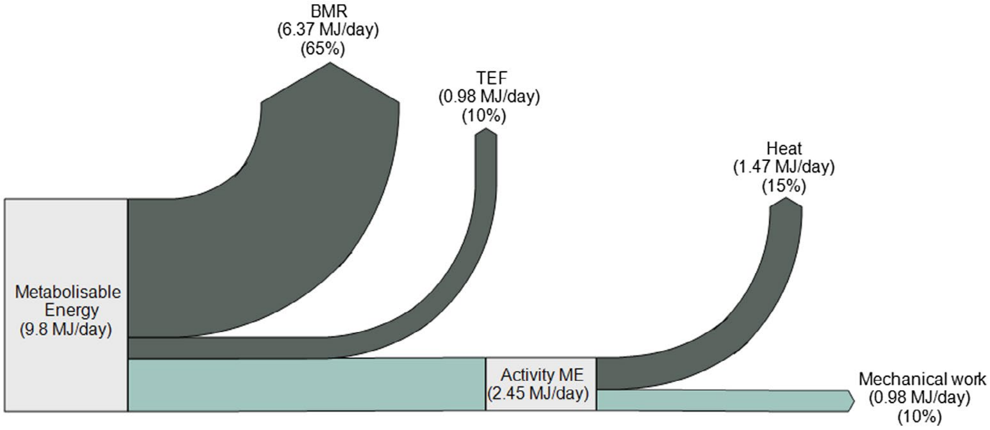
Table 1. Equations for the determination of the basal metabolic rate of adults (Compiled from FAO, WHO & UNU, 2004)

Gender	Age (years)	BMR	
		(MJ/day)	(kcal/day)
Male	18–30	0.063 kg + 2.896	15.057 kg + 692.2
	30–60	0.048 kg + 3.653	11.472 kg + 873.1
Female	18–30	0.062 kg + 2.036	14.818 kg + 486.6
	30–60	0.034 kg + 3.538	8.126 kg + 845.6

Table 2. EE of various activities, expressed as a multiple of BMR (Compiled from Ainsworth et al., 2000)

Activity		METs
Sleeping		0.9
Standing		2.0
Walking	Down stairs	3.0
	For pleasure	3.5
	Up stairs	8.0

Figure 1. Sankey diagram showing the process of developing mechanical work in the human body.



differing assumptions. The UK has approximately 60 million inhabitants, giving a total available energy of 1.47 × 10^{14} J/day (40.8 GWh/day). Although this seems to suggest that there is significant potential, it is somewhat misleading as developing mechanical work results in significant losses. Furthermore it seems fairly obvious that not all of the energy available for physical activity can be harvested due to the need of mechanical work in carrying out everyday activities. Even so, if a small fraction of this potential could be harvested it could produce a significant amount of energy.

3.3. Mechanical work from physical activity

The development of useful mechanical work results in significant losses, however determining an appropriate measure of the efficiency is not straightforward. The development of mechanical work by a single muscle can be carried out with an efficiency of ~40% (He, Bottinelli, Pellegrino, Ferenczi, & Reggiani, 2000), with the energy losses dissipated in the form of heat. A representation of the flow of energy in the developing mechanical work from ME is shown in Figure 1. It should be noted that this refers to the total available potential for harvestable mechanical work over the course of a day. It does not consider the approach to utilising this potential for a particular activity but acts to highlight the limit for energy harvesting potential from the average individual.

Determining the efficiency of carrying out specific activities is more complicated, with several measures of efficiency used within the literature. It was considered that the net efficiency is the most appropriate measure in this instance, as it takes into account all of the energy expended on top of the BMR in performing a physical activity. The BMR is discounted from the efficiency as it occurs regardless of activity and is not a direct result of carrying out the activity, with the net efficiency of different activities given in Table 3. It is assumed that any additional EE over the BMR is a result of carrying out an activity. It is noted that the efficiency of walking and running is significantly higher than most other forms of mechanical work. This is due to the recycling of negative work in the human body, where energy is stored elastically and then released as positive work over the gait cycle (Cavagna & Kaneko, 1977).

Table 3. Net efficiency of carrying out different physical activities

Activity	Net efficiency (%)	Reference
Walking	35–40	Cavagna and Kaneko (1977)
	~35	Umberger and Martin (2007)
Running	45–80	Cavagna and Kaneko (1977)
Cycling	25.7	Capelli, Ardigò, and Zamparo (2008)
Rowing	19.8	Fukunaga, Matsuo, Yamamoto, and Asami (1986)
Ergometer arm work	15.8	Poulsen and Asmussen (1962)
Arm crank	23.4	Goosey-Tolfrey and Sindall (2007)

Table 4. Summary of the parameters assumed in determining the efficiency of producing harvestable mechanical work

Inputs	Metabolisable energy	10.9 (MJ/day)
	Walking EE	16.24 (kJ/min)
	Cadance	90 (Steps/min)
Parameters	Daily BMR	65 (%)
	Rate of BMR	4.64 (kJ/min)
	TEF	10 (%)
	ME-Walking	35 (%)
	Harvestable walking work	0.648 (kJ/min)

$$\text{Net efficiency} = \frac{\text{Mechanical work}}{\text{Total energy expenditure} - \text{BMR}}$$

3.4. Harvesting potential

When considering the potential energy available from human energy harvesting it is evident that much of the mechanical work involved with most activities is not available for harvesting, as it is required to complete an action. An estimate of the energy available for harvesting can be determined by the work done on the harvesting device and is to be termed the harvestable work.

In the case of walking this is a result of the interaction between the foot and the harvesting device, where the harvestable work is given by,

$$\text{Harvestable work} = \text{F.d} = \text{GRF} \times m \times g \times d$$

Where m is the mass of the user, g is gravitational acceleration and d is the displacement. The GRF term refers to the ground reaction force and acts to account for the additional force applied to the ground during walking. Values for the ground reaction force (GRF) during walking on a level surface are found to be 1.2 times the body weight (BW). For stair ascent and descent they are ~1.1BW and 1.6BW respectively (Stacoff, Diezi, Luder, Stüssi, & Kramers-de Quervain, 2005). For the example of a 70 kg individual walking on level ground, where a 10 mm displacement occurs, results in a harvestable work of 8.4 J/step. The proportion of mechanical work that can be harvested from walking is then determined using Table 4,

$$\text{Harvesting potential} = \frac{\text{Harvestable work}}{\text{Energy expended} - \text{BMR}}$$

The BMR has been calculated using the equations set out in Table 1 for each of the four groups set out and for a 70 kg individual. The mean of these values was used to determine an average value, where BMR = 4.62 kJ/min (6.65 MJ/day) is assumed. The flow of energy in developing harvestable energy for a 70 kg individual walking on level ground is represented in Figure 2 (Table 5).

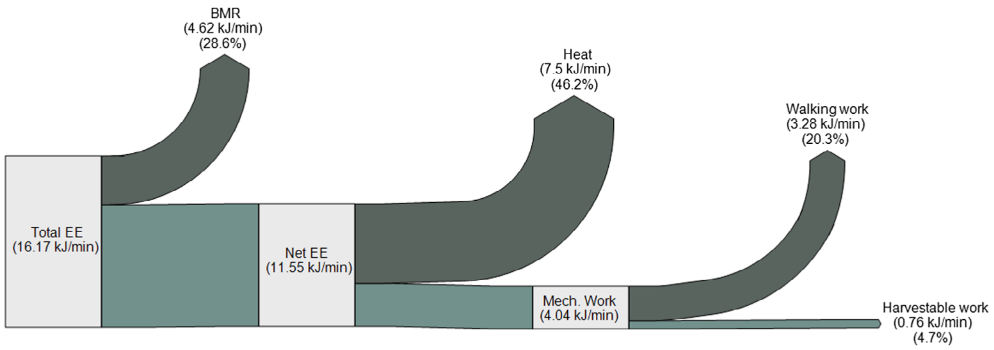


Figure 2. Sankey diagrams representing the use of metabolic energy during walking and the energy available for harvesting.

4. Electrical energy

4.1. Electrical energy conversion

Thus far the process of developing mechanical work by the human body has been discussed. The conversion of this mechanical work into useful electrical energy will now be considered. Several technologies have been implemented as means of converting the mechanical work carried out on a harvesting device into electrical energy. The technologies to be considered here are piezoelectric, electromagnetic and dielectric elastomer generators. A range of conversion efficiencies are considered for each technology based on the relevant literature. It is worth noting that the output energy from Figure 2 is considered to be the input energy into the energy conversion system.

Two types of piezoelectric generators are considered, these being PZT ceramic and PVDF polymer. It is expected that PZT has a fundamental efficiency limit of 56% (Antaki, Bertocci, & Green, 1995), a device was developed by (Shenck, 1999) with an efficiency of 20.1%. One problem associated with PZT is the high elastic modulus which results in small displacements and hence limits the available energy (Starner & Paradiso, 2004). PVDF polymers, which are capable of much larger displacements, however exhibit much lower efficiencies. An upper limit of 25% is expected (Kymissis, Kendall, Paradiso, & Gershenfeld, 1998), however practical device efficiencies are normally closer to 2% (Fourie, 2009).

Electromagnetic generators are a mature technology, but require the input displacement to be converted to high speed rotational motion. This can be achieved through gearing or a rack and pinion system, with single stages capable of 98–99% efficiency (Ewart, 1997). A three stage system is assumed to be capable with an efficiency of >94% for a well designed system. Generator efficiencies of 70% are expected to be achievable in the 10s of Watts range (Arnold, 2007). The practical system presented in (Li, Naing, & Donelan, 2009) achieved 64.7%, although another system operating at similar power levels was presented by (Rome, Flynn, Goldman, & Yoo, 2005) and only achieved a 30–40% practical efficiency.

Dielectric elastomer generators have begun to be considered in recent years and appear to offer good generation characteristics. It is claimed that theoretical efficiencies of 80–90% could be expected (Pelrine & Kornbluh, 2001), with a device presented in (Kornbluh et al., 2011) achieving an efficiency of 33%. It is claimed in this work that high energy densities and low stiffness make dielectric elastomers very well suited to generation from human activity.

The energy output from the generators must then be rectified and conditioned before it is either stored or used by the load. It is thought that this can be achieved simply for electromagnetic generators, with a rectification efficiency of 95% found in (Rome et al., 2005).

Piezoelectric and dielectric elastomer generators are expected to require more complicated electronics, due to the high voltage characteristics of the output (Platt, Farritor, & Haider, 2005) and (Pelrine & Kornbluh, 2001). It was shown in (Lee & Han, 2011) that rectification and conditioning efficiencies of 93 and 90% respectively were achieved for a piezoelectric generator. It is expected that similar efficiencies are achievable for dielectric elastomer generators, however little literature deals with this.

The efficiency of each step in the process of converting mechanical work into useful electrical energy is presented in Table 6, along with the range of overall conversion efficiencies for each generation technology.

Using the example of a 70 kg individual discussed in the previous section, a range of expected energy outputs for each of the technologies presented can be determined, with the results presented in Table 7.

4.2. Energy storage

The useful energy output is then either used directly by a load or stored for use when required. In terms of energy storage, the main technologies to be explored are secondary chemical battery and super capacitor technologies, with Table 8 summarising the round trip efficiencies.

4.3. Energy generation process

The maximum and minimum efficiency of the process of energy generation is represented in Figures 3–5 for PZT, electromagnetic and dielectric elastomer technologies.

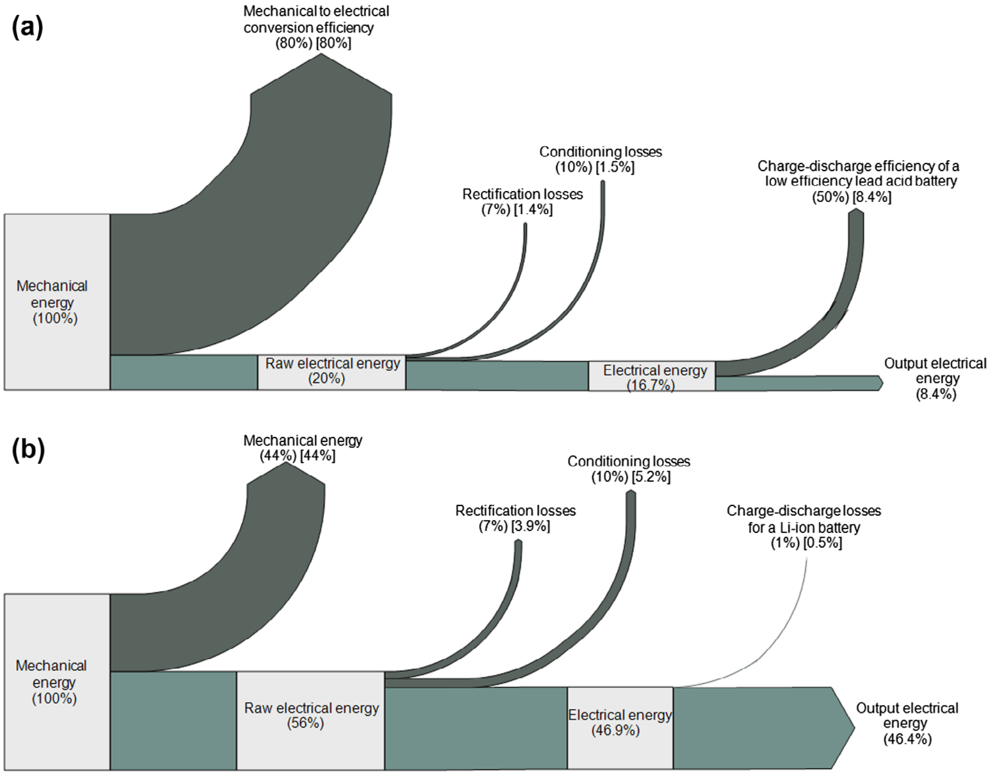


Figure 3. Sankey diagram showing the (a) minimum and (b) maximum efficiency of the process of electrical energy generation for a PZT generator.

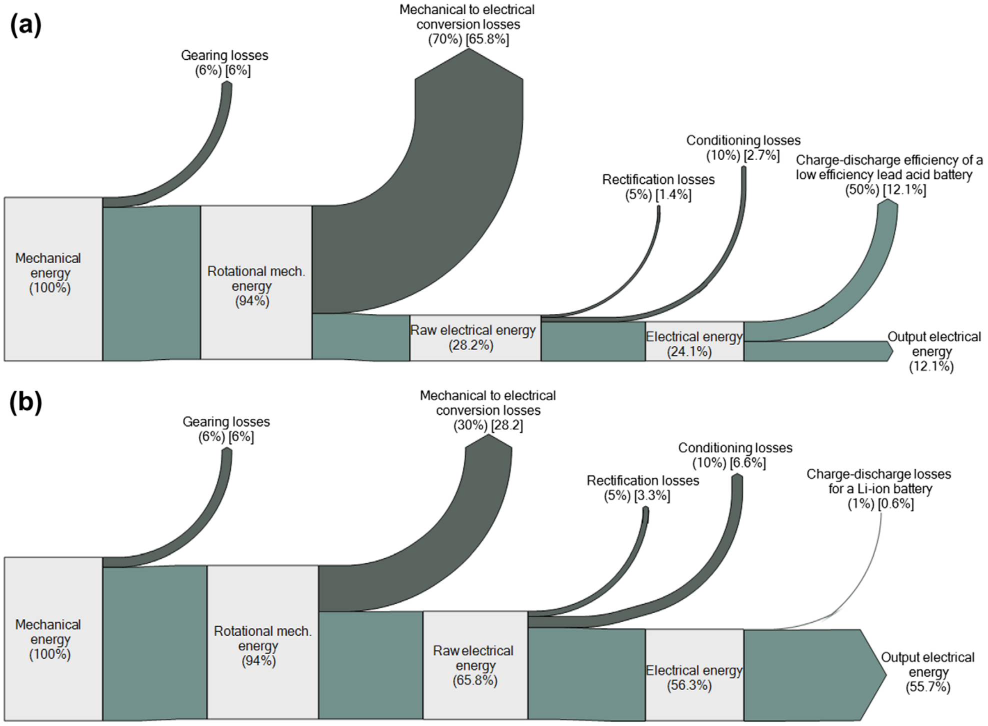


Figure 4. Sankey diagram showing the (a) minimum and (b) maximum efficiency of the process of electrical energy generation for an electromagnetic generator.

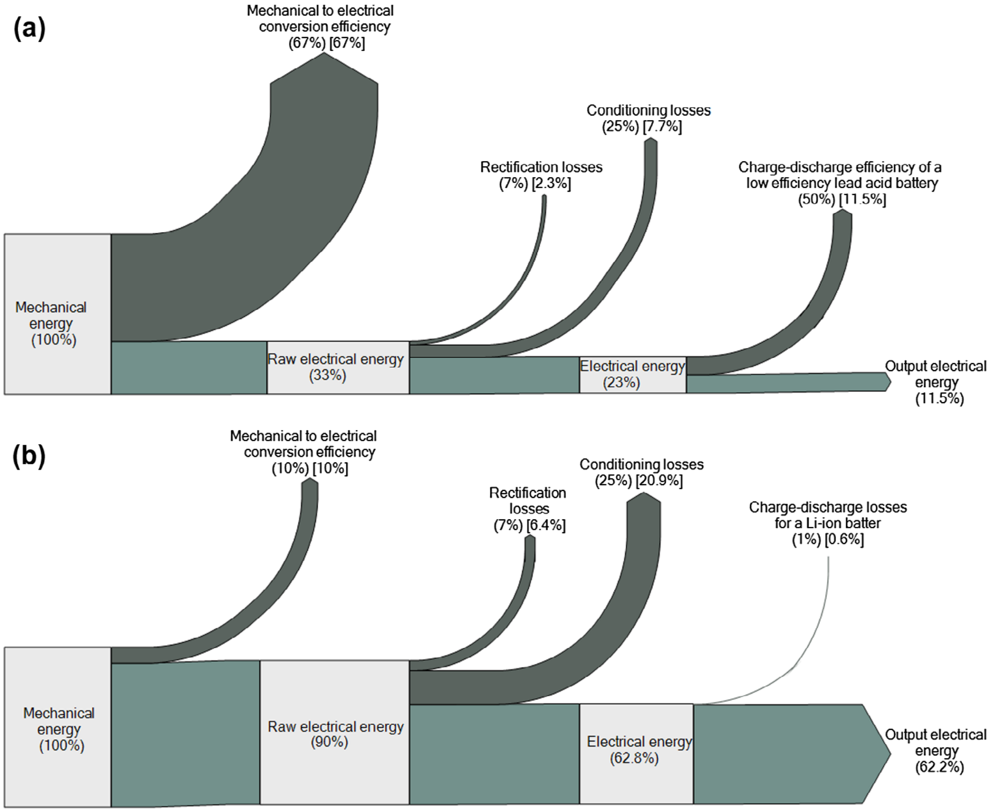


Figure 5. Sankey diagram showing the (a) minimum and (b) maximum efficiency of the process of electrical energy generation for a dielectric elastomer generator.

5. Discussion

In considering the potential for electrical energy generation from human activity it is necessary to consider the source of this energy. Although significant amounts of energy are consumed and expended by the human body over the course of a day, it is evident that only a small proportion of this is available for harvesting in the form of mechanical work. On average, only 25% of the expended energy is used for physical activity, with the remainder being used to carry out functions required by the body to survive. Much of the energy available for physical activity is lost in the process of developing mechanical work, with peak muscle efficiencies in the region of 40%. This results in a total daily energy potential from mechanical work of ~1 MJ, as can be seen in Figure 1.

It is evident that much of this mechanical work is required to carry out the action for the associated physical activity. Walking has been used as an example to try and determine the proportion of mechanical energy that is available for harvesting. Walking at a comfortable speed on level ground results in an increase in EE to 3.5 METs and results in the proportion of energy expended on the BMR during walking being 28.6%. As such more than 70% of the total EE is expended on carrying out physical work. The net efficiency of walking is fairly high when compared to other forms of physical activity, with an efficiency of ~35%. The available energy potential determined for walking is based on the assumptions laid out in Section 2. It is worth noting that the energy potential can be increased by allowing for greater deflection, however, the greater the magnitude of the deflection the greater the effect on the user. It was deemed that a 1 cm deflection would not inhibit the user's action significantly. Using these values it was determined that 4.7% of the total energy expended during walking could be available for energy harvesting, amounting to 8.4 J/step. It is also possible to estimate the potential for energy harvesting from an individual over the course of the day. It has been suggested that the number of steps/day is anywhere between 4,000 and 18,000 steps/day and that 10,000 is a reasonable approximation (Tudor-Locke et al., 2011). This results in a potential from walking of 84 kJ/day (23.3 Wh/day) for a 70 kg person.

The implementation of floor devices on stairs has an effect on both the energy potential and the proportion of energy available for harvesting. Walking up stairs has a negative impact on both the available potential, 7.7 J/step, and the proportion of energy available for harvesting, 3.12%. This is a result of both the lower GRFs and increase in EE. Conversely walking down stairs resulted in an increase in the available energy, 11.2 J/step, and the proportion available to harvesting, 7.47%, owing to the greater value of the GRF and the decrease in the EE value when compared to level walking.

The process of converting this mechanical energy into useful electrical energy can be carried out using a variety of generation technologies, with the range of expected efficiencies shown in Table 5. The highest expected efficiencies are for DE and EM, with system efficiencies of 23–63 and 24–56% respectively. The generation efficiency of commercially available devices is not well presented in the literature, the exception to this being the SDC device where an efficiency of 48% is determined (Paulides & Jansen, 2011). This fits into the higher end of the expected efficiency range for an EM device, which is primarily a result of the high mechanical to electrical efficiency of the generators. In the case of electromagnetic generators, an additional conversion stage is required in translating the motion of the device-user interface into the high speed rotational motion required for efficient operation of the generator. This can be carried out by a gearing system with high efficiency. This additional phase is offset by the relative ease with which the output energy from the electromagnetic generator can be converted into useful electrical energy when compared to piezoelectric or dielectric elastomer generators.

Table 5. Results for the energy expended, developed mechanical work and proportion of energy available for harvesting from level walking and stair use for a 70 kg user

Activity	Harvestable work		Energy expended (kJ/min)	Harvesting potential (%)
	(J/step)	(kJ/min)		
Level walking	8.4	0.76	16.17	6.58
Down stair	11.2	0.69	13.86	7.47
Up stairs	7.7	1.01	36.96	3.12

Table 6. Summary of the efficiency of each step required in the process of converting mechanical work into useful electrical energy

Technology	Gearing efficiency (%)	Mechanical-electrical conversion (%)	Rectification (%)	Conditioning (%)	Overall (%)
PZT	–	20–56	93	90	17–47
PVDF	–	2–25	93	90	2–21
Electromagnetic	94	30–70	95	90	24–56
DE	–	33–90	93	75	23–63

Table 7. Range of expected energy outputs from the proposed energy generation technologies of a 70 kg user for level walking and stair use

	PZT (J/step)	PVDF (J/step)	EM (J/step)	DE (J/step)
Level walking	1.4–3.9	0.2–1.8	2.0–4.7	1.9–5.3
Down stairs	1.9–5.3	0.2–2.4	2.7–6.3	2.6–7.1
Up stairs	1.3–3.6	0.2–1.6	1.8–4.3	1.8–4.9

Table 8. Properties of energy storage technologies

Technology	**Charge-discharge efficiency (%)**		
Reference	**Singamsetti and Tosunoglu (2012)**	**Chen et al. (2009)**	**Perrin and Lemaire-Potteau (2009)**
Lead acid	50–92	70–90	85–93
Nickel cadmium	70–90	60–70	75–86
Lithium ion	80–90	~100	80–98
Super capacitor	–	90+	84–99

The high conversion efficiencies of electromagnetic and dielectric elastomer generators translates into high energy outputs, with the expected outputs for a 70 kg individual presented in Table 7. For level walking the expected energy outputs range from 0.2 to 5.3 J/step, reflecting the large range of expected system efficiencies. The expected range of outputs is reduced for walking upstairs and increased for downstairs, where a maximum of 7.1 J/step is expected. The inclusion of energy storage technologies can have a significant impact on the energy available to the load, although it is expected that high efficiencies can be achieved. All of the technologies presented have been shown to be able to achieve charge-discharge efficiencies of at least 90%, with Li-ion capable of efficiencies of nearly 100%. It appears that the most significant loss occurs in the conversion of mechanical work into electrical energy, due to the wide range of efficiencies and the relatively high conversion efficiency of the other stages.

If it is assumed that the average person takes 10,000 steps/day, giving a range of expected energy outputs of 2–53 kJ/day (0.6–14.7 Wh/day) for an individual. Given that the population of the UK is 60 million, this amounts to a potential for energy generation of 36–882 MWh/day from human walking. This is a significant potential, however harvesting this potential would require a vast expanse of devices Table 9.

6. Conclusions

It is apparent that an individual offers only a limited potential for energy generation, due to the requirements of the human body to carry out the functions necessary to survive and the process of developing mechanical work resulting in significant losses. As a result, for a parasitic harvesting source, such as normal walking, only a small fraction of the developed mechanical work is available as harvestable mechanical work.

Converting the available mechanical work into useful electricity is possible through a range of technologies each with their own pros and cons, although efficiencies of up to 63% are thought to

Table 9. Summary of the results for both harvestable mechanical work and generation potential with a focus on walking

Harvestable potential	**Individual**		**UK**		
	2.45 (MJ/day)		**40.8 (GWh/day)**		
Walking	**Potential**	**PZT**	**PVDF**	**EM**	**DE**
Conversion efficiency (%)	–	17–47	2–21	24–56	23–63
Level (J/step)	8.4 (6.58%)	1.4–3.9	0.2–1.8	2.0–4.7	1.9–5.3
Down stairs (J/step)	7.7 (7.47%)	1.9–5.3	0.2–2.4	2.7–6.3	2.6–7.1
Up stairs (J/step)	11.2 (3.12%)	1.3–3.6	0.2–1.6	1.8–4.3	1.8–4.9
Individual potential (Wh/day)	23.3	4.0–11.0	0.5–4.9	5.6–13.0	5.4–14.7
UK potential (MWh/day)	1,398	239–657	28–294	336–783	322–881

be achievable. For a 70 kg person this amounts to ~5 J/step. Although this is a small amount of energy the total energy scales with both the number of steps taken by a person and the number of people. This results in a potential for energy generation in the UK of up to 900 MWh/day.

In conclusion it appears that significant potential exists for energy generation via human energy harvesting from walking. It is expected that this potential will occur over a very large area and hence is in most situations likely to be a diffuse form of energy, however it is expected that in areas of high activity, significant potential may exist.

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