Development of an auxetic frame for scavenging human kinetic energy

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***Abstract*—Walking, as a routine activity, has a great potential for biomedical energy harvesting, andDielectric Elastomer Generators (DEGs) have high potentials on small-scale wearable applications. In this paper, a test on an instrumented backpack has been performed to evaluate the mechanical energy available. In this task auxetic structures have been proved to significantly increase the DEG performance.**

I. INTRODUCTION

Walking, as a routine activity, has a great potential for biomedical energy harvesting. Center of mass motion, heel strikes, and leg motions are some examples of suitable targets with high energy densities. The use of elastomeric materials allows to develop generators with high flexibility and energy densities, lightweight, and low cost. They are a good candidate to fill the gap in low-frequency and high-stretch energy harvesting area where the other transduction methods are unsuitable[1].For instance, Rome *et al.*in [2]developed a suspended-load backpack that generates 7.4W during fast walking and carrying a 38Kg. The energy gain achievable during walking from the differential forces between human and backpack are significant, but the heavy load will increase the energy expenditure of the user. Thus, the focus of this research is to design a dielectric elastomer generator (DEG) able to scavenge energy from the stretch of the backpack straps without impair the user movement or provide additional load over that of a conventional backpack.The amount of energy gain from a DEG depends on many different material parameters and working conditions, including the mechanicalsetup of the device.In this paper, after having proved that the mechanical energy available in the backpack straps is high enough to scavenge some significant power, different mechanical DEG configurations have been compared in term of energy output, in order to evaluate which one allows to optimally exploit the stretch of the backpack straps during walking.

II. BACPACK CHARACTERIZATION

A. Experimental setup

In order to identify the level of mechanical input available in a backpack instrumented with a DEG strap insertion, the dynamic parameters at stake: load, acceleration and stretching resulting from walking have been identified.The data collection system(Figure 1) is composed by an accelerometer (InvenseSense, MPU-9150), an IR distance sensor (Sharp, GP2Y0A51SK0F), and a load cell (Futek, LSB200, 25lb) all connected to a Teensy 3.2 board, based on an ARMmicrocontroller (32 bit ARM Cortex-M4 72 MHz CPU), to continuously save the data on an memory card. In this phase, the mechanical properties of the DEG have been simulated with different layers of a cheap silicone film integrated on the top of the straps.

FIGURE 1. SET-UP USED TO CHARACTERIZE THE BACKPACK .

The parameters have been evaluated performing five walks for each seven different weights placed in the backpack, ranging from 2.4Kg to 10.9Kg, based on the fact that a backpack should not weight more than 3Kg for a school child and 13Kg for a hiker.

B. Backpack test results

The results of the instrumented backpack are shown in table 1 where the percentages of the average weights and the percentages of the distances along with their standard deviations are reported. It can be seen that the percentage of the average weights sensed by the load cell is quite constant with the backpack load, thus the system is repeatable. Furthermore, the percentages of the distances confirm that, especially for a heavy backpack, there is a deformation close to 45% that can be used as mechanical input for a DEG.

TABLE 1. EXPERIMENTAL RESULTS

Backpack load (Kg)	**Parameters**			
	% W_{mean}	**% W_{std}**	**% d_{mean}**	**% d_{std}**
2.4	24.7	1.6	14.3	0.33
3.4	21.9	1.4	17.8	0.53
5.1	23.9	2.4	23.8	1.4
5.8	23.8	1.17	27.3	1.6
7.5	21.3	0.67	33.3	1.1
8.5	21.7	1.4	37.9	2
10.9	21.5	1.1	44.9	1.5

III. DESIGN OF A DIELECTRIC ELASTOMER GENERATOR (DEG)

A. DEG configurations

In order to transduce mechanical energy a DEG must move between two limit positions:a stretched condition (high capacitance), where the electrical charge has to be placed on the film, and a rest position (low capacitance), where the device surface is minimum, thus the energy stored inside the capacitor increases and power can be scavenged.For a cycle at constant charge *Q*,the net energy gainis determined by the applied mechanical stretch (λ) and the specific energy of the material (U_0)[3].But, in order to evaluate the real energy gain, the ratio ($U_{rel,Q}$) between the net energy gain and the input energy has to be considered.

$$U_{rel,Q} = \frac{U_{H,Q}}{U_{in,Q}} = \frac{1-\alpha^2}{\alpha^2}, \qquad U_{in,Q} = \alpha^2 U_0 \qquad (1)$$

The initial energy ($U_{in,Q}$) is always dependent on the specific energy, but only in the constant charge cycle, is also depending on the contraction ratio α squared, showing that this cycle offers the best relative energy gain. The contraction ratio α is the inverse expansion ratio depending on the stretch λ.

$$\alpha = \frac{A_{min}}{A_{max}} = \frac{z_{max}}{z_{min}} = \sqrt{\frac{C_{min}}{C_{max}}}, \qquad 0 < \alpha \le 1 \qquad (2)$$

In this paper the contraction parameter has been used to compare different DEG configurations: rectangular shape, rectangular shape inserted in a hexagon frame, hexagon frame full, roll, cylinder, bowtie frame full and with a rectangular shape in it. To compare the different configurations, a given stretch on the vertical direction (λ_y=1.15) and a maximum device size are fixed (2x6cm), according to the previous backpack characterization.

B. Configuration comparison

The configurations compared imply different ways of deformation of the DEG for equal mechanical input [4]. The rectangular shape entails a pure-shear stretch, which means that the sample width is constant during the deformation ($\Delta C \propto \lambda^2$). The hexagon frame involves a biaxial stretch depending on the angle variation between the sides ($\Delta C \propto \lambda^4$) and in the worst condition, the cylinder and roll shapes implies a uniaxial stretch of the elastomer ($\Delta C \propto \lambda$). The use of a frame, particularly when it is not full of material (the elastomer will be uniformly stressed) has the additional benefit to provide an initial prestretch to the elastomer, a significant parameter for DEG. However, the hexagon frame doesn't provide an efficient biaxial stretch in term of energy harvesting ($\lambda_x < 0$).

The bowtie frame (Figure 2), named "Rect_in_Bowtie" in table 2, gives the lowest alfa and therefore the higher energy gain ratio ($U_{rel,Q}$ = 0.53).This result can be achieved thanks to the fact that the bowtie is an auxetic frame. This kind of structures replicate the counterintuitive behavior of auxetic material to have a negative Poisson's ratio. When stretched in the longitudinal direction, they undergo a lateral expansion, rather than contracting as usual. The biaxial stretch now has $\lambda_x > 0$ maximizing the capacitance change and hence the electrical energy generated in the mechanical cycle.

TABLE 2. CONFIGURATION COMPARISON

Configuration	**α**	**$U_{rel,Q}$**	**λ_x**	**λ_z**
Rect_in_Bowtie	0.8085	0.5298	1.0755	0.8085
Bowtie_Full	0.8292	0.4543	1.0755	0.8085
Rectangle	0.8696	0.3225	1	0.8696
Hexagon_Full	0.8895	0.2639	0.9739	0.8929
Rect_in_Hexagon	0.8929	0.2543	0.9739	0.8929
Cylinder	0.9325	0.15	0.9325	0.9325
Roll	0.9325	0.15	0.9325	0.9325

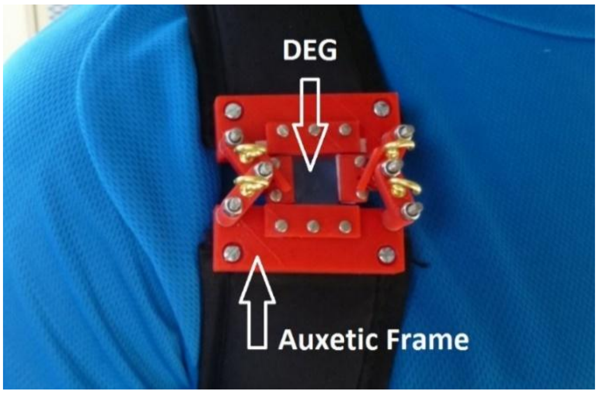

FIGURE2. DEG AUXETIC STRUCTURE

Characterizations on our auxetic structure are under development to determine the net scavenged energy.

IV. CONCLUSION AND FUTURE DEVELOPEMENT

In this paper, it has been proved that the available mechanical energy in the backpack straps during walking is high enough to be scavenged by a DEG. Furthermore, a bowtie auxetic frame has been selected as the best DEG configuration to optimally scavenge the backpack strap stretches. In the future, deeply integrated auxetic structures, with high potentials for the assimilation of DEGs into textile, could be developed.

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