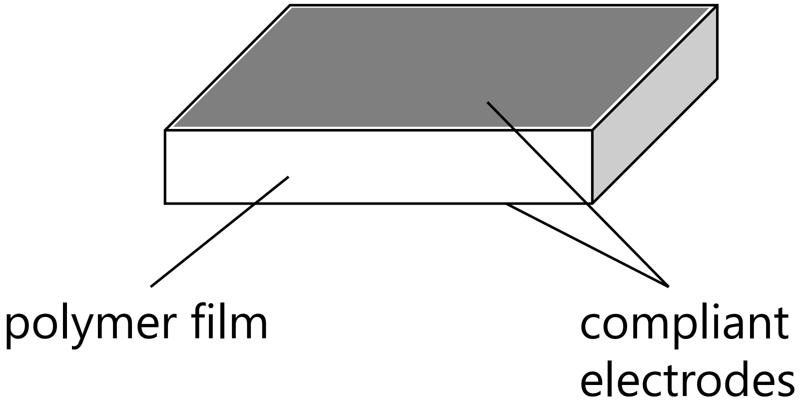
EAPtics project

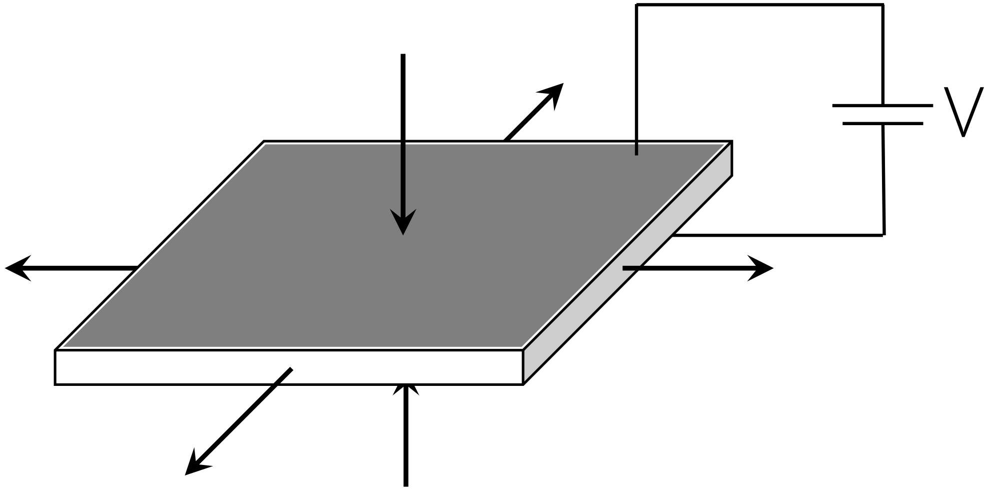
Bio-inspired wearable and soft actuators

VIDEO

https://www.youtube.com/watch?v=DlnLsbtIi5A&feature=youtu.be

working principle

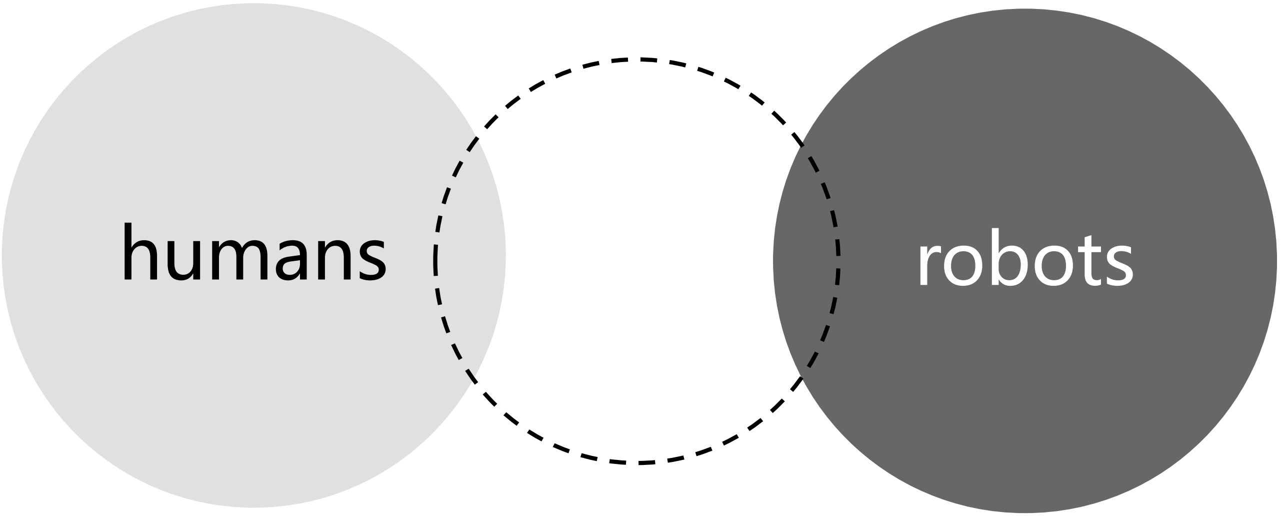




voltage off 

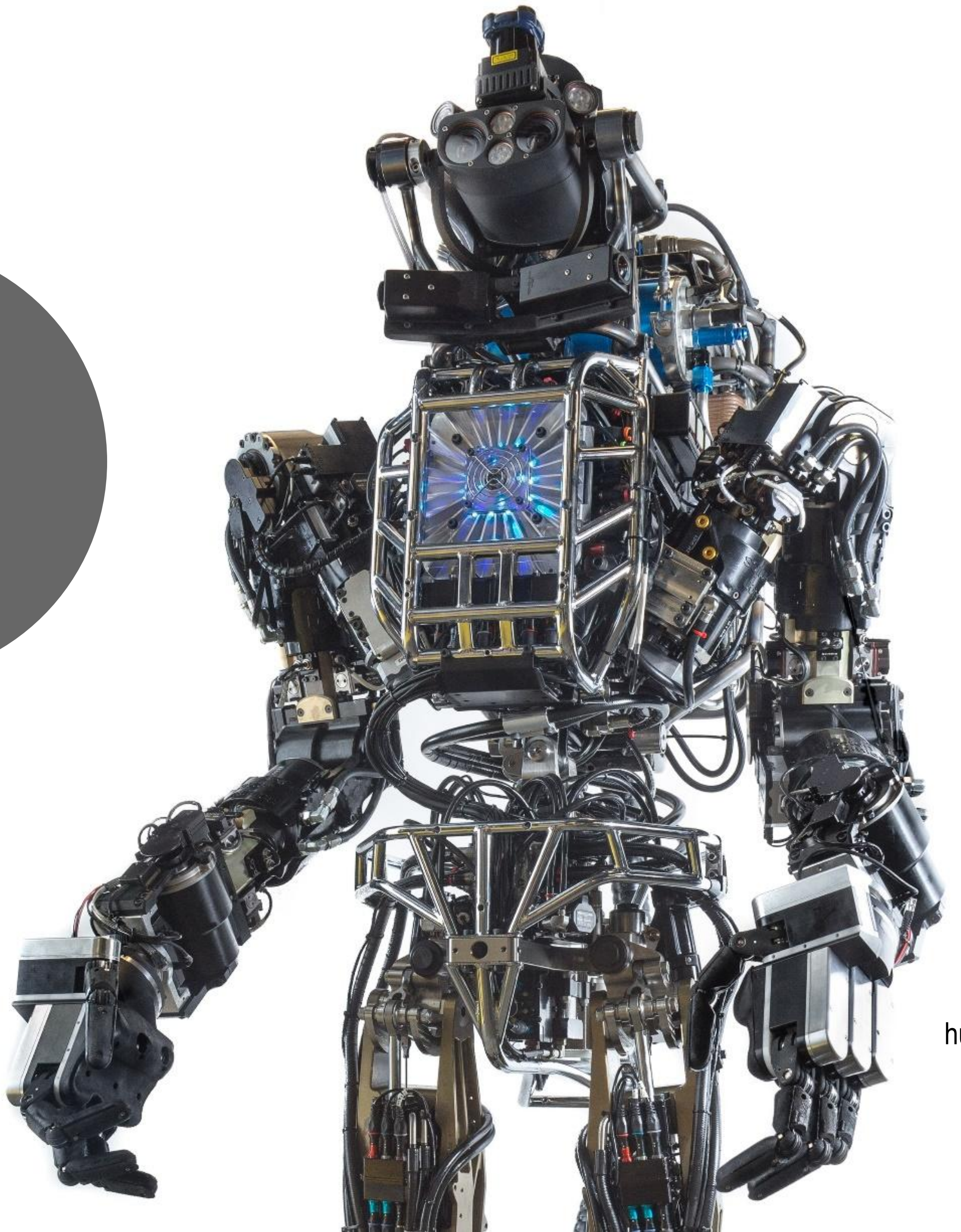
voltage on 

The missing link



Humans and robots are still two worlds far apart, but their integration is necessary to provide support and assistance to an aging population.

Our quest is to find the missing link between these two worlds, making robotics more human-sized.

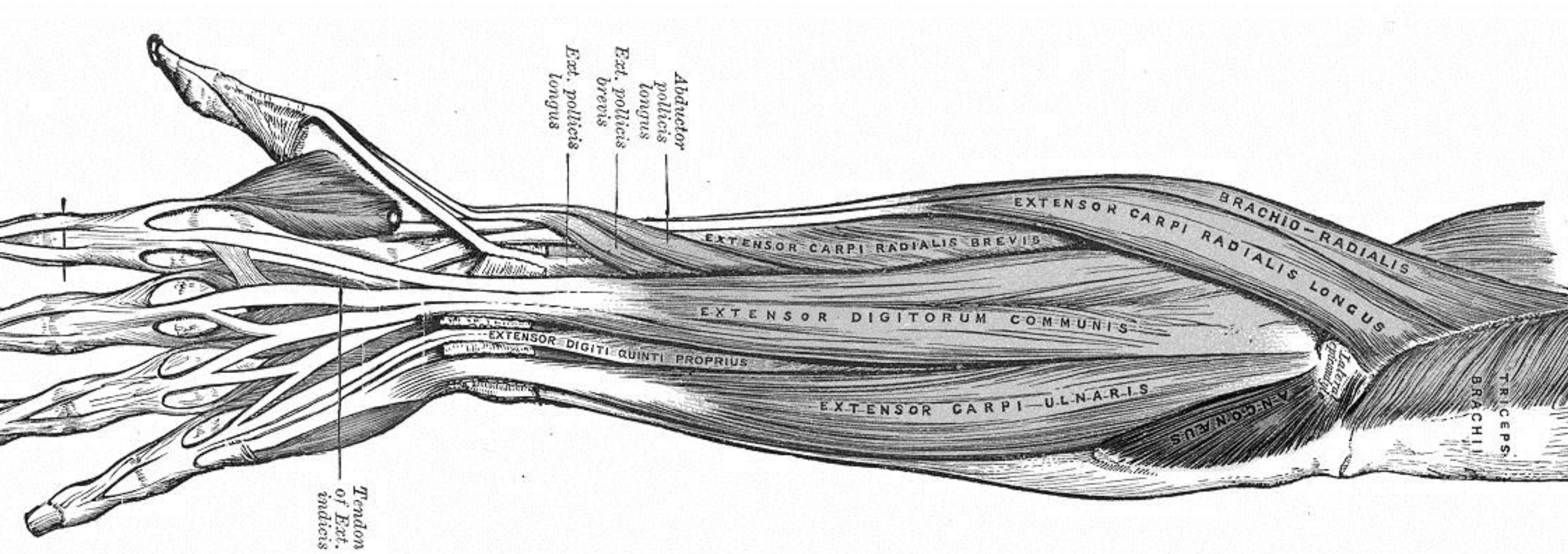


Atlas humanoid robot by DARPA, 2013

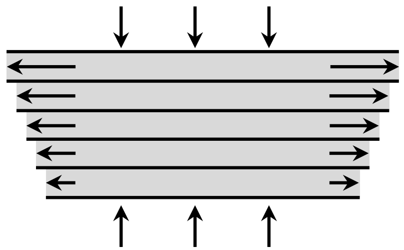
inspired by nature

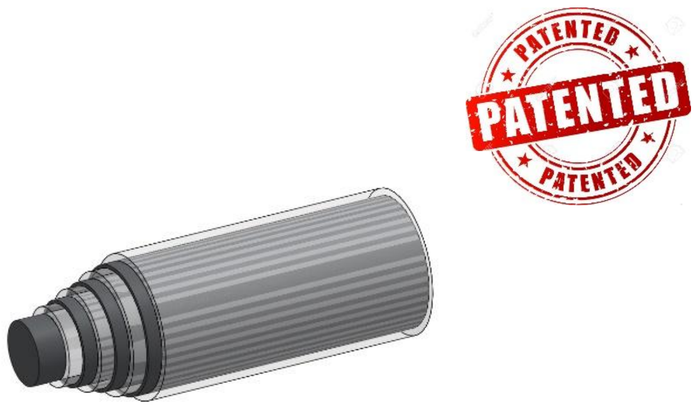
It took millions of years to developed the most efficient machine currently known:

our body



concept design





planar design

multilayer structure

linear/planar/bending actuation

flexible sensor

more efficient than hard robotics

coaxial design

mimesis of muscle fibers structure

mimesis of muscle selective recruitment

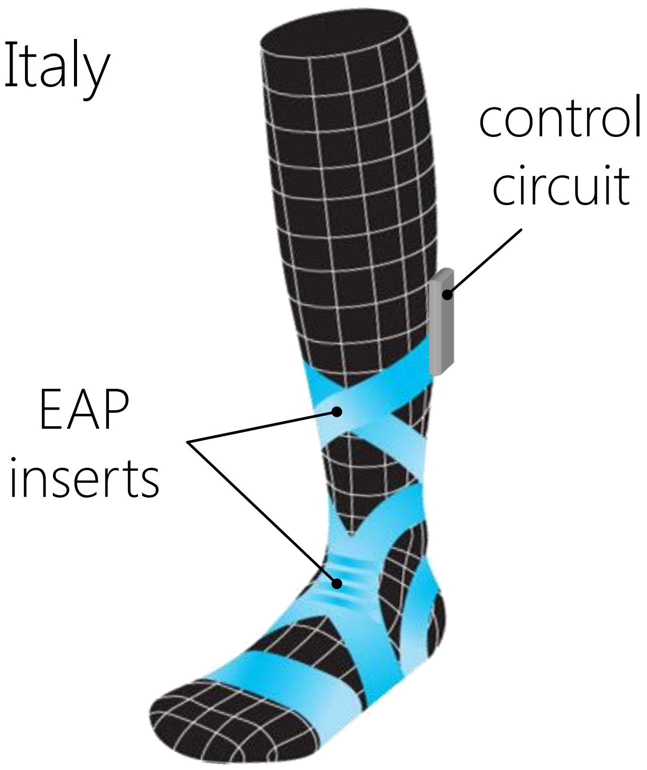
high energy density

improved actuation performance

killer application | active compression stocking

Disease: chronic venous insufficiency – 19 mln patients/year in Italy

- adjustable compression according to the actual need of the patient
- easy fit (particularly relevant for elderly patients)
- active device (against passive traditional stockings)
- empowered functionality at the same price



PATENTS & AWARDS

1. Title: "Dispositivo attuatore deformabile a configurazione assiale. Owner(s): Politecnico di Torino (POLITO) and Fondazione Istituto Italiano di Tecnologia (IIT) Inventor(s): Stoppa Matteo e Pierluigi Freni. Deposit number: TO2014A000241 Data of deposit: 24 March 2014.
2. Title: "Deformable actuating device with coaxial configuration." Owner(s): Politecnico di Torino (POLITO) and Fondazione Istituto Italiano di Tecnologia (IIT) Inventor(s): Stoppa Matteo e Pierluigi Freni. Deposit number: WO2015/145476 A1 Data of deposit: 01 October 2015.

I3P Incubatore Imprese Innovative Politecnico Torino

I° place

The Business Idea for the Future Award 2013

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Chapter 5

Wearable Soft Actuators - EAPtics project

A tremendous variety of devices used today rely on actuators of one sort or another to convert electrical energy to mechanical energy. Conversely, many power generation applications operate by converting mechanical action into electrical energy. Promising recent developments in material processing, device design and system configuration have enabled the scientific and industrial community to focus their efforts on the realisation of smart textiles. In fact, all components of interactive electromechanical systems (sensors, actuators, electronics and power sources) can be made from polymeric materials, to be woven directly into textile structures (sensing and actuating micro-fibres) or printed or applied onto fabrics (flexible electronics). In particular, intrinsic sensing, actuating, dielectric or conductive properties, compliance, lightness, flexibility and the relative low cost of many electroactive polymers (EAP) make them potentially suitable materials for the realisation of such systems. Current EAP actuator sheets or fibers perform reasonable well in the centimeter and mN range, but are not practical for larger force and deformation requirements. In order to make EAP actuators technology scalable a design methodology for polymer actuators is required. Design variables, optimization formulas and a general architecture are required, as it is usual in electromagnetic or hydraulic actuator design. This will allow the development of large EAP actuators specifically designed for a particular application. It will also help to enhance the EAP material final performance. This approach is not new, it is found in Nature. Skeletal muscle architecture has a profound influence on muscle force-generating properties and functionality. Based on existing literature on skeletal muscle biomechanics, the Nature design philosophy is inferred. Formulas and curves employed by Nature in the design of muscles are presented. Design units such as fiber, tendon, aponeurosis, and motor unit are compared with the equivalent design units to be taken into account in the design of EAP actuators. Finally, a complete design methodology for the design of actuators based on multiple EAP fiber is proposed. In addition, the procedure gives an idea of the required parameters that must be clearly modelled and characterized at EAP material level. The solution proposed was patented and extended at European countries (Stoppa and Freni, 2015).

5.1 Introduction

In order to endow fabrics with motor functions, flexible actuating devices are needed. They share with sensors the necessity of overcoming several technological problems in order to allow textile implementations. Multi-functional electroactive fibres and fabrics will give the traditional textile industry a new additional value, the possibility of making daily life healthier, safer and more comfortable, bringing technological advances closer to the public through the use of easy-to-use interfaces between humans measuring devices and actuators.

The most noticeable challenging issues include the identification of efficient principles of operation and suitable configurations, selection of high-performance materials, and implementation of custom fabrication processes. Fabrics with shape-recovery capabilities have been developed (Carosio and Monero, 2004). Despite this, no success in embedding effective and comfortable actuating functions into textiles has been substantially reported so far.

Electroactive polymers are usually divided into two principal classes, according to their actuation mechanism: ionic EAPs and electronic EAPs. The first group relies on electric activation mediated by charge carriers, i.e. ions and/or molecules, while materials belonging to the latter group respond to the stimulation of an electric field. When the triggering mechanism depends on the diffusion of relatively bulky chemical species, the rate of response is slowed down. Consequently, the actuation speed of ionic EAPs is much slower, compared to electronic EAPs: this is their major drawback. On the other hand, smart polymers actuated by electric fields are able to apply relatively small forces and require very high voltages.

In particular, the attention was focused on Electroactive Polymers (EAPs): these polymeric materials work as transducers, converting electrical inputs into mechanical outputs, and vice versa. They show features that cannot be traced in other traditional functional materials (e.g. piezoelectric ceramics), such as large active strains, high energy density, mechanical compliance and flexibility, very low weight, zero noise emission, simple and scalable structures and tailorable properties. All these characteristics make EAPs the actuation system closest to natural muscles (Brochu and Pei, 2010; Carpi et al., 2011b). Despite the first awareness about the potentialities of Electroactive Polymers may be traced back to 1880, just nowadays this technology is moving from academic laboratories to industrial production and commercialization. Therefore, EAPs represent the cutting edge in the context of functional materials (Carpi et al., 2011b; Bar-Cohen, 2002).

A brief look at some electroactive polymers may be useful to get a general picture about the technology and to analyze advantages and drawbacks of different alternatives.

5.1.1 Ionic EAP

Ionic EAPs can be activated, within a surrounding electrolyte medium, by very low voltages (on the order of 1 V). The commonly accepted explanation of the phenomenon attributes the observed deformation to the input/output diffusion of ions (exchanged with the surrounding electrolyte) into/from the polymer sample, driven by the applied voltage. In fact, the voltage produces a variation of the polymer oxidation state, which causes, in order to maintain the global electroneutrality, the necessary modification of the number of ions associated with each polymer chain (doping and dedoping processes) (Bar-Cohen, 2002; Bar-Cohen, 2004). Conducting polymer actuators typically exhibit active strains on the order of 1%-10%, high active stresses (up to tens of MPa), and low driving electrical potential differences (order of 1 V). Nevertheless, the use of conducting polymers as actuators is typically limited by their short lifetimes and high response times. Polyelectrolyte gels (Shiga and Kurauchi, 1990), ionic polymer-metal composites (IPMCs)(Punning, Kruusmaa, and Aabloo, 2007), conducting polymers (Osada and De Rossi, 2013), and carbon nanotubes (Mirfakhrai, Madden, and Baughman, 2007) are examples belonging to the Ionic EAP.

5.1.2 Electronic EAP

On the contrary, electronic EAPs require typically high driving voltages (electric fields on the order of 10-100 V m for electrostrictive polymers and dielectric elastomers). However, progress concerning the reduction of their driving fields is currently occurring. Electronic EAPs show, in comparison with the ionic ones, lower response time and higher efficiency, stability, reliability, and durability. Piezoelectric polymers (Baughman, 1996), electrostrictive polymers (Liu et al., 2005), ferroelectric liquid-crystalline elastomers (Lehmann et al., 2001), and dielectric elastomers (Carpi et al., 2011a) are electronic EAPs.

In order to describe the potential applicability of EAP-based actuators to electronic textiles, the most highly performing material are the Dielectric Elastomers.

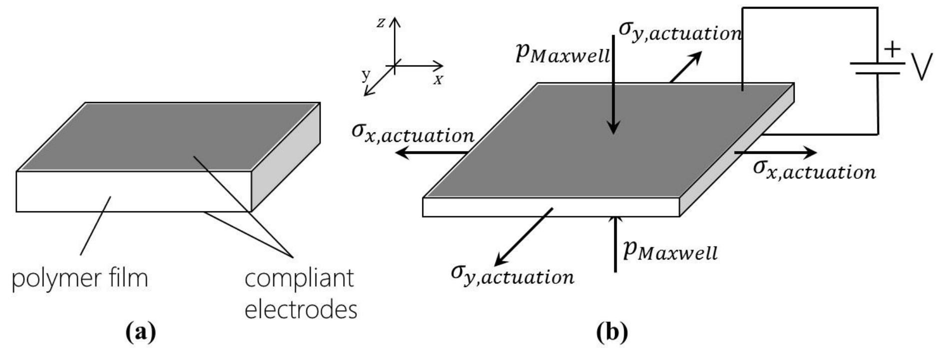

FIGURE 5.1: Dielectric Elastomer working principle. (a) Structure of the DE. (b) Mechanical deformation when a voltage is applied.

5.2 DE Modelling

Dielectric Elastomers (DE) represent the EAP class with the highest achievable active strains (order of 100%), as well as considerably high active stresses (up to 1 MPa) (Pelrine et al., 2000). They consist of insulating rubbery polymers, having a low elastic modulus. When a thin film of such materials is sandwiched between two compliant electrodes (e.g., made of carbon conductive grease), and a high voltage difference is applied between them, the polymer undergoes an electric field sustained deformation, consisting of a thickness squeezing and a related surface expansion (Pelrine et al., 2000; Pelrine, Kornbluh, and Joseph, 1998). The achievable large deformations are mainly due to a Coulombian effect, established by means of the electrostatic interactions occurring among free charges on the electrodes.

The resulting effect on the elastomer is a net contraction in thickness and a planar expansion (Figure 5.1). The excellent figures of merit possessed by dielectric elastomers in several respects (high actuation strains and stresses, fast response times, high efficiency, stability, reliability, and durability) make them the most highly performing materials currently available for polymer actuation. The price for achieving these high-level capabilities is represented by the high driving electric fields required (order of 100 V m). Thus, the actuation voltage can reach order of kV, but the capacitive nature of the solution guarantees little currents ($100\mu A - 1\,mA$) and, therefore, very low power consumption.

Both silicone rubbers and acrylic elastomers are used as dielectric elastomers. Furthermore, applying a prestrain to the material, efficiency can be highly improved and preferential actuation in one direction can be realized (Brochu and Pei, 2010).

Based on the principle of operation, two directions are possible to perform work against external loads.

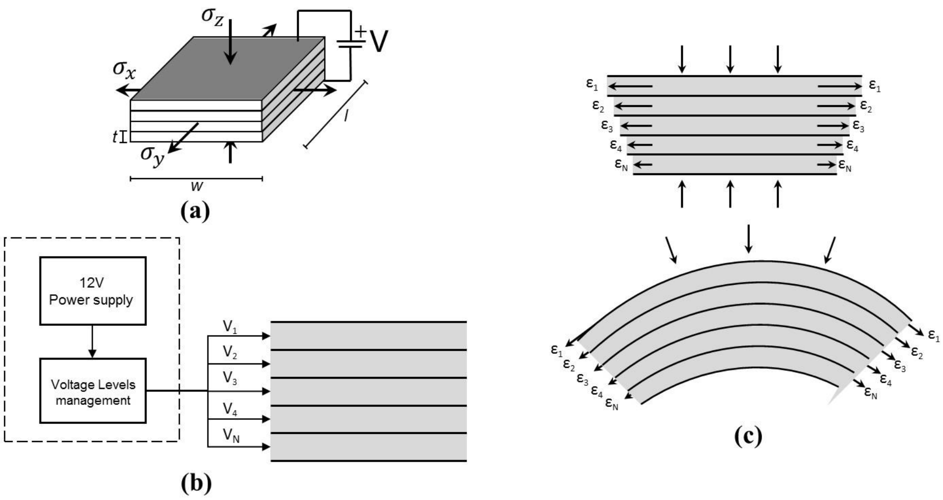

FIGURE 5.2: (a) Dielectric Elastomer multilayer design. (b) Voltage differentiation for each layer. (c) DE deformation according to the voltage applied.

- Work in the planar directions (expanding actuator): under electrical activation of a DE basic unit the film expands in the x, y plane and can thus work against external pressure loads in both planar directions x and y;

- Work in the thickness direction (contractile actuator): under electrical activation the electrodes squeeze the DE film in the thickness direction (z). Thus, the actuator can work against external tensile loads acting in the direction of the electric field lines of the compliant capacitor.

Many configurations for dielectric elastomer actuators have been proposed and demonstrated, including planar, tube, roll, extender, diaphragm, and benders (Ashley, 2003; Carpi and Rossi, 2005; Rosset and Shea, 2013; Chakraborti et al., 2012). Tube, and mainly, roll actuators are flexible devices potentially suitable to endow fabrics with linear (along a line) actuation functionalities. These actuators can elongate under electrical stimulation.

5.2.1 Multilayer design

The dielectric material can be reasonably assumed to be incompressible, therefore, $l \cdot w \cdot t = cost$ where l is the length, w the width and t the thickness of a single the dielectric layer. Or alternatively

$$(1 + s_x)(1 + s_y)(1 + s_z) = 1 \tag{5.1}$$

where s_x, s_y and s_z are the strains (it has been used s to not confuse with the dielectric constant ε) in the three directions. The electrostatic stress generated across the electrodes is the Maxwell pressure, described by:

$$p = \varepsilon_r \cdot \varepsilon_0 \cdot E^2 \tag{5.2}$$

where ε_r is the material relative dielectric constant, ε_0 is the vacuum dielectric constant and E is the applied electric field. Furthermore, the previous equation can be written as a function of voltage V and dielectric thickness t:

$$p = \varepsilon_r \cdot \varepsilon_0 \cdot \left(\frac{V}{t}\right)^2 \tag{5.3}$$

Taking into account the hypothesis that the dielectric material linearly elastic and isotropic (with a Young modulus Y) the thickness strain is given by:

$$s_z = \frac{-p}{Y} = \frac{-(\varepsilon_r \cdot \varepsilon_0 \cdot E^2)}{Y} = \frac{-(\varepsilon_r \cdot \varepsilon_0 \cdot (V/t)^2)}{Y} \tag{5.4}$$

For a definite polymer thickness, order of 100 V m electric field can be reached by applying high voltages, which may have disadvantages in many applications. In order to reduce the driving electric fields, polymers with a high dielectric constant (or permittivity) are necessary. In fact, according to the Eq. 5.3, the strain generated by a dielectric elastomer actuator is proportional to both the square of the applied electric field and the material dielectric constant (Pelrine, Kornbluh, and Joseph, 1998).

Considering a repetition of this planar structure in a stackable format, the multilayer structure resulted is made of N active layers. Figure 5.2 depicts an example of a multilayer geometry. Each layer performs a different linear elongation, so that $s_N > s_4 > s_3 > s_2 > s_1$. The resulting actuation is both a linear expansion along the x axis and a bending along the y-axis.

According to the equation 5.3, the planar strain along the polymeric dielectric increases with the bias applied and, therefore $s_N > s_4 > s_3 > \varepsilon_2 > s_1 \Leftrightarrow V_N > V_4 > V_3 > V_2 > V_1$.

Different voltage levels for different layers allow a fine control of the actuation, in terms of magnitude and direction of the deformation. Furthermore, thanks to superposition principle, the multilayer configuration allows to reduce of one order of magnitude the voltage applied (300-400 V). Notwithstanding the high voltage, the current is very low, around $10\mu A$.

5.2.2 Coaxial design

In order to endow fabrics with actuating functions, fiber-shaped actuators may be particularly useful. At the end of the 1990s, conducting polymer

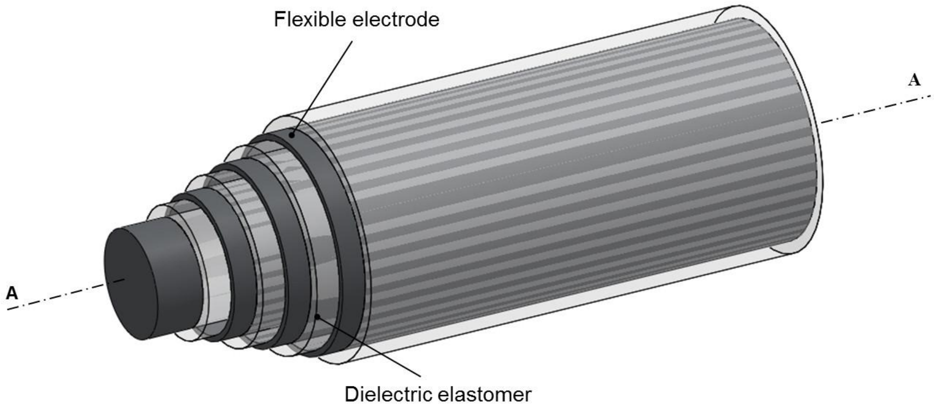

FIGURE 5.3: Dielectric Elastomer coaxial design.

fiber actuators was represented (Mazzoldi et al., 1998) obtaining a fiber-like structure have shown strains of about 0.3% and active stresses of about 3 MPa, for driving voltages lower than 1 V. However, the deformation of a conducting polymer was strongly anisotropic, with a deformation along the radial size, making the fibers not suitable for practical usage. Figure (5.3) shows the solution proposed which exploits the advantages of the multilayer geometry and turns them into a coaxial configuration. A coaxial structure allows to design fiber-actuators that can be endow within a fabric. As mentioned above, different voltage levels act different EAP layers obtaining a fine control of the final deformation along the axial direction. Furthermore, the coaxial solution leads in terms of energy stored, improving the efficiency in compare with a planar geometry. Since the EAP configuration can be approximated to a parallel-plate capacitor, its capacitance (C) is

$$C = \varepsilon \frac{S}{t} \tag{5.5}$$

where ε the dielectric constant, S the surface are of the plates d is the distance between the them. Therefore the energy stored (W) is

$$W = \frac{1}{2} C V^2 = \varepsilon \frac{S}{2d} V^2 \tag{5.6}$$

As described in Eq. 5.6, the energy stored is directly proportional with the surface area (S) and with the square of the voltage (V). Moreover, it is inversely proportional with the plates distance (d), in our case the thickness (t) of the dielectric elastomer. The coaxial approach leads relevant benefits in terms of energy efficiency and force generated. This is confirmed from the fact that, at the same volume (Figure 5.4), a planar geometry has always a smaller surface area then a cylinder ($l^2 < \pi l^2$). In particular the Eq. 5.7 demonstrates analytically this assumption with a multyplanar and coaxial

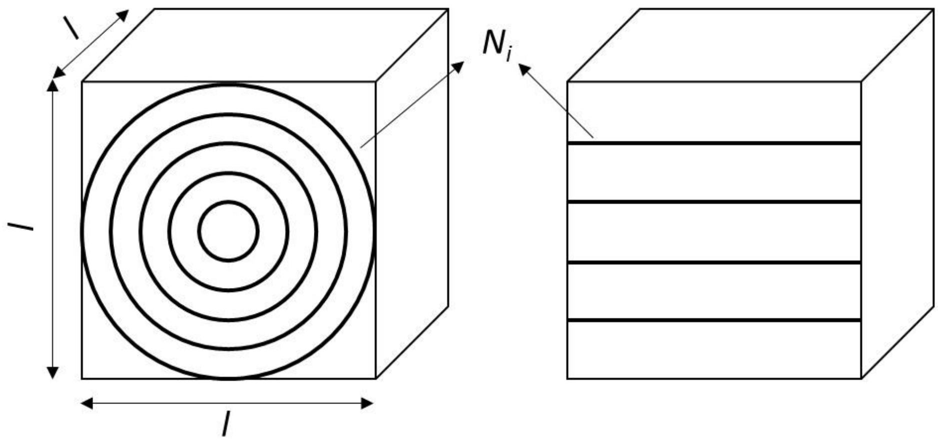

FIGURE 5.4: Comparison of coxial and planar architecture. The geometry are inscribed within a cube with the same volume and number of layers.

architecture. Figure 5.5 shows the final actuation result of a single EAP coaxial fiber.

$$
\begin{aligned}
S_{i,p} &= l_i^2 \\
S_{i,c} &= \pi d_i \cdot l
\end{aligned}
\tag{5.7}
$$

where d is the diameter of the cylinder, $S_{i,p}$ and $S_{i,c}$ are the $i-th$ surface area of a plane and a cylinder, respectively. Considering an equal number of layers (N) and coaxial cylinder inscribed within a cube with the same volume, the sum of surface areas $S_{N,p}$ and $S_{N,c}$ are respectively

$$
\begin{aligned}
S_{N,p} &= l_i^2 \cdot N \\
d_i &= l - (i-l) \cdot \frac{l}{N} \\
S_{N,c} &= \sum_{i=1}^{N} \pi l^2 \left[1 - \frac{i-1}{N}\right]
\end{aligned}
\tag{5.8}
$$

By solving the series $S_{N,c}$, the initial assumption is demonstrated as follows

$$
\begin{aligned}
S_{N,p} &< S_{N,c} \\
l^2 N &< \pi l^2 \left[N - \frac{N-1}{N}\right]
\end{aligned}
\tag{5.9}
$$

where the inequation is always respected for $N > 1$.

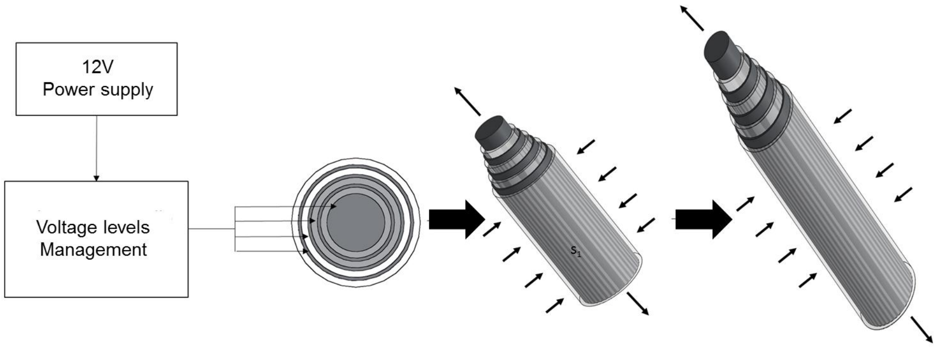

FIGURE 5.5: EAP coaxial fiber activation with a voltage differentiation.

The result is a resizing of the device and an increase of the force generate, following by the Eq. 5.4.

Considering the coaxial principle and investigating into the skeletal muscle architecture, the hierarchical structure of the muscle fibers can be approximated as a whole of EAP coaxial fibers able to generate a movement in response to electrical stimulus. Figure 5.6 enables to compare the muscle structure with a multi-fibers coaxial EAP. Taking into account the chance to activate individually each fiber with different potential, the "muscle hierarchical selective recruitment principle" can be mimicked. This allows to obtain the following advantages:

- to adjust the force produced;
- to control the direction of the deformation;
- to further reduce of the tension applied.

5.3 Control Circuit and Proof-of-Concept

The electroactive polymers need high voltage to be activated, typically in the order of $3 - 5\,kV$. The use of passive components such as resistors and capacitors has been suggested as a method for simple and inexpensive coupling of electrical and mechanical response of the actuator (Pelrine et al., 2008). The aim of the circuit proposed is to test the possibility of controlling the polymer actuator layer at different voltage with an AVR microcontroller. The circuit consists of four blocks:

- a variable power supply provides stable voltage 0-12 V and current of 125 mA for the high voltage converter;

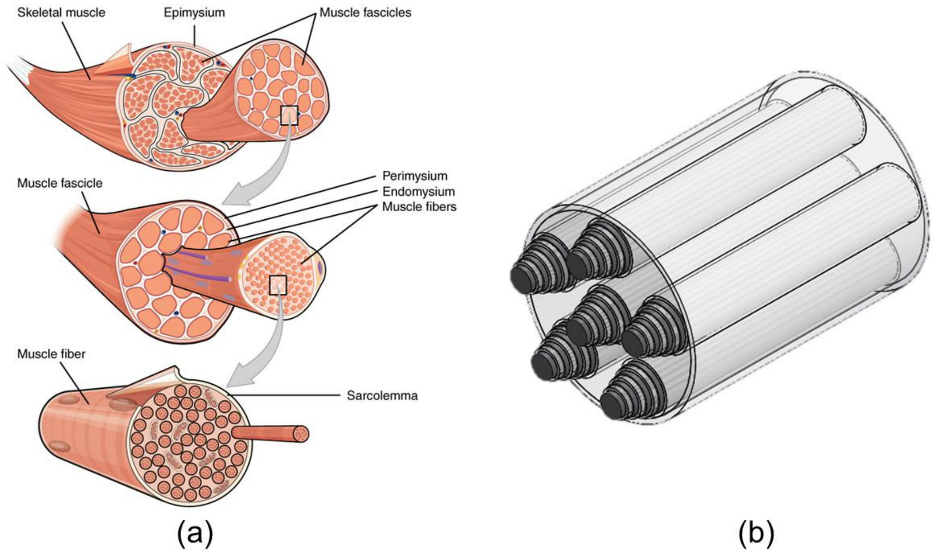

FIGURE 5.6: (a) Muscle hierarchical structure. (b) Multi-fibers coaxial EAP

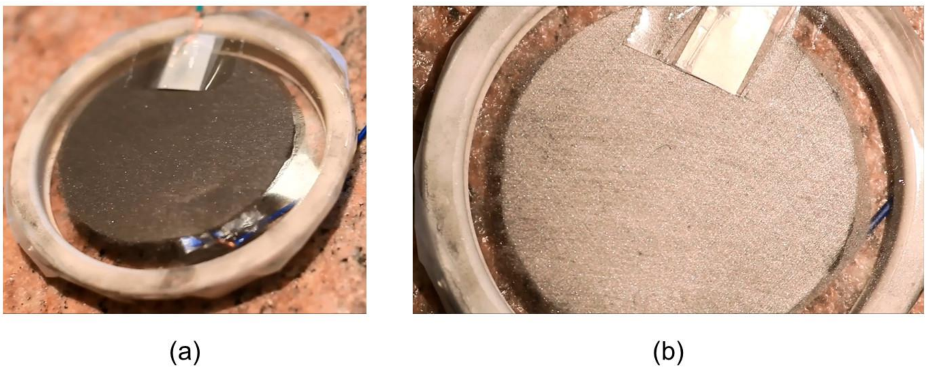

FIGURE 5.7: EAP proof-of-concept.

- an AVR microcontroller and digital potentiometer MCP4131 adjust the behaviour of the actuator. Digital potentiometer has a range of 128 values;
- a commercial high voltage DC/DC converters (Series GMA Itek Power High Voltage DC-DC converter) converts incoming voltage of 0-12 V to high voltage (0-3 kV);
- five voltage dividers provide different high voltage output, from 3 kHz to 50 V.

The high voltage DC to DC converters provides an output voltage available in the range 100 V to 3 kV with a input of 1-12 V range and a maximum output power of 1.5 W.

The test of the electronic circuit was performed using a single EAP layer (thickness of $100\mu m$) based on VHB 3M acrylic silicon material and monitoring the behaviour. Initially the VHB was pre-stretched and attached on a rigid frame. Then, thanks to the adhesive property of the material, the flexible electrodes was made with a deposition of micro-particles of graphite on both sides. Finally, two copper connectors attached with carbon grease to the electrodes allow the electrical connection with the circuit. Figure 5.7 shows the EAP proof-of-concept able to change the diameter size of $1\,mm\,kV$. The system was tested with different voltages adjusted with both the digital potentiometer and the voltage dividers. The DC-DC high voltage converter has shown a linear input-output characteristic, however q.e.d. the material does not change its shape with a voltage lower than 1 kV. Another aspect monitored was the time relaxed that resulted around 100 ms, mainly due to the elastic recovery of the material.

5.4 Discussion

A new concept of the EAP geometry inspired by the muscle architecture and a proof-of-concept of the EAP working principle based on dielectric elastomer has been presented in this Chapter. A deep analysis of the EAP multilayer configuration, well known among the scientist community, in addition to the application of different voltages for each layer, lead relevant improvements within the soft actuator technology. A fine control of the deformation and lower voltage applied in compare with the literature are part of these improvements. Since an excessive increase in the number of layers can lead to a stiffening of the actuator, the coaxial geometry aims to solve this issue. Increasing the surface area of the electrodes, a performance improvement is obtained without affects the mechanical properties of the material. Furthermore, a coaxial structure allows to develop active fibers, which can be potentially woven within a fabric and fill the gap of the wearable man-machine interface. This solution was patented and brought to a further level of innovation, taking inspiration from the natural muscle anatomy. In principle, a multi-fibers coaxial configuration would allow further improvement of the EAP fibers performance introducing the change to control the strength and movement of the fiber with a selective activation of the fibers, as it happens for the muscle fibers.

Despite these promising improvements, there are several challenges to overcome, from material, electronic and integration point of view. Firstly, the material selection has be focused on dielectric elastomers with a lower anisotropy and lower ε_r value in order to increase the electrostatic effect. Furthermore, together with a reduction of the layers thickness the driving voltage can be reduced, reaching voltages used normally with the electronic

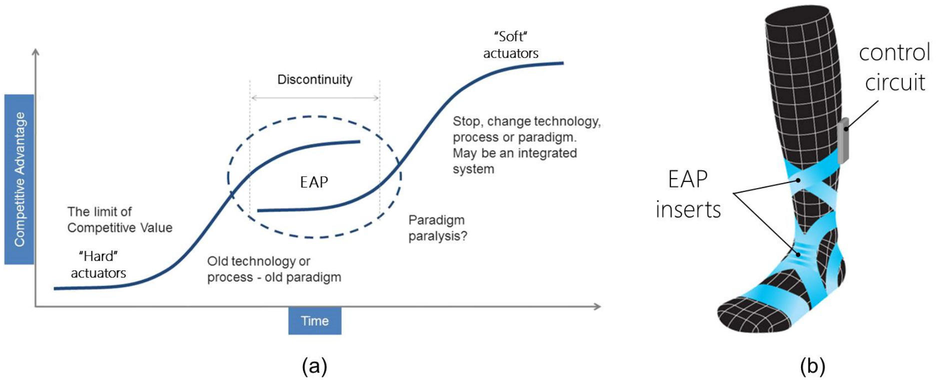

FIGURE 5.8: (a) EAP technology trend in compare with the traditional "hard" actuators. (b) Active compression stockings concept.

consumer. Besides, with lower driving voltage, the overall size of the electronic circuit can be reduced.

Another issue is the material-circuit interface through metallic plates. Actually, the wiring of the flexible electrodes with the electronic circuit is fragile and peak effects generated by the metallic plates can pierce the elastomeric layer. Carbon grease improves the connection of the plates, however is not perfectly stable. Finally another challenge regards the manufacturing processes, in particular for the coaxial configuration. Techniques used to develop optical fibers, mainly based on extrusion processes, have to be studied and evaluated.

Despite these and other challenges (such as improvement of device reliability and efficiency), the integration into fabric of EAP-based actuating, electronic and power functions represent one of the means of having great potentialities for the development of completely wearable electronic textiles. Figure 5.8 (a) depicts graphically the EAP technology trend in compare with the well know traditional actuators devices. Currently, the EAPs are within the discontinuity with lower competitive advantages than the commercial product, but with a promising growth of the technology filling the gap and leading new promising applications.

A further development of the manufacturing processes of the EAP fibers with the optimization presented in this Chapter will allow to fill the existing gap between the mechanical actuator and the human body interaction.

5.5 Application Scenario

The near-future developments of such EAP-based smart-textiles open new challenges. One of them concerns the improvement of the wearability of EAP devices by means of textile-compatible configurations and shapes, preferably in fiber form. This implies the development of device manufacturing processes (extrusion, electrospinning, wet- or dry-spinning, casting, etc.) and textile technologies (weaving, coweaving, knitting, jacquard, coating, printing, etc.) for their integration into fabrics. Nature took million of year to develop the mostly efficient machine: the human body. Taking inspiration from the body anatomy and physiology followed by an smart material and electronic technology improvement, new generation of wearable device will be not so far.

Following a benchmark of the possible technology application, the medical field was selected with aim to propose a solution against the Chronic Venous Insufficiency disease (CVI). In CVI states, venous blood escapes from its normal antegrade path of flow and refluxes backward down the veins into an already congested leg. Venous insufficiency syndromes are most commonly caused by valvular incompetence in the low-pressure superficial venous system but may also be caused by valvular incompetence in the high-pressure deep venous system (or, rarely, both). CVI pathology is the 3^{rd} most widespread cause of death in Europe (Eberhardt and Raffetto, 2014), with 19 mln patients/year. Current solution is to wear compression stockings, static and highly uncomfortable medical device. The therapy is strongly compressed by the refusal to use the compression stockings due to their inconvenience and low efficiency. To tackle these issues, stirrups of EAP actuators can be embedded within the stockings with the following advantages:

- active device against passive traditional stockings;
- adjustable compression according to the actual need of the patient;
- easy fit thanks to the temporary expansion of the stockings size, particularly relevant for elderly patients;

Figure 5.8 (b) shows a possible interfacing of the EAP actuators with the human body anatomy.