Force control of a tendon driven joint actuated by dielectric elastomers

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Abstract:
Dielectric elastomers are a subclass of electronic electroactive polymers, often referred to as polymeric artificial muscles due to their ability to produce large deformations when stimulated by an externally applied electric field. Similarly to biological muscles, dielectric elastomers are able to actively modulate their intrinsic compliance, making the use of this technology extremely interesting in applications were the system must adapt to unknown environments and safely interact with it. In this paper, we discuss the peculiar characteristics of a single joint system actuated by two antagonistic elastomer actuators. A closed loop scheme, able to control the position and the stiffness of the joint by modulating the force developed by the two artificial muscles, is presented.

Keywords: dielectric elastomers, artificial muscles, closed loop force control, antagonistic configuration

Introduction

Dielectric elastomers are a class of Electroactive Polymers (EAPs), constituted by soft, rubber-like materials with excellent insulating properties [1][2].
In the last years, many novel devices, both sensors and actuators, have been introduced exploiting the dual nature of dielectric elastomers. When employed as sensors, an external pressure or a strain deformation applied to the material results in a change of capacitance, which can be electronically measured. As an actuator, an applied voltage to the compliant electrodes which cover the surfaces of a dielectric elastomer film develops an electrostatic attractive force which squeezes the material, generating mechanical work.
Dielectric elastomers actuators are capable of operating with fast working cycles and of producing large strains and forces, approaching the capabilities of mammalian muscles. For this reason, this class of materials has recently gained increasing attention, especially in the study of novel, “muscle-like” actuation mechanisms which can be employed in prosthetics, rehabilitation and robotics. As an example, most of today’s robots are composed by rigid and heavy structures unable to adapt and safely interact with unknown environments. On the contrary, dielectric elastomers offer the promise of a lightweight and energy efficient actuation, and have a degree of intrinsic compliance which can be actively adjusted in order to adapt to a large range of situations.
With respect to this last point, a system composed of a joint driven by antagonistic actuators is both capable of controlling the angular position of the end-effector and also of modulating its stiffness, by changing the level of coactivation of the actuators. This control strategy can commonly observed in biological systems: by conveniently coordinating the activation of two (or more) muscles acting on the same skeletal joint, the central nervous system is capable of controlling the joint impedance, thus fixing its posture and stabilizing its course of movement in the presence of external force perturbations (Fig. 1).
In this paper we discuss the properties of a tendon driven mechanical system, inspired to the antagonistic arrangement of a simple rotational musculoskeletal joint, actuated by two dielectric elastomer actuators.

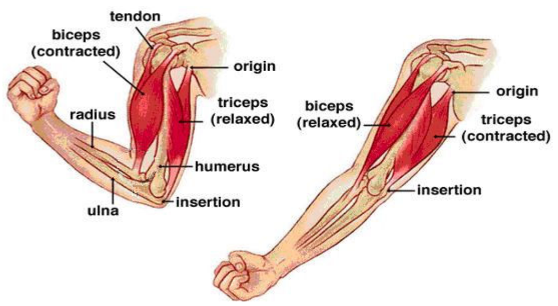

Fig. 1: *Musculoskeletal system of an arm. The biceps ant the triceps work as an antagonistic pair of muscles and are responsible for the flexion and extension of the forearm.*

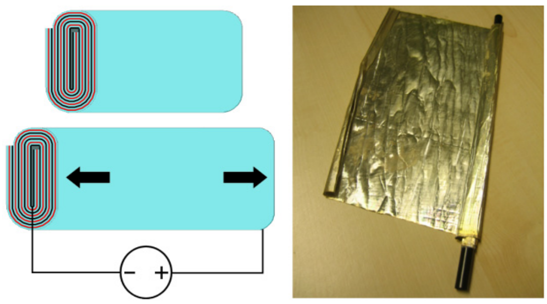

Fig. 2: *Left: operating principle of an elastomer elongating roll actuator. Right: picture of the dielectric film employed in the device fabrication.*

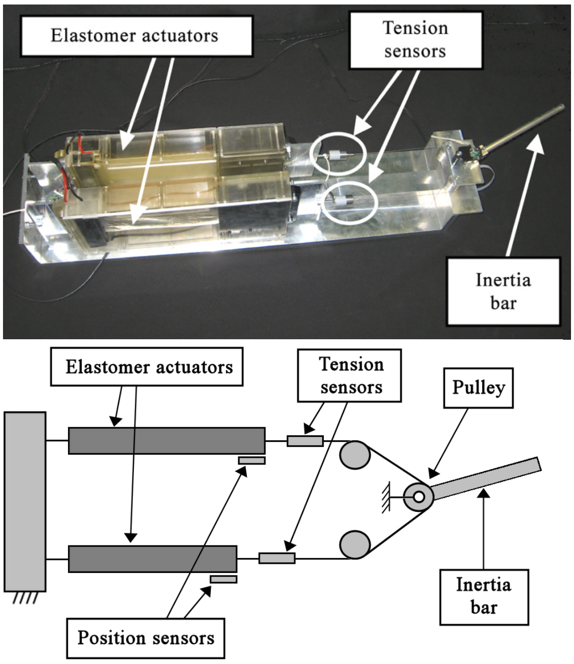

Fig. 3: Experimental setup

Design of the antagonistically actuated joint

A large variety of motions can be obtained from dielectric elastomer devices by arranging the material in different ways [2-5]. Among the different solutions, we chose a configuration reported in literature as elongating elastomer roll (Fig. 2). This configuration provides a linear motion along the roll principal axis and has the advantage of not requiring complex manipulation of the material during the fabrication of the device (which is instead typical of other actuating configurations, e.g. the multilayer stack). It must be noticed that these actuators have the characteristic of elongating when electrically activated, and not of contracting as muscles do.
About 4 *m* of PolyPower film, a commercially available EAP material produced by Danfoss [6], were manually rolled in order to obtain two actuators, each of them 150 *mm* long.
In order to investigate the properties of a system driven by a pair of antagonistically arranged dielectric elastomer actuators, we developed the experimental setup shown in Fig. 3. On one side of the roll, the two actuators are fixed to the base frame. On the other side, they are connected through stainless steel tendons to a pulley which moves an aluminium bar. The two dielectric elastomers have thus the functionality of an antagonistic pair of muscles, whose levels of activation control the angular position of the joint.
The actuation properties of the employed elastomer rolls are completely described in terms of developed stress and strain as a function of the applied voltage (Fig.4). It can be noticed that, besides the intrinsic non-linear stress-strain characteristic (which depends on the material properties) and the quadratic dependency on the applied voltage (according to the Maxell's pressure equation [2]), the applied prestrain increases the actuator performances in terms of developed force and displacement range.
Moreover, since the actuators are made of soft silicone material, and the rotational joint is actuated by tendon cables, they are completely unable to develop a pushing force on the joint. For this reason, both the actuators have to be conveniently preloaded. In this framework, the controller strategy, which is responsible of actuating the joint, commands the elongation of one of the artificial muscles, with the consequence of releasing part of its initial preload. This implies that the maximum tendon tension is obtained when the dielectric elastomer actuator is not powered, while the minimum tension (which cannot be zero, to ensure the proper alignment of the tendons and the pulley) is obtained at full power.
In order to measure the cable forces, custom-made force sensors, based on semiconductor strain gauges, were developed and placed on the tendons.

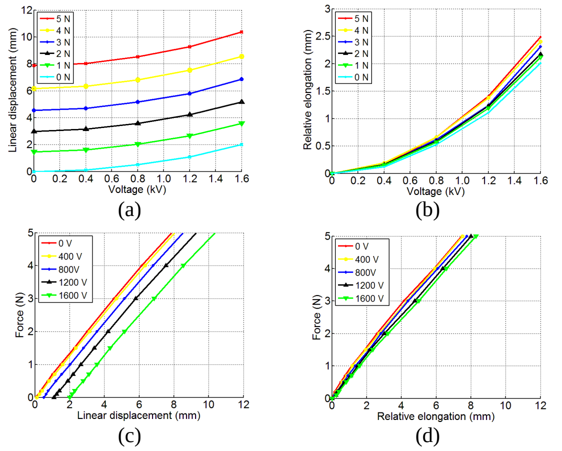

***Fig. 4:** Voltage-elongation and force-elongation relationships of one of the two elastomer actuators, expressed as a function of an externally applied load and an externally applied voltage respectively.*

Position and force control

A closed loop control scheme was developed and implemented on a custom DSP board based on the Motorola 56807 microcontroller. A high voltage amplifier (Trek 609E-6) is used to convert the control signals generated by the DSP board into a proper driving voltage (0-2kV) for the dielectric elastomer actuators (Fig. 5).
The control algorithm consists of two PID regulators, which independently control the tendon tension of the two dielectric elastomer actuators, and of an external controller, which acts as a reference generator for the two inner force control loops. The proposed control strategy has two major

advantages. Firstly, the gains of the force control loops can be independently adjusted and easily tuned in order to optimize the response of the two dielectric elastomer actuators. Secondly, different reference generators can be used in order to obtain systems with different behaviors (e.g. minimum jerk trajectories, gravity compensation, time-varying stiffness profiles etc.) without modifying the inner control loops.

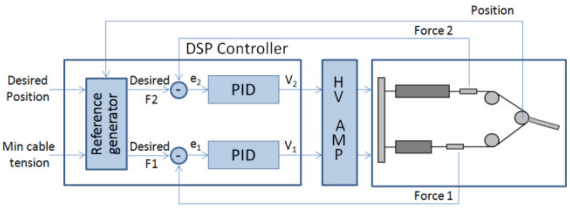

***Fig. 5:** Position and force control scheme for the antagonistically actuated joint.*

An example of possible reference generator, which generates a coordinated motion of the actuators in order to control the angular position of the joint and the tendons tension (which must be always greater than a preset lower bound, in order to maintain a proper preload), is here described.
From the dynamical point of view, the system can be modeled by the following set of equations:

$$I\ddot{q} + mg\sin(q) = \tau \quad (1)$$

$$\tau = (F_1 - F_2)r = [r \quad -r]\cdot[F_1 \quad F_2]^{\mathrm{T}} = J^{\mathrm{T}}\cdot F \quad (2)$$

$$F_i = -k_i(q, V_i)rq \quad (3)$$

Where q is the rotational degree of freedom, I is the equivalent inertia of the bar along its axis of rotation, τ is the overall torque acting on the pulley of radius r connected to the joint and F_i is the force developed by each actuator.
According to these equations, the angular position of the joint can be controlled by computing a fictitious torque reference τ_d as a function of the position error (i.e. the difference between the desired and the current position). The desired tendon forces $F_d=[F_{1d},F_{2d}]$ can be thus obtained from the computed desired torque τ_d by inverting equation (2), with the constraint of maintaining a minimum tendon tension F_{min}. It is shown in [7] that the solution to this constrained problem (valid for a generic n-DOFs system with a number of actuators m > n) is:

$$F_d = \left(J^T\right)^{\dagger}\tau_d + \left[F_{\min} - \min\left(\left(J^T\right)^{\dagger}\tau_d\right)\right]\cdot\ker\left(J^T\right) \quad (5)$$

By tracking the computed reference forces F_d, the system is thus able to track an external position reference command q_d while guaranteeing a minimum tendon tension $F_{\min}$ (Figs. 6-7).

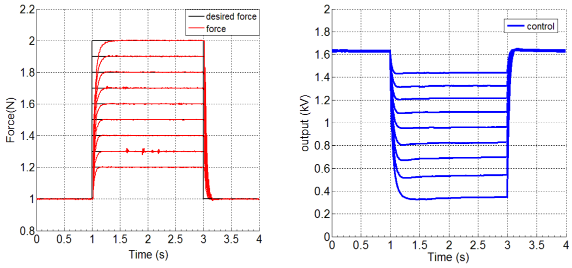

***Fig. 6:** Step response of the inner force control loop.*

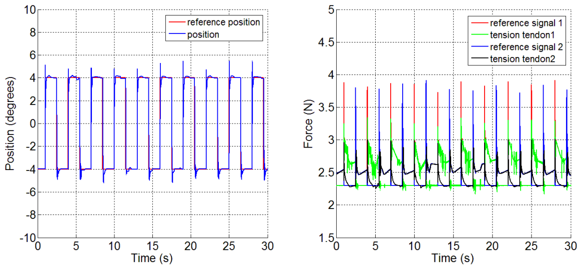

***Fig. 7:** Plot of the angular position of the joint tracking a square wave reference signal (left) and of the resulting tendon tensions, which are never less than the commanded minimum force (right).*

Stiffness control

As previously mentioned, an antagonistically actuated system can modulate the stiffness at the joint by controlling the level of coactivation of its actuators. According to equations (1) and (2), the stiffness σ of the joint can be expressed as:

$$\sigma = \frac{\partial\tau}{\partial q} = r^2\left[k_1(q,V_1) - k_2(q,V_2) + q\left(\frac{\partial k_1(q,V_1)}{\partial q} - \frac{\partial k_2(q,V_2)}{\partial q}\right)\right] \quad (4)$$

Where the term $k_i(q,V_i)$, representing the active force-elongation characteristic for each dielectric elastomer actuator, can be modeled from the isotonic and isometric measurements performed on the devices (Fig. 8)

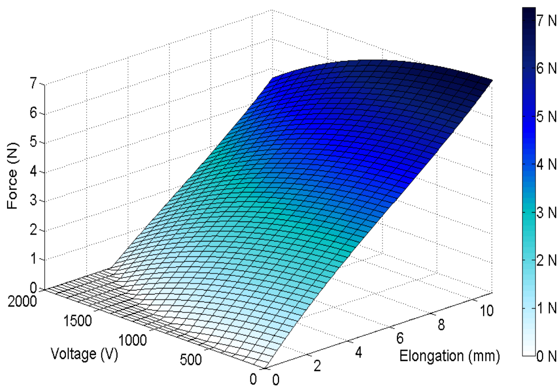

***Fig. 8:** Model of the active force-elongation characteristic curve of the actuators, plotted as a function of the applied voltage.*

From the presented equations (1-4), a model of the system can be computed in order to obtain a prediction of the joint stiffness for different levels of actuator coactivation and initial preloads (Fig. 9).
The plots of the estimated and measured joint torque and stiffness are shown in Fig. 10. It can be noticed that the maximum value of stiffness is obtained when the two actuators are fully contracted (i.e. when no power is applied) and decreases (even if by a small amount) when the two artificial muscles are electrically activated.
This limited stiffness variation can be explained by noticing that the actuator stress–strain relationship is quasi-linear in its range of motion, which is about two millimeters around the equilibrium point obtained by applying the initial preload. This undesirable characteristic depends on both the intrinsic passive material properties and the maximum amount of force variation (presently few Newtons) which the actuator is actively able to develop in this small operative range.
A larger stiffness variation can be therefore obtained by selecting materials able to withstand higher electric fields (thus increasing the amount of developed force) and by shifting the actuator operative range in steeper region of the curve (by increasing the initial preload). Experiments will be performed with the next prototypes of actuators, which are currently under development.

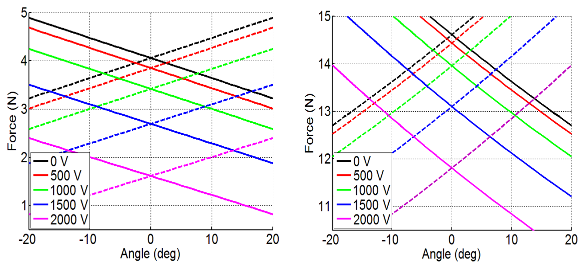

Fig. 9: *Force-displacement planes for different levels of actuator preloads. The points where the lines intersect correspond to the equilibrium points of the joint. The angle between the actuators characteristics implicitly defines the joint stiffness.*

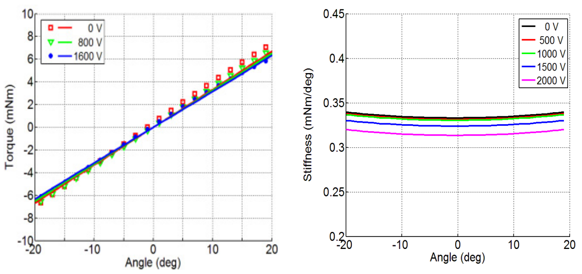

Fig. 10: *Left: estimated (solid line) and measured (dashed line) joint torque. Right: computed joint stiffness for different levels of coactivation of the two elastomer actuators.*

Conclusions

In this paper we described a mechanical system in which two antagonistic dielectric elastomer actuators are used to control a rotational joint. A closed loop scheme based on the independent force control of the two actuators was presented. The proposed controller is able to track a reference position command while guaranteeing a minimum tendon tension. The capability of the system to regulate the joint stiffness by coactivating the two actuators was also analyzed. The results indicated that the current actuators performances allow the adjustment of the joint stiffness only in a small operative range.
Future work will focus on the comparison between different actuating configurations (e.g. contractile stacks vs. elongating roll actuators) and the investigation of advanced control schemes able to achieve more complex, biologically inspired behaviors (i.e. minimum jerk trajectories, time varying stiffness profiles etc.)

Acknowledgments

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