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# Towards variable-stifness dynamic hand splints based on dielecric elastomer transducers

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## Abstract

Patients affected by motor disorders of the hand and having residual voluntary movements of finger can benefit of self-rehabilitation programs to be performed by means of so called dynamic hand splints. These systems consist of orthoses equipped with elastic bands or springs which exert a passive resistance to voluntary elongations of one or more fingers. So, such systems allow for rehabilitation of fingers that still can voluntarily be moved against the recovery force of the counteracting elastic component. Although attractively simple, this approach is limited by the impossibility of modulating the counteracting action in real time. This does not allow for customized training and real-time control, of the rehabilitation exercise, which might desirable to improve the rehabilitation efficacy. To solve this problem, electromechanically active versions of dynamic hand splints are needed. To address this issue with a solution relying on compact and light-weight devices, we are currently studying possible benefits of using dielectric elastomer (DE) transducers as variable-stiffness devices. The transducer is connected to a tendon wire, to be pulled and released by the user, and to a load cell. A processing unit controls the stiffness, so as to train the patient according to desired rehabilitation plans. We show here the current stage of implementation of this concept using a multilayer transducer made of the Danfoss PolyPower DE film.

## Introduction

Patients affected by motor disorders of the hand and having residual voluntary movements of finger can benefit of self-rehabilitation programs to be performed by means of so called dynamic hand splints. These systems consist of orthoses equipped with elastic bands or springs which exert a passive resistance to voluntary elongations of one or more fingers (Fig. 1). So, such systems allow for rehabilitation of fingers that still can voluntarily be moved against the recovery force of the counteracting elastic component. Although attractively simple, this approach is limited by the impossibility of modulating the counteracting action in real time. This does not allow for customized training and real-time control, of the rehabilitation exercise, which might desirable to improve the rehabilitation efficacy. To solve this problem, electromechanically active versions of dynamic hand splints are needed. To address this issue with a solution relying on compact and light-weight devices, we are currently studying possible benefits of using dielectric elastomer (DE) transducers as variable-stiffness devices [1]. The transducer is connected to a tendon wire, to be pulled and released by the user, and to a load cell. A processing unit controls the stiffness, so as to train the patient according to desired rehabilitation plans. The current stage of implementation of this concept is reported below.


Fig. 1. Dynamic hand splints: (a) a state-of-the-art example of passive splint equipped with an elastic band; (b) schematisation of the concept here proposed, consisting in the substitution of the passive elastic band with active elastic actuators.

## Materials and methods

**Designed, manufacturing and electromechanical characterization of the multilayer DE transducer**

The transducer was developed using the Danfoss PolyPower DE film. According to the state of the art of dynamic hand splints, we fixed as a target for our actuator an active force of about 1.4 N. To meet this requirement, we considered a multilayer structure made of 14 layers of the PolyPower film, able to deliver 0.1 N each. We designed each layer as a 4 cm-wide stripe driven at 2.5 kV. The PolyPower film was cut in 14 rectangular stripes (40mm x 180mm) to be stacked in a multilayer pile (Fig. 2). The transducer was characterized in terms of force-elongation curve, obtained by means of a double-column dynamometer. Different curves up to an elongation of 20 mm were measured while driving the actuator either at constant voltage, or at constant stiffness.

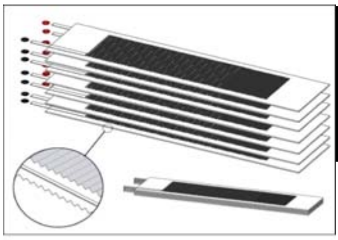


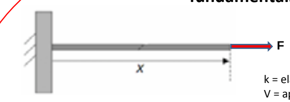

Fig. 2. Drawing and picture of the multilayer DE transducer. The inset shows a magnification of the surface corrugation of the PolyPower film.

**Stiffness control**

A stiffness control strategy was aimed at inducing the transducer to exhibit in the force (F) – elongation (ΔL) plane a characteristic response with a higher slope (i.e. a higher stiffness dF/dL ), as compared to those of the curves at null and maximum applied voltage (i.e. 0 V and 2.5 kV). In particular, we chose to implement a straight line passing through the following points: $F=F_{0V}$, ΔL=0 and $F=F_{x0}$, ΔL=ΔLmax, where: $F_{0V}$ is the force when the elongation is null and the voltage is maximum (V=Vmax=2.5 kV); $F_{x0}$ is the force when the elongation is maximum (ΔL=ΔLmax=20mm) and the voltage is null. Accordingly, simple calculations led to the following control relation:

$$V = Vmax\left(1-\sqrt{\frac{F^2-F_{0V}^2}{F_{x0}^2-F_{0V}^2}}\right)$$

**Stiffness modulation in DE transducers: fundamentals**




k = elastic constant
V = applied voltage
Y = Young's modulus of the material
Vol, w, A = volume, width & cross-section of the elastomer film
$\varepsilon\varepsilon_0$=dielectric constant of the material

Stiffness:

$$K=\frac{dF}{dx}=k-bV^2$$

$$b=\frac{\varepsilon\varepsilon_0 w^2}{Vol} \qquad k=\frac{F}{(x-x_0)}=\frac{YA\left(\frac{x-x_0}{x_0}\right)}{x-x_0}$$

Reference: [2]

## Results and discussion

Results of its electromechanical characterization at constant voltage or constant stiffness are presented in Fig. 3. This figure shows two evidences. First, the developed multilayer actuator was able to generate an active force close to the expected theoretical value, about 1.4 N (with a slight variation with elongation). Second, the implemented stiffness control allowed us to change the transducer stiffness, and to keep it constant within the elongation range.

The most useful advantage of the proposed concept is represented by the possibility of customizing and controlling in real time the rehabilitation exercise. The stiffness can be controlled *a priori* or adjusted in progress according to the patient's need and actual neuro-muscular performance. This is not proper to state-of-the-art passive hand splints, and is achievable with DE transducers that have inherent elasticity, compact size, light weight, versatility of design, portability, shock-tolerance, acoustic silence, and low power consumption. Such features make them particularly attractive as compared to alternative actuation technologies that might be considered to develop active hand splints [1].

As a drawback, according to the state of the art of the DE transduction technology, active hand splints based on DE transducers currently require a high-voltage driving circuitry, which is relative expensive. This is a general problem for the whole field of DE transduction, which is focusing scientific and industrial efforts worldwide to produce films than can be driven at lower voltages.

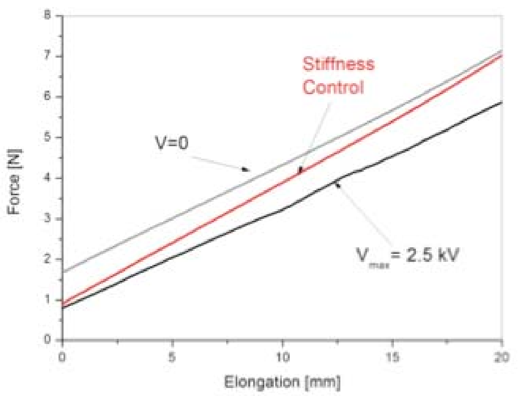



Fig. 3. Force-elongation curves of the multilayer DE transducer for different driving conditions: constant voltage and constant stiffness.

## Conclusion and future developments

The developed multilayer DE transducer and the implemented stiffness control were demonstrated to show adequate performance to consider the DE transduction technology as a suitable choice to develop dynamic hand splints for finger rehabilitation.

Following this proof-of-concept demonstration, future work should be aimed at developing a real hand splint, by arranging the DE transducer in an ergonomic housing. Notably, the maximum force could straightforwardly be increased by stacking more layers.

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This work won the "*Danfoss PolyPower Innovation Contest 2010*". A video of the work is available online [3]. Support from Danfoss PolyPower is gratefully acknowledged.

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[3] Video of the "Danfoss PolyPower Innovation Contest 2010": http://www.youtube.com/watch?v=nIQWDxAXBuI