Smart Textiles Toward a Wearable Motion System

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Abstract — **This paper presents the development of an innovative measuring system devoted to the human movement analysis using smart textiles that are realized with electrically conductive elastomer composites (CEs). CEs show piezoresistive properties when a deformation is applied and in several applications CEs can be integrated into fabric or other flexible substrate as a strain sensor. Moreover, integrated CE sensors may be used in biomechanical analysis to realize wearable kinesthetic interfaces that are able to detect posture and movement of the human body. Clinical requirements such as comfort, good fit and unobtrusivity are satisfied. Actually, CEs behavior presents some peculiar non-linear phenomena, requiring a complex treatment of signals.**

Keywords: smart textiles, CE sensors, quaternions.

I. INTRODUCTION

The analysis of human movement is generally performed by measuring kinematic variables of anatomic segments using *tracking systems* devices, that are accelerometers, electromagnetic sensors or stereophotogrammetric systems. The main disadvantages of these devices in particular tasks, such as in clinical ones, are their invasivity, complexity and the difficulty of bringing them in the user daily environment.

In the present application, our efforts have been focused to achieve the following goals:

- the measurement of kinematic variables by using *kinesthetic wearable sensors*, realized by CEs smeared on an elastic fabric that should not bound natural body movements (Section II);
- the development of human limbs mathematical models whose input controls are the processed sensor signals (Section III);
- the integration of both acquisition and signal processing in a dedicated software package, which supplies a representation of user movements in an interactive tridimensional environment (Section IV).

II. KINESTHETIC WEARABLE SENSORS

The CE we use is a mixture, composed by silicon rubber and graphite, that is previously diluted with trichloroethylene and then it is smeared on an elastic fabric substrate according to the shape and the desired dimensions for the sensors (see Fig. 1). The treated fabric is placed in an oven at a temperature of about 130°C to speed up the crosslinking of the solution and in about 10 minutes the sensing fabric is ready to be employed.

In terms of quasi-static characterization, a sample obtained of 5mm in width presents an unstretched electrical resistance of about $1k\Omega$ per *cm*, and the gauge factor is about 2.8 ($GF=l(R-R_0)/R(l-l_0)$, where R is the electrical resistance and l is the length of the specimen). The temperature coefficient ratio is $0.08K^{-1}$. Capacity effects are negligible up to 100*MHz* (other aspects are reported in [1] and in [2]).

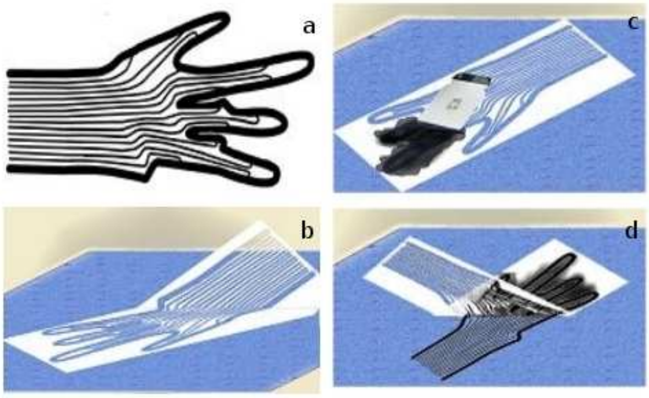

Figure 1: Realization process for a sensorized glove: a) Mask; b) Application on fabric; c) Smearing process; d) Result.

Dynamical behaviour of sensors is more complex because the material shows non-linear peculiarities. Figure 2 shows the output of a sample stretched with trapezoidal ramps in deformation. We can note that:

- both increasing and decreasing ramps produce always overshooting peaks, whose amplitude is function of the deformation velocity dl/dt (where l is the sample length);
- overshoots are followed by a relaxing transient, whose length is too long to suitably code human movements.

In order to address those issues, many approaches were used. In Section IV we present a method used to reduce the transient time.

A. Realization of a Prototype for the Upper Limb

In order to monitorize kinematic variables of the upper limb by means of a sensorized shirt, the great deal was to determine the sensors position around articulations. A theoretical approach was investigated, by searching an optimization criterion for the global content of *information* collected by the system. Unfortunately this technique resulted very onerous in terms of required computational resources. So, finally, an euristic approach was adopted: a sample of sensorized tissue was continously repositioned around articulations during the execution of natural movements, searching the positions which produced the best output. Figure 3 shows both the mask and the prototype realized. All sensors are represented by the segment series which compounds the bold track, whereas the thin tracks represent the connection to the electronic acquisition device (so that any kind of wire is needed onto the garment).

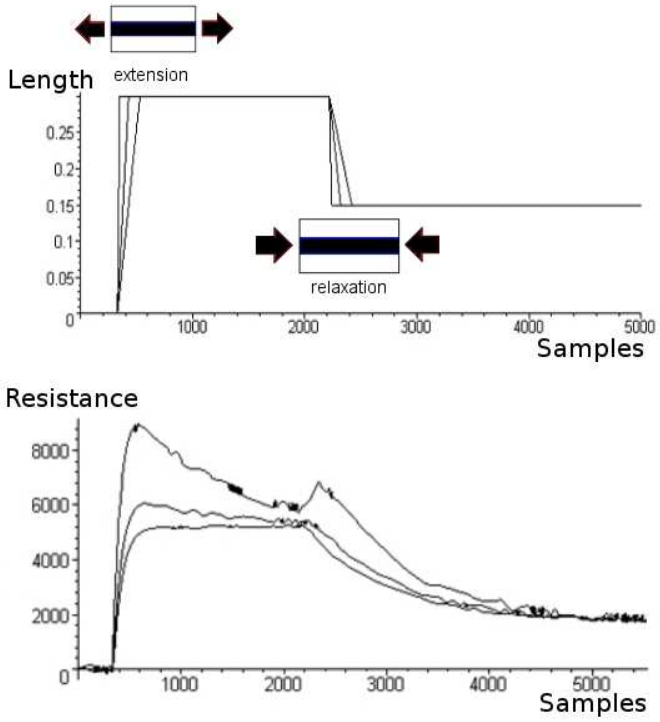

Figure 2: Response of a CE sample excited by trapezoidal ramps of deformation.

III. KINEMATIC MODELS OF HUMAN ARTICULATIONS

In many fields such as biomechanics, robotics and computer graphics, hierarchical structures are used in articular body modelling for robots, human representations or for other creatures. An articulated body can be thought as a series of rigid segments connected by joints. In the present work we used ideal joints. This allowed us to maintain a practical parameterization of movements without trivializing the human articulation movement.

A. The Human Upper Limb Model

From an external point of view, an upper limb model have at least 7 DOFs, corresponding to rotational movements. These ones, described by kinesiology, are listed in Table I:

SHOULDER	***ELBOW***	***WRIST***
Flexion/Ext. Abduction/Add. Intra/Extra rot.	Flexion/Ext. Pronation/Sup.	Flexion/Ext. Abduction/Add.

Table I: Upper limb degrees of freedom.

Figure 3: From the top: the sensor track and the prototype for the upper limb.

Figure 4 shows the model we considered. The articular complex of the shoulder has been parameterized as a *ball and socket* joint, whereas elbow and wrist present a succession of two rotational joints.

Since joints allow only rotational movements, three different parameterizations was considered to describe rotations: the *Euler-Cardan* angles, the *axis/angle parameterization* (a.k.a. *exponential map*) and finally the *unit quaternion* representation. There is not a general criterion to prefer one parameterization with respect to the others. The choice depends on the particular application and on the use of forward or inverse kinematics. The crucial point is the presence of *singularities*, a classic control problem. Euler angles provide the orientation with the use of three parameters, but get two singularities, known as *gimbal-lock* [3]. The exponential map adds a parameter with respect to Euler angles but solves only one singularity. In order to address both singularities, unitary quaternions must be used.

IV. KINEMATIC SENSOR SYSTEM (KSS)

KSS is the software package developed which integrates both acquisition and processing of signals with the visualization of articular segments motion. KSS was developed rigourously using only Open Source Software. The concept was to provide a GUI representing a user's Avatar in a tridimensional interactive environment which movements are driven by sensorized garments (see Fig. 5). Trials were considered in clinical remote rehabilitation tasks for post-stroke patients.

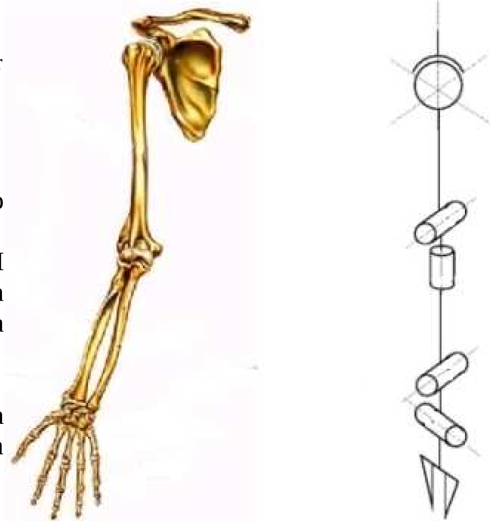

Figure 4: The upper limb model.

A. *Posture Recognition and Animations*

The main problem in kinematic reconstruction with CE sensors was to define a map between *sensor space* (named *S* and intended as acquired sensors outputs), and *configuration space* (named *Q* and intended as lagrangian coordinates that define links position in kinematic models).

To address this issue, we adopted a strategy by creating and relating discrete subspaces of *S* and *Q* using a clusterization procedure during a calibration phase. Then recognition was performed acquiring the generic sensors outputs and searching through the calibration positions the closest one in the least square sense. When a posture was recognized, the program performed an animation, giving the sense of transition within calibration positions. This step was done using the *spherical linear interpolation algorithm* (Slerp) provided by quaternions algebra, that is explained in [4].

Using interpolation on quaternions realized fluid and realistic animations, unlike simple interpolation on Euler angles. Moreover, the absence of singularities in unit quaternions permitted the execution of each arbitrary trajectory in the configuration space. In other words, that means the possibility of representing each kind of movement.

B. *Transient time reduction*

As explained in section II, the treatment of signals is essential for the reduction of the transient time. When the specimen is motionless, e.g. after a deformation (see Fig. 2 where $dl/dt=0$), the trend of the electrical resistance can be expressed by an combination of exponential functions:

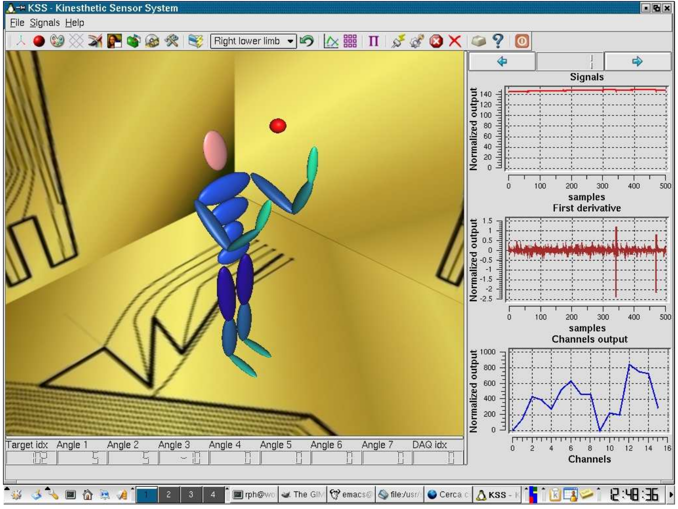

Figure 5: Snapshot of the KSS software.

$$Y(t) = c_0 + c_1 \exp(-\omega_1 t) + \ldots + c_p \exp(-\omega_p t) \qquad (1)$$

It was proved experimentally that the poles ω_i of Eq. 1 depend neither on the amplitude of the strength, nor on it velocity. So they was calculated once for a certain specimen during a calibration phase by evaluating an exponential least square regression.

It is clear that if the pole values are known, during a transient time, the only coefficients which have to be calculated are the c_is and in particular c_0, which represents the final value. For this step, we developed an algorithm based on iterate integrations of Eq. 1. By summing al least *k* copies of Eq. 1 evaluated on contiguous samples (which corresponds to a numerical integration) we obtained the vector of c_is as the least square solution of an over-dimensioned linear system.

V. RESULTS AND CONCLUSIONS

The whole system developed was submitted to a series of trials (see Fig. 6) in order to collect informations about the suitability for wearable motion tracking analysis applied to clinical remote rehabilitation tasks. Results are the following:

- The use of elastic fabric is non-invasive, easy to use and does not constrain natural body movements;
- The designed sensor track with the criterion presented in section II.*A* has lead to a repeatable recognition of the five main DOFs of the kinematic chain that compounds the human upper limb, that is flexion-extension and abduction-adduction movements. Regarding rotational movements, we're

currently investigating the possibility of integrating other kind of wearable sensors into smart textiles;

- Algorithms developed have given good results and are structurated in a way that a rigorous application to each sensor will permit a refining of the actual *S->Q* map;
- The *KSS* software package resulted intuitive and easy-to-use, matching guidelines for required applications.

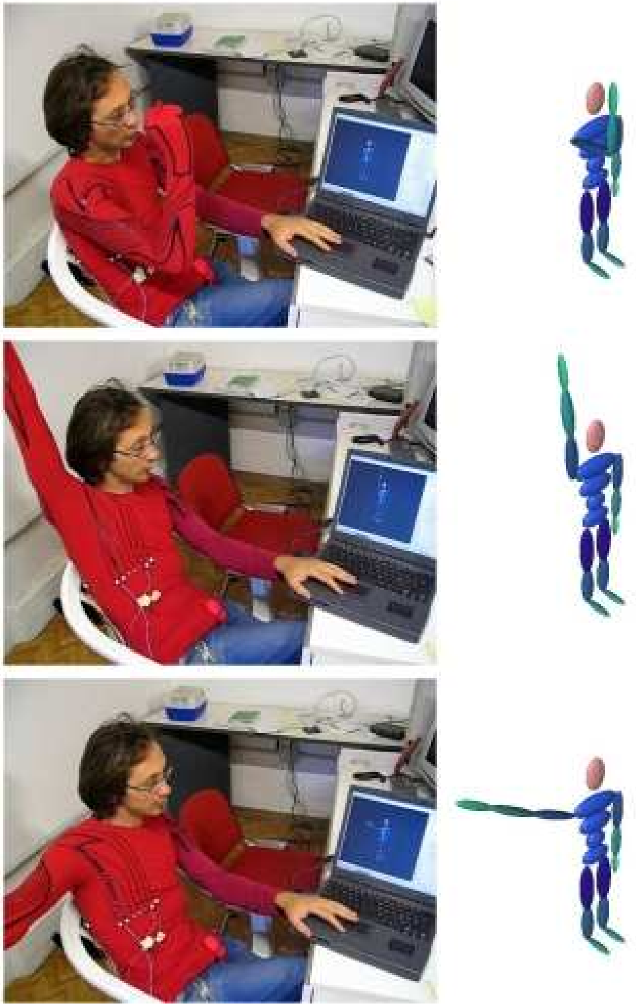

Figure 6: Posture recognition trials.

However, the main result of this work has been the demonstration that kinesthetic wearable sensors are suitable for application of kinematic reconstruction and motion tracking. Obtained data are preliminary but strongly encouraging, sign of the great potential of this whole technique.

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