Proceedings of the 2005 IEEE
Engineering in Medicine and Biology 27th Annual Conference
Shanghai, China, September 1-4, 2005

Wearable kinesthetic systems for capturing and classifying body posture and gesture

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Abstract— **Monitoring body kinematics has fundamental relevance in several biological and technical disciplines. In particular the possibility to know the posture exactly may furnish a main aid in rehabilitation topics. This paper deals with the design, the development and the realization of sensing garments, from the characterization of innovative comfortable and spreadable sensors to the methodologies employed to gather information on posture and movement. In the present work an upper limb kinesthetic garment (ULKG), which allows to reconstruct shoulder, elbow and wrist movements and a kinesthetic glove able to detect posture an gesture of the hand are presented. Sensors are directly integrated in Lycra fabrics by using conductive elastomer (CE) sensors. CE sensors show piezoresistive properties when a deformation is applied and they can be integrated onto fabric or other flexible substrate to be employed as strain sensors.**

I. INTRODUCTION

This work deals with the development of an innovative measuring system devoted to the human movement analysis. Our main aim is to provide a valid alternative comfortable instrumentation useful in both several rehabilitation areas, sport disciplines and multimedia field. The analysis of human movement is generally performed by measuring kinematic variables of anatomic segments by employing accelerometers, electrogoniometers, electromagnetic sensors or cameras integrated in finer equipment as stereophotogrammetric systems. Several disadvantages in remote rehabilitation tasks derive from the use of these technologies which are mainly applied in the realization of robotics or mechatronics machines (such as MIME or MIT-MANUS [3]). They often result invasive, complex and unable to satisfy safety requirements for the presence of mechanical parts while they move. In literature, several studies are devoted to realize electric devices with high wearability properties [1], [5], [6]. The main drawbacks of wearable sensing systems available on the market are their weight, the rigidity of the fabric which they are made of, the dimension of the sensors used, and all the other properties which make them obtrusive. In particular, conventional sensors often require the application of complex and uncomfortable mechanical plug in order to position the sensors on garments. In the present work, we focused our efforts in the realization of new systems for the measurement of the human body kinematic variables by means of sensorized garments such as an Upper Limb Kinesthetic Garment (ULKG) and a Sensing Glove.

II. WEARABLE CONDUCTIVE ELASTOMER SENSORS

The CE we use is realized by a silicon rubber and graphite mixture and it can be smeared on an elastic fabric substrate according to the shape and the desired dimensions for the sensors by using an adhesive mask. This technology provides both sensors and wiring by using the same elastic material and avoids the use of obtrusive metallic wires which may bound movements of the kinematic chain under study. The production process to obtain sensing substrate is reported in [9]. The main properties of CE sensors are here summarized. The CE sensor gauge factor is about 2.8 and the temperature coefficient ratio is $0.08K^{-1}$. Capacity effects showed by sensors are negligible up to $100MHz$. Complexity arises in the dynamical characterization, because the material shows several non-linear peculiarities. Moreover, after a feedback linearization, sensors need to be regulated to be used in our applications. This matter is widely described in [9]. By using Lycra as a substrate we have obtained a sensing fabric which allows us to manufacture garments capable of monitoring human movements. In particular, by designing the spreading mask according to the location of the joints we desire to monitor, we have obtained meaningful information from garments. Two different kinesthetic interfaces are presented in the following.

III. THE UPPER LIMB KINESTHETIC GARMENT

An upper limb kinesthetic garment (ULKG) which detects the posture of wrist, elbow and shoulder has been developed by using the presented technology and it is going to be used in post-stroke patients rehabilitation (My-Heart, EU-IST, VI Framework). The ULKG is integrated in a health care service which allows patients to continue the rehabilitation training at home or in unsurveyed environments, and without the help of physicians, after the intensive rehabilitation period. The ULKG acquires information on the joints of the upper limb by 20 sensors spread on a shirt. It monitors shoulder, elbow and wrist joints. Figure 1 shows the ULKG prototype, where all sensors are represented by the segment series which compounds the bold track. Thin galley proofs constitute the wiring system.

IV. THE SENSING GLOVE

A suitable mask was used to print CE sensors over a Lycra glove (in Figure 2 the sensing glove prototype is shown) a set of sensors and wires. Also in this case, no conventional

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Fig. 1. ULKG prototype

Fig. 2. The sensing glove prototype

and cumbersome cables are necessary to connect the sensors from the glove to external electronics. This configuration is the evolution of an earlier prototype where the connections between sensors and acquisition device were realized by means of metallic wires, which, inevitably, bounded certain movements.

V. GARMENT ELECTRICAL MODEL AND ELECTRONIC ACQUISITION TECHNIQUES

In Figure 3 the mask used to realize the ULKG is shown. The bold black track represents the set of sensors connected in series (S_i), and covers the main joints of the upper limb (shoulder, elbow and wrist). The thin tracks (R_i, Figure 3) represent the connection between the sensors set and the electronic acquisition system.

Since the thin tracks are made of the same piezorestive CE material, they undergo a not negligible (and unknown) change in their resistance when the upper limb moves. Therefore the analog front-end of the electronic unit is designed to compensate this resistance variation. In Figure 3 the electric schematic is reported. While a generator supplies the series of sensors S_i with a constant current I, the acquisition system has been provided by an high input impedance stage realized by instrumentation amplifiers (represented in Figure 3 by the set of voltmeters). Thank to this configuration, only a little amount of current flows through the connecting wires, which have resistance values R_i, and so the voltages which fall on R_i are negligible if the current I is big enough. Using this configuration we obtain

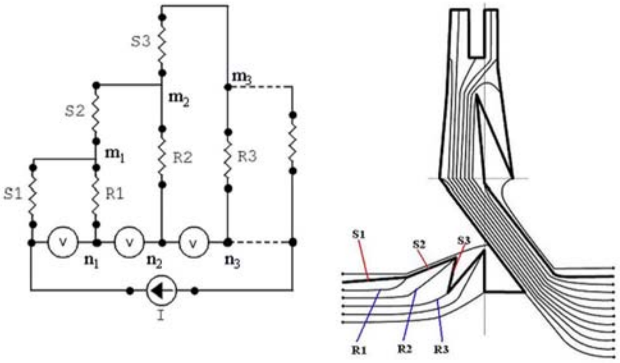

Fig. 3. The electronic acquisition scheme (on the left) and the mask utilized for the realization of the ULKG (on the right)

TABLE I
UPPER LIMB DOFS

shoulder	elbow	wrist
flexion-extension abduction-adduction intra-extra rotation	flexion-extension pronation-supination	flexion-extension abduction-adduction

$$V_{n_i} \approx V_{m_i} \qquad (1)$$

where V_{n_i} and V_{m_i} are the voltages in the nodes n_i and m_i, respectively. In conclusion, the voltages measured by the instrumentation amplifiers are equal to the voltages which fall on the S_i that is related to the resistances of the sensors. In this way, the thin galley proofs perfectly substitute the traditional metallic wires and a sensor, consisting in a segment of the bold track between two thin tracks, can be smeared in any position to detect the movements of a certain joint.

VI. KINEMATIC MODELS OF HUMAN JOINTS

Output signals from sensorized garments have been used to drive a model of human kinematic chains. A kinematic chain can be thought as a series of rigid segments connected by *joints*. In the present work we used ideal joints in order to maintain a practical parameterization of movements (rotations) without trivializing the human joint movement. As an example, from an external point of view, an upper limb model has at least 7 DOFs, corresponding to rotational movements. These ones, described by kinesiology [2], are described in Table I. In the model we have developed, 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. This choice is made in order to present an intuitive position and gesture reconstruction in terms of practical mathematical parameterizations. Moreover, the union of several kinematic models developed (upper limb, lower limb, trunk and neck) have been joined to form an *Avatar* with human appearance (Figure 4).

VII. RECONSTRUCTING OF KINEMATIC CONFIGURATIONS

We have developed a software package, named Kinematic Sensor System (KSS), which integrates both signal acquisition and processing, providing a visualization of joint segment motion in a tridimensional interactive environment.

When a kinesthetic garment is worn by a user which holds a given position, the set of sensors assumes a value strictly related to it. If the number of sensors is large enough and if the sensor locations are adequate, the values presented by them uniquely characterize the considered position. Hence, in order to perform *posture recognition* and *representation* KSS defines a map between the *sensor space*, $\mathcal{S}$, which contains the values of the sensor outputs, and the *configuration space*, $\mathcal{Q}$, i.e. the lagrangian coordinate space which describes the status of the kinematic model. We have implemented this map both by a clusterization of the space $\mathcal{S}$ via a least square technique into the space $\mathcal{Q}$ and by the interpolation of the discrete map produced by the clusterization [4]. By using the second solution it is possible to map every position performed by an user in a set of angle values. Results of this working mode are reported in next section both for the sensing glove and the ULKG. The first solution has been applied by using the norm

$$\delta_i = \sqrt{\sum_{i=1}^{c} \left(s_i^2 - \mathcal{S}_{ij}^2\right)} \tag{2}$$

as the clustering function, where $\mathcal{S}_{ij} \in \mathcal{S}$ are the centers of the clusterization lattice and $s_i \in \mathcal{S}$ represent the real value of the sensors. Moreover the software performs biomimetic animations, between clusterized positions by using a geometric representation in quaternion algebra: orientations acquired during calibration in terms of Euler angles are translated in terms of unit quaternions and transitions are defined through the *spherical linear interpolation algorithm (Slerp)* described in [7]. Using quaternions make animations fluids and realistic, unlike simple interpolating Euler angle or exponential map do. Moreover, the absence of singularities in unit quaternions permits the execution of each arbitrary trajectory in the configuration space. In other words, each kind of movement is representable. Some positions of the upper limb recognized from the ULKG and represented by the avatar are reported in Figure 4. The system, using the ULKG, is under validation in stroke rehabilitation tasks. It is able to teach, to evaluate and correct movements constituting a rehabilitation protocol. The objectivity of the data acquired on patient performances consents to store and send them to doctors and therapists which may evaluate tasks and patient progress, remotely. The health care service in which the ULKG is inserted is described in [8].

VIII. RESULTS

A. Sensing Glove Performances

The sensing glove, in its posture detection functionality, has been tested in movements involving the metacarpophalangeal (MP) joint (in flexion-extension), the proximal interphalangeal (PI) joints and the distal interphalalgeal (DI) joint of the forefinger. Some of these data are collected in Table II. The average error percentage in detecting the angle is about 4%. The real angles are measured by using an appropriate electrogoniometer set.

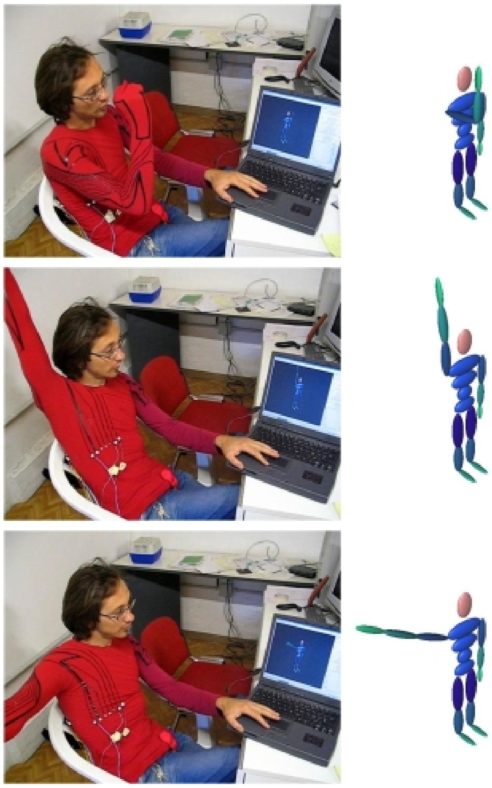

Fig. 4. Posture recognition using the ULKG and graphical representation.

TABLE II

PERFORMANCES OF THE SENSING GLOVE

	MP	PI	DI
Real Extimated	45 45	45 45	0 0
Real Extimated	45 45	22.5 25.31	22.5 15.47
Real Extimated	45 45	45 42.19	45 45
Real Extimated	75 80.16	75 67.5	25 32.34
Real Extimated	60 60.47	0 0	0 8.44
Real Extimated	22.5 22.5	22.5 22.5	22.5 22.5

B. ULKG Performances

Results from trials on the ULKG are reported. The device output (blue paths) is compared with the results of a motion detection executed by commercial electrogoniometers (red paths). A composition of flexion and abduction of the shoulder (Figure 5) and a circling of the wrist (Figure 6) are presented. Finally, an elbow flexion is shown in Figures 7. Both shoulder rotation and elbow pronation-supination have performed qualitative results in terms of sensor signal trends but these responses have not yet been analyzed because the electrogoniometers we used are not capable to detect such responses and an identification of the ULKG along this movement direction has not been possible. The error is always less than 5%.

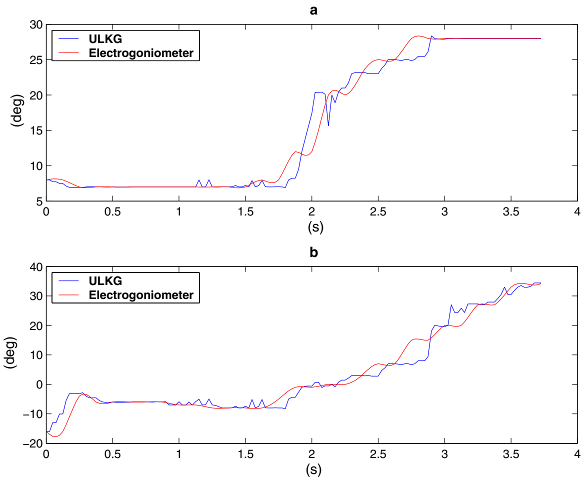

Fig. 5. Extension (a) and flexion (b) angles versus time of the shoulder. The red line is the goniometer output, while the blue one represents the ULKG response.

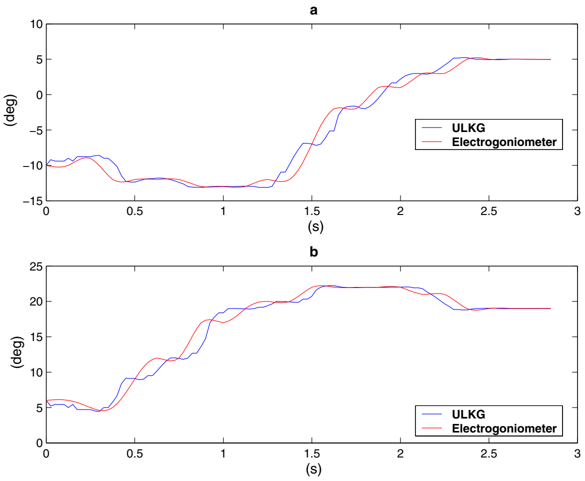

Fig. 6. Flexion (a) and abduction (b) angles of the wrist versus time. The red line is the goniometer output, while the blue one represents the ULKG response.

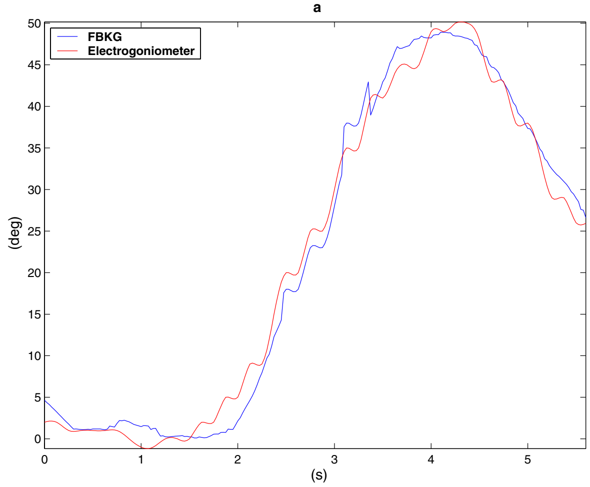

Fig. 7. Flexion angle of the elbow . The red line is the goniometer output, while the blue one represents the ULKG response.

IX. CONCLUSION

In this work a collection of sensorised garments for the human body gesture, posture and movement evaluation has been presented. The main advantage ensured by these prototypes is the possibility of wearing them for long period and being monitored without discomfort. Several issues, deriving from the employment of the new technology which has consented the realization of these unobtrusive devices have been addressed. Moreover, it has been pointed out the use of these sensorised garments as valid alternative and comfortable instrumentation applicable in several rehabilitation areas, in sport disciplines and multimedia field. Finally, results on the performances of the sensing systems were reported. Trials effectuated on the realized prototypes has pointed out good results: the performances of the Kinesthetic Garments are comparable with the ones deriving from commercial electrogoniometers.

X. ACKNOWLEDGMENTS

This research, with particular emphasis on the post stroke rehabilitation part, has been funded by the European Commission through MyHeart project - IST 507816.

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