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Wearable kinesthetic system for joint knee flexion-extension monitoring in gait analysis

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Abstract— **In this paper we investigated on the possibility of using a wearable kinesthetic system for monitoring flexion-extension of the knee joint during deambulation. The final goal was to provide an unobtrusive technique to identify the clinical stage of the recovery process of patients affected by venous ulcer. These patients have great difficulty in walking depending on the severity level of disease and after a surgical operation they usually progressively improve up to recover their normal walking capability. Typically, they are monitored by means of invasive instrumentation. On the contrary, our wearable system is comfortable and non-invasive for the patient. A preliminary pilot test was performed in order to discriminate healthy subjects with a normal walk, from injured subjects. Two discriminating criteria, based on the flexion-extension excursion and its variance, respectively, were envisaged. The latter parameter resulted more effective. In order to determine the discrimination threshold an experimental ROC curve was traced. Finally sensitivity and specificity of the test were experimentally computed.**

I. INTRODUCTION

GAIT analysis is generally performed for measuring kinematic variables of anatomic segments with tracking devices that include accelerometers, electromagnetic sensors or finer equipment such as stereophotogrammetric systems. Although this methodology is widely accepted, it is still quite complex and difficult to be used in clinical environments. Moreover, instrumentation costs, especially camera systems, are very high. The recent development of "intelligent" materials [1] allows to design and produce a new generation of garments using electrically conductive elastomer composites (CEs) [2]. CEs show piezoresistive properties when a stress is applied, and in several applications they can be integrated into fabrics or other flexible substrates to be used as strain sensors [3]. In the present paper, we investigate on the possibility of using a lower limb sensorized garment for quantitatively analysing flexion-extension of the knee of subjects afflicted with venous ulcers localized in the lower limbs [4]. Specifically, we propose to use a sensorized fabric band wrapped around the knee. Unlike conventional devices, the Knee-Band (KB) is unobtrusive due to its lightness, adherence and elasticity, hence very suitable for the clinical environment. The final goal was to provide a friendly technique to identify the clinical stage of the recovery process of patients who suffer from venous ulcers. These patients find difficulties in walking depending on the severity level of the disease, and usually demonstrate improvements in their walking capability after undergoing a surgical operation [5]. Usually, they are monitored by means of invasive instrumentation, which analyzes the reduction of the diameter of the lower limb without verifying walking. On the contrary, our wearable system is comfortable and minimally invasive for the patient. As the validation tool, a preliminary pilot test was performed in order to discriminate between healthy subjects with a normal walk and pathologic subjects after having undergone post-operational therapy. Two different discrimination criteria were used to identify which population, health or injured, subjects belong to. The first criterion is based on the flexion-extension excursion, while the second one takes account of its variance. The latter parameter provided better results. In order to determine the discrimination threshold an experimental ROC curve was traced. Finally, sensitivity and specificity of the test were experimentally computed.

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Fig. 1. Sensorized shoe for marking the gait cycle.

II. MATERIALS

The prototype of the sensing garment has been realized deposing the CEs over a sub layer of cotton Lycra® and building a sensorized shoe devoted to the gait cycle synchronism. The sensorized shoe consists of a pressure sensor realized of the same material of the KB, which is placed on the sole near the heel as shown in Figure 1. The CEs mixture is smeared on the fabric previously covered by an adhesive mask cut by a laser milling machine. The mask is designed according to the shape and the dimension desired for sensors and wires. After smearing the solution, the mask is removed. Then, the treated fabric is placed in an oven at a temperature of about 130 centigrade degrees. During this phase the cross-linking of the solution speeds up, and in about 10 minutes the sensing fabric is ready to be employed. This methodology is used both for sensing areas and connection paths, thus avoiding to employ metallic wires to interconnect sensors or link them to the electronic acquisition unit [6]. In this way, no rigid constraints or linkages are present and movements are unbounded [7].

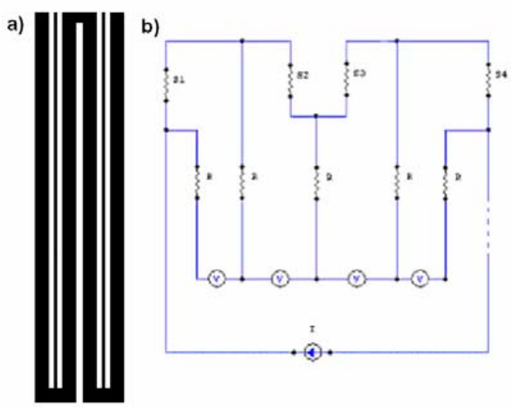

Fig. 2. The mask used for the sensorised KB.(a) The equivalent electric scheme of the KB.(b)

Figure 2a shows the mask for realization the KB; the bold black track represents four sensors connected in series and covers the knee joint. The thin tracks represent the connection between the sensors and the electronic acquisition system. Being the thin tracks made of the same piezorestive mixture, they undergo a not negligible (and unknown) change in their resistance when the knee bends. To face this inconvenient, the analog front-end of the electronic unit is designed to compensate the resistance variation of the thin tracks during the deformations of the fabric. The electric scheme is shown in Figure 2b. While a generator supplies the series of sensors *Si* with a constant current I, the acquisition system is provided by a high input impedance stage realized by instrumentation amplifiers and represented in Figure 2b by the set of voltmeters. The voltages measured by the instrumentation amplifiers are equal to the voltages which fall on the *Si* that is related to resistances of the sensors. In this way, the thin tracks perfectly substitute the traditional metallic wires and a sensor, consisting of a segment of the bold track between two thin tracks, can be smeared in any position to detect the movements of a joint. The KB acquires information on the flexion-extension of the knee from 4 sensors spread on a leotard and a step-signal from the sensorized shoe [8]. Moreover, the prototype consisted of an "on body unit" dedicated to the acquisition of signals from the KB and the Bluetooth transmission to a remote PC as shown in Figure 3.

Fig. 3. The overall prototype consisting of a KB, sensorized shoe and an "on body unit". Front (left side) and back (right side) views.

III. METHODS

The prototype was used in a clinical application consisting of the gait monitoring on subjects affected by venous ulcers localized in the lower limbs. A test for discriminating between pathologic and normal walking was performed by the acquisition of flexion-extension signals from the knee joint during movement. Next, experimental data were validated in order to assess goodness of the methodology. Nine subjects, five females and four males, were volunteered to participate in the study. The "normal" sample was made of four voluntaries, three males and one female, belonging to university context with a mean age of 32 years. Each subject was required to fill in a suitable anamnesis questionnaire in order to verify they did not undergo lower-limb injuries, disease or trauma. The "pathologic" sample consisted of five patients, four females and one male (mean age about 73 years), in-patient in a clinic specialized in vascular diseases, with special competences in cutaneous ulcers treatment, that was the medical partner in this work. The presence of the pathology under study was certified by consulting clinical folders.

IV. EXPERIMENTAL PROTOCOL

After the measurement system was correctly applied, taking care of arranging the sensors upon the knee articulation, each subject was required to walk freely on a level ground. By means of a wireless communication system, based on Bluetooth protocol, data were transferred in real time from an on-body unit to a personal computer, where a software interface let the operator monitorize signals from the sensorized garnment, including diagnostics and current settings. In a five gait cycle observation interval the flexion-extension signals were acquired and the correspondent files stored for offline elaboration.

V. Data Analysis

In the typical signal from a sensor of KB (continuous curve in Figure 4) resistance increases during flexion and decreases while the articulation extends, according to the piezoresistive effect. Voltage shows the same behaviour, because the supply current was fixed for this kind of measurement. The synchronized matching with step-signal acquired from the sensorized shoe (dashed line) allowed us to detect the “gait cycle”, or the elemental reference interval of the analysis. A single step-signal is an “on-off” signal where the low-level indicates that the foot is in contact with the ground, while the high-level indicates lifting

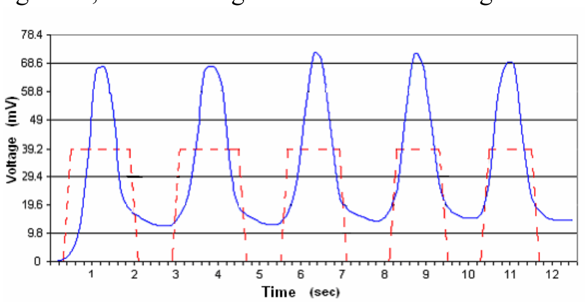

Fig. 4. Flexion-extension of the central sensor of KB (continuous curve) and signal coming from the shoe sensor (dashed curve) which marks the gait cycle.

In order to extract significant variables for discrimination, two different approaches were studied. The first one, based on the evaluation of flex-extension capability, was referred to as the ***width excursion*** parameter E, defined in Equation (1).

$$E = \left| V_M - \left(\frac{\left(\left| V_A - V_B \right| \right)}{2} + V_A \right) \right|. \qquad (1)$$

V_M represents the maximum voltage width in the maximum flexion instant; V_A is the voltage value when flexion starts;

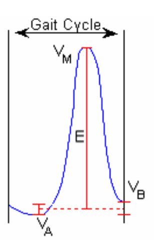

Fig. 5 Graphical representation of the width excursion

V_B indicates the voltage value in the maximum extension instant such as shown in Fig.5. The second approach proposes to analyze gait discontinuity during the observed interval. To this aim we referred to as the ***irregularity*** parameter IR, or standard deviation over a sample made up of average width excursion values, on the five gait cycles, regarding to the couple of central sensors (IR_c) and the couple of lateral ones (IR_L). In order to integrate information coming from each couple of sensors, standard deviation was calculated with respect to their average value:

$$E_{m_C} = \frac{E_{C_1} + E_{C_2}}{2}. \qquad (2) \qquad\qquad E_{m_L} = \frac{E_{L_1} + E_{L_2}}{2}. \qquad (3)$$

E_{C_i} (i = 1, 2) indicates the width excursion regarding to central sensor i, while E_{L_i} represents the width excursion related to lateral sensor ***i***. IR parameters were computed by “non distortion” method such as shown in Equation (4);

$$IR = \sqrt{\frac{\sum \left(x - \bar{x} \right)^2}{(n-1)}}. \qquad (4)$$

where x represents the sample arithmetical mean, while n is the dimension of the sample.

VI. Results

According to graphic representation of both IR_c and IR_L parameters over the entire recruited population (see Figure 6), several important issues have to be addressed:

- IR values showed fundamentally to be higher for pathologic subjects than for normal ones, confirming how they reveal an irregular knee flexion-extension during normal walking.
- A good discrimination between the two populations was obtained.
- IR values are higher in patients 5 and 1, which have a larger ulcer size, as it is known in clinical folder.
- Figure 6 reports on the discrimination on the basis of the irregularity of the mean value of central sensors IR_c and shows the graphical discrimination of subjects according to the irregularity of the mean value of lateral sensors IR_L. The graph IR_c reports a normal subject (normal 4) classified as belonging to the pathologic group, while in IR_L graph he is rightly recognized as normal. This means that, for our application, lateral sensors of KB resulted more specific than the central ones.

VII. Test Evaluation

The test validity has to be intended as the capability by the test to discriminate between normal and pathological subjects within the recruited population. Receiver Operative Characteristic (R.O.C.) curves analysis provided his scientific support in this evaluation, mainly to decide the best cut-off value of parameters for discrimination. A R.O.C. curve is a graphic representation of sensitivity versus false positive rate (FPR) for different cut-off levels of the measurement variable.

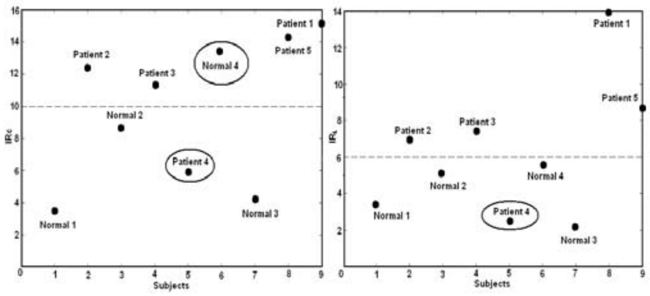

Fig. 6 Graphical representation of IR_c and IR_L parameters.

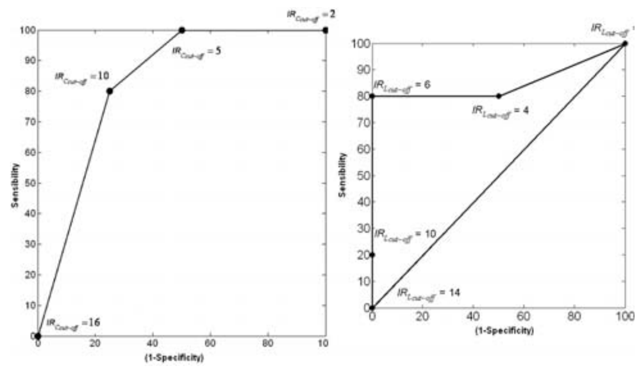

Fig. 7 Central sensor and Lateral R.O.C. curves.

The best decisional value ensures maximum of sensitivity to the minimum FPR. By this method, optimal cut-off value of irregularity was detected both for central sensors and for lateral ones (see Figure 7) and the test characteristic parameters were computed, in terms of sensibility, specificity and positive predictive value (PPV), as shown in the Table I. Positive predictive value is directly proportional to disease prevalence in the study population. For a good

TABLE I
SENSITIVITY, SPECIFICITY, PPV AND VPN VALUE OF THE SENSORS CENTRAL AND LATERAL

Central sensors		Lateral Sensors	
Sensitivity	80%	Sensitivity	80%
Specificity	75%	Specificity	100%
PPV	80%	PPV	100%
VPN	75%	VPN	80%

test a high PPV is more significant if prevalence is high too. In our study prevalence was high enough (55%), so PPV values of 80% and 100% gave to the test a good validity score, together with high sensibility and specificity. Lateral sensors showed to be equally sensitive but better specific and predictive than central ones. However these results should be verified over a wider population.

VIII. CONCLUSION

In this paper we reported on the possibility of using a wearable kinesthetic system for testing the improvement of patients who suffer from venous ulcers after a surgical operation during normal walking. As a validation tool, a preliminary pilot test has been realized, which reports a good capacity of discriminating health from injured subjects. Furthermore, results demonstrated the possibility to discriminate the severity level of the disease during normal walking in the pathologic group. Therefore this prototype could be a means that allows clinicians to monitor patients without causing any discomfort during the recovery process after a surgical operation.

Next developments aim at extending this application to the study of hip motion. Finally, it has been pointed out that the use of these sensorized garments can be considered a valid alternative and comfortable instrumentation applicable in several rehabilitation areas, such as in sport disciplines and in the multimedia field.

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