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Development and evaluation of a novel low-cost sensor-based knee flexion angle measurement system

Giovanni Saggio *, Lucia R. Quitadamo, Lorenzo Albero

Department of Electronic Engineering, University "Tor Vergata", Via del Politecnico 1, 00133, Rome, Italy

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A B S T R A C T

Background: Knee injuries form a large part of musculoskeletal trauma in sporting activities and the rehabilitation can require a long period, for both the patients and the specialists, to restore healthy condition. A reliable, portable, and low-cost system that could allow quick, simple, and effective measurement of knee flexion angles would greatly improve the evaluation of the rehabilitation process and the subsequent planning procedure, with meaningful reduction of recovery time and cost.

Methods: A novel tool for nonstop measurements of knee flexion angles based on the adoption of an elastic sensor embedded in an easy-to-realize wearable kneepad has been proposed. We fully characterized this tool in terms of accuracy, repeatability, and reliability of measure, and validated it against the gold-standard Vicon.

Results: Our tool demonstrated good reproducibility and repeatability among testers (mean range of measures = $5.82° \pm 1.93°$) and high accuracy (root mean square error $< 1.28°$), together with good reliability (intraclass correlation coefficient between 0.80 and 0.91).

Conclusions: The proposed tool demonstrates good performance, is portable, cheap, easy to use, and allows automatic measurements, so as to be a valuable system for accurate nonstop measurement of knee angles.

Clinical Relevance: Our sensor-based measurement system is suitable for the evaluation of the rehabilitation course after knee traumas, because it furnishes a low-cost but accurate monitor of knee flexion movements, during an amount of time as long as desired.

1. Introduction

The use of wearable sensors for the measure of body movement has widely increased in the last years in clinical settings, in particular for rehabilitation purposes. This is because detailed and accurate measurement of flexion/extension angles of human joints can provide information on the outcome of therapeutic or surgical interventions. In such a frame, the most relevant examples come from wearable sensory gloves [1–4].

In clinical settings, it would be of great importance to adopt wearable sensors also for the evaluation of knee range of motion because, as reported in [5], knee injuries account for 40% of musculoskeletal traumas in sporting activities. The knee is a very complex joint, both anatomically and biomechanically, hence rehabilitation could be a complex process that can extend even for several months before a complete recovery [6]. A wearable sensor-based technology, which is low cost, portable, and easy to manage, could allow a continuous measure of the flexion of the knee, within its maximum range of motion. This would allow evaluation of the therapeutic course even at home, with great benefits in terms of time and money saving, both for the medical operators and for the patients. Usually, in clinical settings, the measurement of the knee joint angles, and of all the human joint angles too, is mainly performed by means of coarse visual estimation or mechanical/electro-goniometers. Mechanical goniometers are simple to use but can suffer from measurement errors, potentially due to wrong placement of the goniometer on the subject's leg and from poor inter-rater reliability too [7]. In the case of goniometers, the probability of errors exponentially increases as the time-to-measure increases, so that their usage should be curtailed.

Electro-goniometers are based on sensors such as potentiometers, accelerometers, or strain gauges [8,9], so as to provide more accurate results than their mechanical counterparts, but are prone to crosstalk errors caused by the rotation between the two endblocks (named *general crosstalk*), and by the characteristics of each sensor (known as *individual crosstalk*), so that compensating procedures are necessary [10–12]. O'Donovan et al. [13] used a combination of rate gyroscope, accelerometer, and magnetometer sensors to measure joint angles, obtaining good accuracy but low repeatability. Specifically for the knee angles measurement, Cooper et al. [14] used a combination of inertial sensors and Kalman filters that showed quite promising results

* Corresponding author. Tel.: +39 06 72597260; fax: +39 0623314067.
E-mail address: saggio@uniroma2.it (G. Saggio).

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(error <4°), but had limitations due to poor stability of the filters. Bennet et al. [15] measured knee angles on the basis of digital photos. Ferriero et al. [16] used an augmented reality system superimposing a virtual goniometer on the image, but both groups experienced insufficient accuracy because of malalignment problems. Fiber-optic goniometers have been used as sensors because of their noteworthy property to be wearable devices, but tests demonstrated a disagreement in comparison with gold-standard measurement systems, which can result as high as 10° [17]. Currently, gold-standard measurement systems are some photogrammetric devices, such as the Vicon, that are able to guarantee the most accurate and reliable motion analysis [18,19]. Nevertheless, their high performances are paid for in terms of too high a cost and the necessity of trained staff and dedicated rooms. These are the main reasons of a low diffusion, especially in clinical settings.

Our work intends to overcome some of these limitations by developing a low-cost and easy to use tool capable of furnishing high repeatability and reliability of the measure.

2. Materials

2.1. Sensor

Our tool finds its working principle on a simple and low-cost elastic sensor, which is a unique cylindrical flexible polymer component, 1 mm in diameter and 15 cm in length, with spade electrical terminals at each end (Images Scientific Instruments Inc., Staten Island, NY, USA). The nominal resistance is 1000 ohm per inch and linearly increases with elongation. It was convenient to adopt a sensor's rest length slightly greater (16 cm in our case) than the nominal one and to not overcome 50% in elongation to always guarantee a linear behavior of the sensor's length value versus electrical resistance.

2.2. Measurement setup

We designed an ad hoc measurement setup to measure the resistance versus elongation characteristic of the sensor. It consisted of a linear extender, moved by a controlled stepper motor (Trinamic Pandrive PD1-109-57, Hamburg, Germany), 1 μm in resolution so that the sensor could be automatically elongated/contracted to known percentages, as many times as requested. Resistance values were acquired by means of a digital multimeter (Fluke 8846A). The overall system was managed via a custom-made Labview routine.

2.3. Sensory kneepad

The wearable kneepad, termed sensory kneepad, has the sensor embedded in a Lycra® track, directly located on the knee, as shown in Fig. 1. This solution allowed a replicable placement and avoided malalignment during knee movement. The track was made stable thanks to its particular shape, narrower in its central part, and by means of two hooks used to anchor the sensor to two border adjustable fastener bands; these bands allowed an easy adjustment of the kneepad to the anatomy of the testers' leg. We increased the adhesion of the kneepad to the skin by means of silicon strips located on the inner side of the bands. Finally, we adopted a zigzag design for the seams so as to guarantee a free elongation of the elastic textile under all test conditions.

2.4. Wooden frame, knee phantom, goniometer

We built a support and guidance wooden frame (Fig. 2a) to replicate subjects' knee flexion angles and to perform repeatability tests. The structure consisted of two wooden boards linked by means of a hinge so as to allow the rotation of one plane with respect to the other within 0 and 120°, approximately the same interval spanned by a human knee. External locks allowed blocking the structure to some predefined angles, 15° spaced.

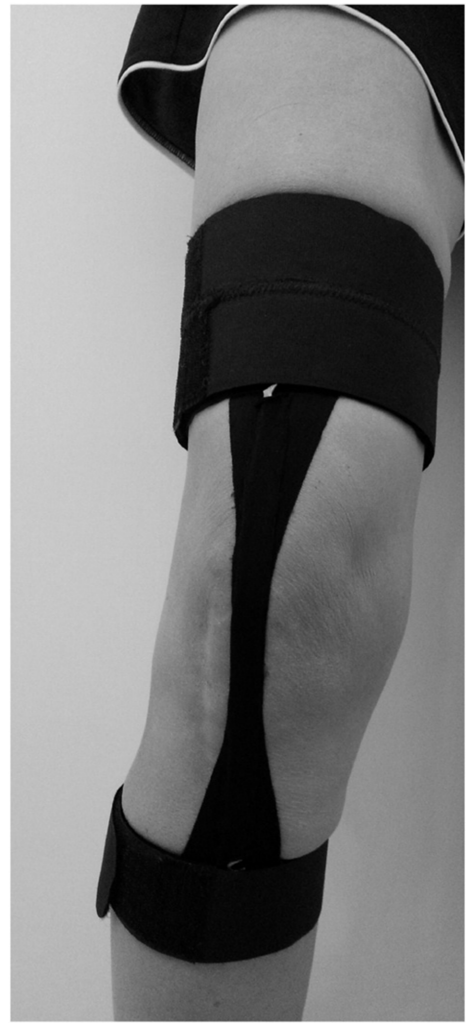

Fig. 1. The Lycra kneepad. The sensor is embedded into the Lycra track, which is directly located on the knee and connects the two lateral bands fastened on the subject's limb.

In addition, we built a knee phantom to simulate the knee joint. The phantom was made using two polyvinyl chloride (PVC) pipes 11.5 cm in diameter, linked by a hinge and a soft coating (Fig. 2b).

Finally, we used a manual goniometer as a reference, graduated from 0° to 120° and 1° in resolution.

3. Methods

3.1. Sensor response in ideal and real conditions

Elastic sensors linearly increase/decrease their electrical resistance when mechanically elongated/shortened, as reported in the datasheets provided by the manufacturer. In our study, the sensors were inserted into the kneepad, so they experienced a bending effect too. For this reason, we performed two different tests in order to evaluate the overall response of the sensors obtained under both elongation/shortening and bending conditions. Eight different sensors were measured and their responses were averaged to obtain a characterization representative of the whole sensor family.

Initially, we measured, by means of the linear-extender setup, the sensor response after simple elongation/shortening procedures (ideal case), within the 16–24-cm range at 1-mm steps; in this way, we obtained an array of elongation and electrical resistance values.

Then, in order to simulate the in vivo condition of the sensors working jointly with the knee, the same eight sensors were inserted (one at a