Study of Performance of Knitted Conductive Sleeves as Wearable Textile Strain Sensors for Joint Motion Tracking

Cristina Isaia, Simon A. McMaster and Donal McNally

Abstract— **Textile-based strain sensors combine wearability with strain sensing functionality by using only the tensile and electrical properties of the threads they are made of. In this study, two conductive sleeves were manufactured for the elbow and three for the knee using a Santoni circular machine with different combinations of elastomeric and non-elastomeric yarns. Linearity, repeatability and sensitivity of the sleeves resistance with strain were compared during 5 repetitive trials, each of them consisting of 4 sequences of 50 joint flexion-extension cycles. All knitted conductive sleeves registered motion over 1000 cycles, proving their suitability for joint motion tracking. In addition, sleeves whose inner layer was made only with nylon exhibited the highest sensitivity and predictability of changes (i.e. a linear trend of the non-elastic deformation). On the other hand, sleeves whose inner layer was made with lycra and polyester or lycra and nylon showed a more balanced performance in terms of linearity, sensitivity and repeatability either for low or high number of cycles. Based on requirements, knitted conductive sleeves show a potential for application in rehabilitation both in healthcare and sports.**

I. Introduction

Human motion detection is important for treating medical conditions (e.g. musculoskeletal diseases), for rehabilitating after injuries (e.g. stroke), for improving athletic performance and for assessing the design of orthosis and prosthesis. Motion analysis based on conventional strain sensors relies on devices made of rigid materials (e.g. metals or semiconductors), which are typically bulky, hard-to-wear and withstand small strain (less than 5%). An unobtrusive solution, comfortable to wear and feasible to fit the human body, is offered by textile-based strain sensors. They combine wearability and high flexibility with large strain sensing functionality [1] and provide strain measurements based on the electrical properties of the threads they are made of. Therefore, wearable textile strain sensors are increasingly important to track movements of the human body, either small strain (e.g. respiration [2]) or large strain (e.g. 55% deformation during walking [3]), to assist in sports and remote health monitoring [4], and for soft robotics [5].

Fabric strain sensors are proposed as wearable devices for measuring joint angles. To monitor the desired knee flexion angle on a wearer, [6] integrated a polypyrrole-coated nylon-lycra sensor into a base sleeve using press-studs. [7] attached an elastic conductive webbing made of polyamide fibres coated with carbon particles and polyester yarn to a woven fabric, which was used for monitoring the flexion angle of elbow and knee. However, both wearable solutions did not embed the sensor into the garment but attached it on its surface as an external sensing element.

Conductive yarns alone offer moderate levels of strain. Therefore, to facilitate sound tensile recovery, the grade of elasticity in fabrics can be increased by knitting conductive yarns along with elastomeric yarns. Depending on the type of elastic yarn used (e.g. single or double-covered, core–spun), the tensile and conductive properties of knitted strain sensors can be affected and thus their sensitivity performance [8].

The sensing mechanism in textile strain sensors upon stretching/recovery is due to different factors correlated to each other: (1) length variation of the conductive yarn contributing to the length-related resistance (according to Ohm's law [9]), (2) structural deformations of the loop geometry affecting the number of contact points and contact pressure and, thus, the contact resistance (according to the Holm's contact theory [10]), and (3) change in the conduction path due to transformation of the equivalent electrical network associated to the fabrics structure [11].

In this research, unlike the flat-bed knitting technology employed in previous works for producing strain sensing fabric [12], a circular knitting machine was used for manufacturing and integrating the textile conductive sensor *into* the garment during the same knitting process. The outcome was knitted conductive sleeves, which were sensitive to the strain caused by the motion of the wearer's joints. Different combinations of elastomeric and non-elastomeric yarns were chosen and their overall sensing properties compared during repetitive joint motion. For their properties, the knitted conductive sleeves will be referred to as *smart* sleeves in the rest of the paper.

The objectives of this work are the characterisation of the electrical properties of knitted conductive sleeves during repetitive flexion-extension cycles and their performance evaluation when different materials are used.

II. EXPERIMENTAL SET-UP

A. Materials

Two elbow sleeves and three knee sleeves (Footfalls and Heartbeats (UK) Limited) in Fig. 1 were manufactured on a Santoni X - machine, a single cylinder intarsia machine with 4 feeds, 12 gauge, and 144 needle count. Each sleeve comprised a knitted conductive sensor, which was 90 mm x 15 mm (height x width) and made of silver plated nylon. The

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response of the sensing area to the joint motion (i.e. flexion-extension) was changes in the fabric conductivity due to the stretching-recovery of the fibres. The novelty from previous research on knitted strain sensors during cyclic loading [13] was replacing stainless steel spun staple fibre yarn (i.e. short fibres) with silver multifilament yarn (i.e. 100% continuous conductive fibres), which significantly improved the sensor response in terms of repeatability over time [14]. The stitch pattern of the sensor used in this research is described in [15]. To avoid any direct contact between the skin and the conductive area of the sensor, each sleeve included an inner layer which was sewn in the interior part of the garment. The materials used for the sensor, the sleeve and the inner layer are described in Table I for the elbow (E prefix) and knee (K prefix) sleeves.

Figure 1 a) Close-up of the knitted sensor in the knee sleeve b) Knee sleeve in flexion c) Knee sleeve in extension d) Experimental set-up e) Elbow sleeve in flexion f) Elbow sleeve in extension

TABLE I. SMART SLEEVES AND THEIR COMPOSITION

Smart Sleeves id	**Materials**		
	Sensor	***Sleeve***	***Inner layer***
E4	Silver plated nylon (300 dtex)	Lycra (22 dtex)	Nylon (600 dtex)
E5	Silver plated nylon (300 dtex)	Lycra (22 dtex)	Lycra (20 dtex), polyester (300 dtex)
K1	Silver plated nylon (300 dtex)	Lycra (20 dtex) and nylon (600 dtex)	Nylon (600 dtex)
K3	Silver plated nylon (300 dtex)	Lycra (20 dtex)	Lycra (20 dtex), nylon (600 dtex)
K4	Silver plated nylon (300 dtex)	Lycra (20 dtex)	Lycra (20 dtex), polyester (197 dtex)

B. The equipment

The equipment used for investigating the sensing properties of the smart sleeves during flexion-extension trials consists of the HUMAC NORM machine (HUMAC2015®/NORM™) and a dedicated acquisition system. In this study, the HUMAC NORM machine was preferred to other systems (e.g. optical technologies) for offering repetitive knee/elbow joint movement according to a set angle/speed and, thus, for tracking joint motion under repetitive conditions. The equipment in Fig. 1(d) includes the HUMAC NORM Isokinetic Machine, a power supply, an electronic board working as a constant current generator, a data logger (NI USB 6003) and a PC with the MATLAB® Analog Input Recorder. The constant current generator was set to 10 mA and data acquisition was 1 kHz.

III. METHOD

A. Test protocol

Written consent was obtained by a healthy volunteer after the test protocol was approved by the University of Nottingham Faculty Research Ethics Committee. The test protocol was purposely designed for performing repetitive flexion-extension of the joint of interest under a controlled range of motion (0° - 90°, with 0° being calibrated for the full extension) and at a constant rotation rate (±60 °/s for flexion and extension, respectively). These values were chosen considering the joint operating range and speed of a real application. The dynamometer was set to continuous passive motion (CPM), i.e. regardless of whether the user's muscle was shortening/lengthening. Such operating mode stemmed from a research and not a rehabilitative goal.

For each *smart* sleeve in Table I, the testing procedure consisted of 5 trials, each of them comprising 4 sequences of 50 flexion-extension cycles with 10 second rest in between. Each trial was repeated after a 5 minute rest interval without modifying the sensor and the parameters in the HUMAC software. The experiment was conducted at 21±1°C and 45±5% relative humidity.

B. Signal processing

Fabric electrical voltage and current, joint angle and rotation speed were simultaneously collected with the acquisition system of Fig. 1(d) and post-processed in MATLAB. The calculated resistance was filtered with a Savitzky-Golay filter, whose frame size (f = 317) was adapted to the stretch-recovery speed of the fabric sensor and the polynomial order (N=1) to the observed shape of the signal. Next, peak analysis on the filtered resistance was conducted, with the maximum and minimum resistance values being detected for each cycle and associated with the motion performed. Interpolation curves passing through the maximum and minimum filtered values were then established. To describe the sensitivity of the fabric-transducer, the *peak-to-peak span* was calculated by subtracting the interpolated minimum curve from the interpolated maximum one.

C. Linearity evaluation

One of the phenomenon influencing the performance of fabric sensors is the fibre-fibre slippage. Fabrics are fibrous materials which, under strain, undergo often irreversible slippage between fibres, resulting in changes in dimensions of the assembly and, therefore, overall non-linear deformation of the fabric. As a result, non-linearity and hysteresis are expected in the sensor response to the performed motion.

In this research, a study of hysteresis was conducted to quantify the sensor non-linearity during repetitive range of motion. In particular, the *mean* hysteresis areas, H_m, and their relative change (based on averages over 50 cycles) were calculated for all candidates of Table I at 200 and 1000 cycles (for rehabilitative and sports applications, respectively):

- Mean hysteresis area of the initial 50 cycles (H_{m_50}):

$$H_{m_{50}} = \frac{\sum_{i=1}^{50} H_i}{50}, \tag{1}$$

- Initial 200 cycles relative change ($h_{\_200i}$):

$$h_{200_i} = (\textstyle\sum_{i=150}^{200} \frac{H_i}{50} - H_{m_{50}})/H_{m_{50}}, \tag{2}$$

- Final 200 cycles relative change ($h_{\_200f}$):

$$h_{200_f} = \frac{\sum_{i=950}^{1000} H_i/50 - \sum_{i=800}^{850} H_i/50}{\sum_{i=800}^{850} H_i/50}, \tag{3}$$

- Overall relative change over 1000 cycles ($h_{\_1000}$):

$$h_{1000} = \left(\textstyle\sum_{i=950}^{1000} \frac{H_i}{50} - H_{m_{50}}\right)/H_{m_{50}}. \tag{4}$$

In addition, to measure the predictability of the non-linear deformation, a curve fitting with a linear profile was performed in each sequence of every trial and the corresponding R^2 coefficients were extracted. In this paper, R^2 over 1000 cycles was reported for the initial and last 50 cycles, $R^2_{H\_50i}$ and $R^2_{H\_50f}$, respectively.

D. Repeatability evaluation

The fabric deformation over time affects also the repeatability of the electrical response of textile sensors during repetitive elongation-recovery cycles. To measure the repeatability of the response of *smart* sleeves during flexion-extension trials, the *standard deviation* of the hysteresis areas, σ_H, and its relative change were calculated:

- During the initial 50 cycles ($R_{\_50i}$):

$$R_{50_i} = \sigma_H(H_1, H_2 \ldots . H_{50}), \tag{5}$$

- During the last 50 cycles ($R_{\_50f}$):

$$R_{50_f} = \sigma_H(H_{950}, H_{951} \ldots . H_{1000}), \tag{6}$$

- Overall relative change over 1000 cycles ($r_{\_1000}$):

$$r_{1000} = (R_{50_f} - R_{50_i})/R_{50_i}. \tag{7}$$

E. Sensitivity evaluation

The sensitivity of the *smart* sleeves was determined as the ratio between the peak-to-peak span of the fabric electrical resistance and the span of the joint angle. As the peak-to-peak span increases with the non-elastic fabric deformation and thus with cycles, so does sensitivity. Therefore, it was also important to characterise the linearity of this increasing trend. To compare performance, the following sensitivity values were calculated:

- Sensitivity of the first (S_1) and last cycles (S_{1000}),
- Mean sensitivity of initial 200 cycles (S_{m_200i}):

$$S_{m_{200_i}} = \frac{\int_1^{200} S(c)\, dc}{200}, \quad \text{with } c \text{ number of cycles} \tag{8}$$

- Mean sensitivity of final 200 cycles (S_{m_200f}):

$$S_{m_{200_f}} = \frac{\int_{800}^{1000} S(c)\, dc}{200}, \quad \text{with } c \text{ number of cycles} \tag{9}$$

- Overall relative change over 1000 cycles ($s_{\_1000}$):

$$s_{1000} = (S_{1000} - S_1)/\ S_1, \tag{10}$$

- Linear sensitivity trend for initial 200 cycles ($R^2_{S\_200i}$),
- Linear sensitivity trend for final 200 cycles ($R^2_{S\_200f}$).

F. Sleeves performance comparison

To allow a straightforward performance comparison, radar plots were drawn based on evaluation criteria (high values) for linearity ($1/H_{m\_50}$, $R^2_{H\_50i}$, $R^2_{H\_50f}$, $1/h_{\_200i}$, $1/h_{\_200f}$, $1/h_{\_1000}$), sensitivity (S_1, S_{m_200i}, S_{m_200f}, $1/s_{\_1000}$, $R^2_{S\_200i}$, $R^2_{S\_200f}$) and repeatability ($1/R_{\_50i}$, $1/R_{\_50f}$, $1/r_{\_1000}$).

IV. RESULT AND DISCUSSION

A. Overall electrical characterisation

The electrical response of all *smart* sleeves during repetitive joint motions was studied. Fig. 3(a) shows the resistance variation with the angle performed for the E5 elbow sleeve during trial 1 (1^{st} to 200^{th} cycle) and trial 5 (800^{th} to 1000^{th} cycle). Fig. 3(b) shows the hysteresis during equivalent cycles. The textile sensor detected the type of motion executed, i.e. *flexion* (from maximum to minimum resistance values) and *extension* (from minimum to maximum resistance values) and exhibited reliable performance up to 1000 cycles. These results highlighted the potential of *smart* sleeves for joint motion tracking. The low resistance measured over time suggests that the *smart* sleeves are less sensitive to external factors (e.g. sweat, or humidity).

B. Effect of materials on sleeves performance

Materials used for sleeve and inner layer have an effect on the overall performance. Elbow sleeves whose inner layer was made only with nylon (i.e. E4, Fig. 4(a)) exhibited higher overall sensitivity (S_1, S_{m_200i}, S_{m_200f}), higher linearity ($1/h_{\_200f}$) and repeatability ($1/R_{\_50f}$, $1/r_{\_1000}$) after a considerable number of cycles and a more predictable (i.e. linear) deformation trend ($R^2_{H\_50i}$ and $R^2_{H\_50f}$). This is due to higher stiffness of nylon compared to lycra/polyester which delays the irreversible fibres deformation responsible for loss of linearity. On the other hand, elbow sleeves whose inner layer was made with lycra and polyester (i.e. E5) show better overall performance in terms of linearity, sensitivity and repeatability both for low ($1/H\_{m50}$, $1/h\_{200i}$, $R^2{}\_{S\_200i}$, $1/R\_{50i}$) and high number of cycles ($1/h\_{1000}$, $R^2{}\_{S\_200f}$, $1/s\_{1000}$). Knee sleeves, whose inner layer consisted of nylon only (i.e. K1, Fig. 4(b)), exhibited a higher sensitivity (S_1, S_{m_200i}, S_{m_200f}, $R^2{}_{S\_200f}$). Knee sleeves with lycra and nylon (i.e. K3) or lycra and polyester (i.e. K4) in the inner layers presented similar good performance in terms of linearity ($1/h\_{1000}$, $1/h\_{200f}$, $R^2{}_{H\_50i}$, $R^2{}_{H\_50f}$), sensitivity and repeatability, with K4 having a more comfortable wearability due to polyester.

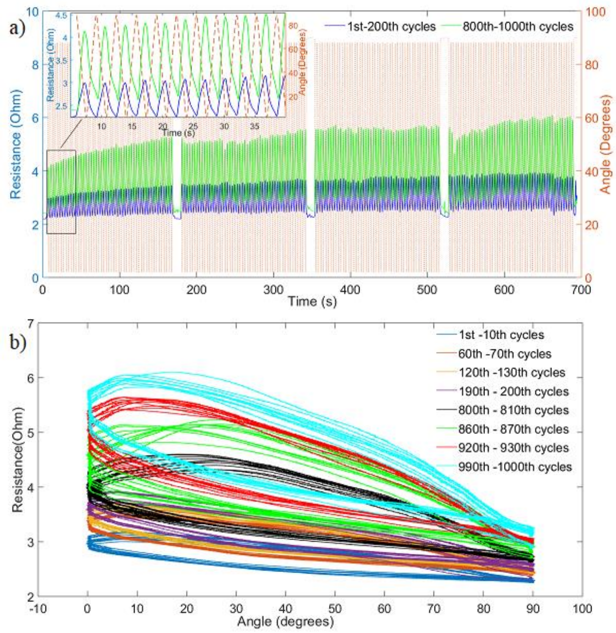

Figure 3. a) Fabric resistance variation with time for the E5 elbow sleeve during 1st-200th cycles (blue) and 800th-1000th cycles (green) b) Hysteresis curves for the corresponding interval

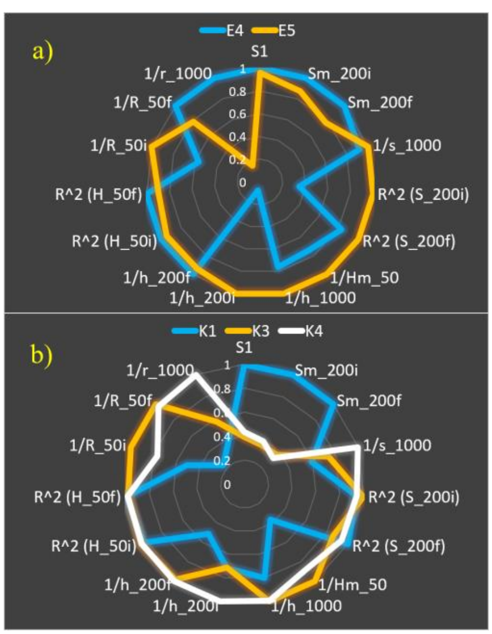

Figure 4. Performance comparison for the a) elbow and b) knee sleeves

V. Conclusion

This research studied performance of knitted conductive sleeves (with the textile conductive sensor integrated *into* the garment) and proved their potential as textile strain sensors for joint motion tracking. An evaluation method was proposed (based on specific parameters per application) and radar plots were used for straightforward comparison. Knit candidates can be selected based on durability of the overall sensing properties, low hysteresis and comfort (i.e. E5, K3 and K4) or high sensitivity response (i.e. E4 and K1). Future research aim is to use *smart* sleeves for rehabilitative and sports purposes with portable power and acquisition units.

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