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Development of a Knitted Strain Sensor for Health Monitoring Applications †

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Abstract: As an emerging technology, smart textiles have attracted attention for rehabilitation purposes to monitor heart rate, blood pressure, breathing rate, body posture and limb movements. Compared with traditional sensors, knitted sensors constructed from conductive yarns are breathable, stretchable and washable, and therefore, provide more comfort to the body and can be used in everyday life. In this study, knitted strain sensors were produced that are linear with up to 40% strain, sensitivity of 1.19 and hysteresis of 1.2% in absolute values, and hysteresis of 0.03 when scaled to the working range of 40%. The developed sensor was integrated into a wearable wrist-glove system for finger and wrist monitoring. The results show that the wearable was able to detect different finger angles and positions of the wrist.

Keywords: knitted strain sensor; health monitoring applications; smart textiles; wearable textiles

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1. Introduction

Flexible and wearable sensors have gained attention in recent years for a variety of applications, including human–device interfaces and the monitoring of health indicators such as respiration rate, heart rate and body position [1–3]. Conventional sensors are often integrated into structures as an external element or attached to the surface, but these create discomfort for the user due to the bulky and rigid nature of electronic devices such as IMUs for health monitoring purposes [4]. In this context, textile-based strain sensors offer a new generation of devices that combine wearability, lightness, comfort and stretchability with strain-sensing functionality. They can be comfortably worn and sense a wide range of body strains for a vast number of health monitoring applications, thus making them a good alternative to traditional bulky electronic sensors and making wearable systems more feasible [5].

By using textile-based strain sensors, it is possible to investigate and identify the ideal rehabilitation posture by analyzing the physiological properties of finger and wrist movements. For these wearable sensors, several materials and methods have been investigated to monitor the different parts of the body such as the finger, wrist, arm and leg for rehabilitation purposes. Ryu et al. investigated the performance of the knitted strain sensor in a glove by using silver-plated yarns to distinguish the finger movements, and the electrical responses of the compressive strain demonstrated strong stability and linearity through various finger rolling angles [6]. Lee et al. also concluded that the developed glove might be useful to amputees as a tool that allows them to rehabilitate or regulate a myoelectric prosthesis by putting the sensing elements into the glove and producing the whole-garment knitting technique for ease of commercialization [7]. Isaia et al. evaluated the performance of strain sensors knitted with various conductive yarns in terms of their sensing properties, hysteresis and comfort for joint motion-tracking applications during repetitive flexion–extension cycles [8,9]. Textile-based and knitted strain sensors have been proposed in many studies but have been less useful in practical applications due to the differences in measured strain during loading and unloading (hysteresis). In recent work [10], however, we were able to develop knitted strain sensors with extremely low hysteresis values. In this study, we integrated those sensors into a wrist-to-finger wearable demonstrator, the performance of which was tested.

2. Materials and Methods

In the previous study [10], a textile-based strain sensor was developed with a specific knitting technique, and its electromechanical performance was tested and reported as a hysteresis of 0.03 and a gauge factor of 1.19; in the following study, this newly developed strain sensor was integrated into a wrist-to-finger wearable system. A 1 $\times$ 1 rib-knit design was chosen for the strain sensor design and knitted on a Stoll CMS 530 machine using conductive yarn from Shieldex with a yarn count of dtex 235 and initial resistance of $\leq$600 Ω/m, and elastic yarn from Yeoman of Nm 15. Utilizing the plating technique, knitted strain sensors were produced by positioning the conductive yarn inside and the elastic yarn on the outside of the knitted structure (See Figure 1). In the second stage of the study, this developed knitted strain sensor was integrated into the wrist-to-finger wearable system to monitor the movements of the finger and wrist, as shown in Figure 2. Apart from the knitted sensor part in the wearable system, woven cotton fabric was selected for the rest of the design to be able to have a non-elastic and adjustable structure. A Bluetooth Arduino Nano and a power supply were integrated into the wrist-to-finger design using conductive yarns. According to the finger and hand size, the design can be easily modified, and this helps with ease of manufacturing in the later stages. The electromechanical performance of the knitted strain sensor was tested in the course-wise direction by performing four test cycles at 30 mm/min, using a custom-made tensile tester, and the resistance response during tensile extension–relaxation tests was assessed. The performance of the wrist-to-glove design during finger and wrist movements was evaluated and the movements were recorded.

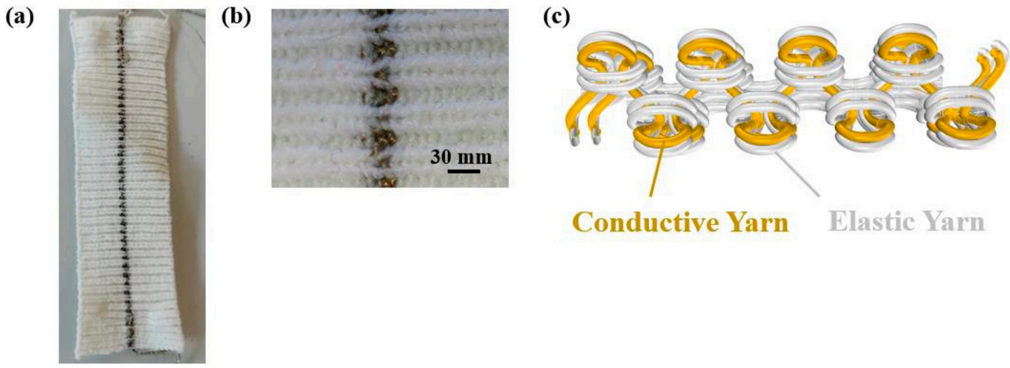

Figure 1. (**a**) The developed knitted strain sensor; (**b**) optical images of the sensing region which shows the conductive yarns (yellow) positioned inside and elastic yarns outside (white); and (**c**) illustration of the conductive and elastic yarn positioning within the knitted structure.

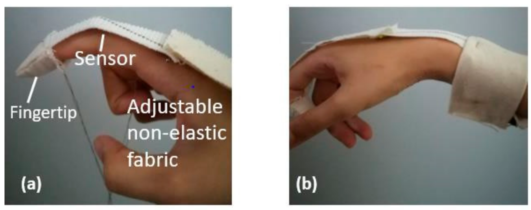

Figure 2. The wearable sensor-glove system with a knitted strain sensor to monitor (**a**) finger movements and (**b**) wrist movement.

3. Results

3.1. Electromechanical Performance of the Knitted Strain Sensor

The electromechanical performance of the knitted strain sensor was investigated and is illustrated in Figure 3. The sensor works linearly over a range of 40% with a hysteresis value and gauge factor of 0.03 and 1.19, respectively. The hysteresis along the strain axis amounts to 1.2% (absolute value) and 0.03 when scaled to the working range of 40% [10]. Because of the high linearity and low hysteresis, this developed sensor is found to be promising for monitoring finger or wrist movement, and the sensor is integrated into the wearable system to test its performance.

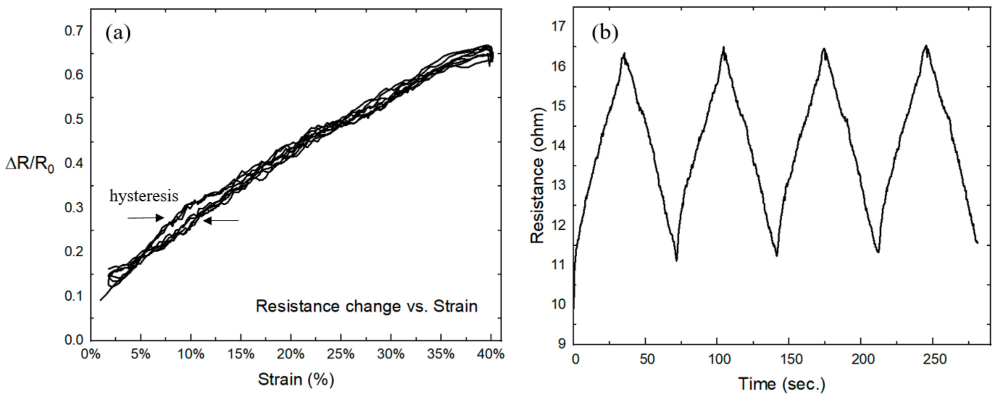

Figure 3. The developed knitted strain sensor graphs under four cyclic tests: (**a**) relative resistance change versus strain and (**b**) resistance versus time.

3.2. Performance Evaluation of Wrist-to-Finger Monitoring System

Bending the finger and wrist deforms the fabric, causing the sensor to change resistance. In this way, finger and wrist movements can be directly detected and monitored. Figure 4a shows the results of finger motion detection at different bending angles by the wrist-to-finger wearable system, targeted at 30°, 60° and 90°. This shows that with the increase in the bending angle of the finger joint from 30° to 60°, and then to 90°, the change in the relative resistance value increases. To investigate the wrist monitoring, the same test was applied to the wrist-to-finger wearable system, and the plot also provides distinguishable patterns in the flexed and unbent positions, as shown in Figure 4b. Note that tests were performed to demonstrate the effects, and the bending angles were not well controlled. However, the observed signal changes were seen to be measurable.

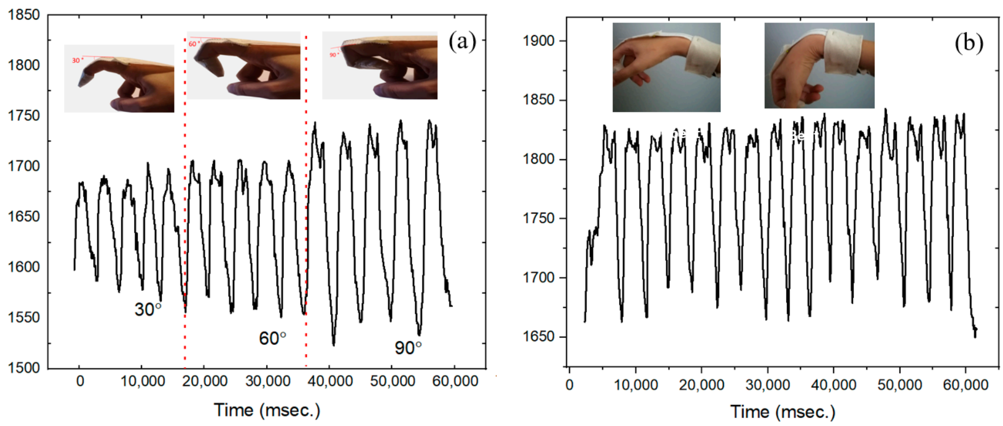

Figure 4. The wrist-to-finger wearable system: (**a**) finger movement monitoring at different angles of 30, 60 and 90°, and (**b**) wrist monitoring.

4. Discussion

For applications such as posture monitoring, VR and rehabilitation, it is desired to have integrated, soft and stretchable strain sensors. We used a novel knitted sensor to construct a wrist-to-finger demonstrator. The measurement showed that it is possible to distinguish between the bending angles and loads of the fingers and the wrist [10]. When the sensor is implemented into the wrist-to-finger system, overall, it performs linearly. The small differences observed in peak values during the tests can be attributed to both the slipping of the garment with respect to the skin and the reproducibility errors inherent to manual movements. In a future study, these irregularities could be amended by fixing the wearable system to the joints of the body.

5. Conclusions

We produced a linear knitted strain sensor with low hysteresis and a working range of at least 40%. The developed knitted sensor can easily be utilized as a part of a wearable system to monitor finger and wrist movement without interfering with the existing fabric performance and appearance. The adjustable wearable system demonstrates the usefulness of the newly developed sensors and has the potential to be used for rehabilitation purposes in health monitoring applications.

Author Contributions: B.B. conceived the study and carried out the testing; S.G. and K.M.B.J. supervised and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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