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Optimization of SWCNT-Coated Fabric Sensors for Human Joint Motion Sensing

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Abstract – This study explored the feasibility of utilizing an SWCNT-coated fabric sensor for the development of a wearable motion sensing device. The extent of variation in electric resistance of the sensor material was evaluated by varying the fiber composition of the SWCNT-coated base fabrics, attachment methods, number of layers, and sensor width and length. 32 sensors were fabricated by employing different combinations of these variables. Using a custom-built experimental jig, the amount of voltage change in a fabric sensor as a function of the length was measured as the fabric sensors underwent loading-unloading test with induced strains of 30 %, 40 %, and 50 % at a frequency of 0.5 Hz. First-step analysis revealed the following: characteristics of the strain-voltage curves of the fabric sensors confirmed that 14 out of 32 sensors were evaluated as more suitable for measuring human joint movement, as they yield stable resistance values under tension-release conditions; furthermore, significantly stable resistance values were observed at each level of strain. Secondly, we analyzed the averaged maximum, minimum, and standard deviations at various strain levels. From this analysis, it was determined that the two-layer sensor structure and welding attachment method contributed to the improvement of sensing accuracy.

Keywords: SWCNT (Single Wall Carbon Nano-Tube), Fabric sensor, Wearable motion sensing, Strain test.

1. Introduction

Recently, the term “Wearable Health Care Systems” has emerged as a generally accepted key phrase in the field, with research on the related systems being actively pursued. This term refers to a clothing type that is most suitable for implementation of authentic wearables; because of this recently developed demand, the development of textile-based sensors has become essential. Garment-integrated sensors equip clothes with a smart-sensing capability, while preserving the comfort of the user. In addition, an increase in demand for human movement analysis in the areas of sports movement training, rehabilitation therapy, etc., has led to various studies on methods of sensing and monitoring of human movement. Existing methods for measuring human movement, however, have many limitations. For example, methods such as 3D full-body scanners that use infrared rays or motion capture systems are limited in how they measure the bending or obscured body parts and the detailed movements of joints. Furthermore, most of these methods require the use of large, expensive equipment with space constraints. Therefore, wearable sensing via garment-integrated sensors has been promoted as an alternative solution to traditional body sensing techniques [1].

In this study, Single-walled Carbon Nano Tubes (SWCNT)-coated fabrics were used as sensors to measure human movement. Carbon Nano Tubes (CNTs) are allotropes of carbon with a cylindrical nanostructure. These cylindrical carbon molecules have distinctive properties, which are valuable in the fields of nanotechnology, electronics, optics, and additional fields of materials science and technology. In particular, owing to their extraordinary thermal conductivity and mechanical and electrical properties, carbon nanotubes find applications as additives to various structural materials.

We have applied various methods to processed the SWCNT-coated fabrics, subsequently measuring and analyzing their respective performance by measuring changes in electrical resistance in order to realize an optimized fabric sensor that is able to effectively measure human joint movement when integrated into a garment.

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2. Review of Wearable Sensors for Human Activity Monitoring

Electrocardiogram (ECG) electrodes have been developed using various textile technologies including sputtering or electroless plating on the fabric surfaces and embroidering or knitting with stainless steel yarns [2]. Gi et al. [3] developed a textile-based inductive sensor by using machine embroidery and applied it to a non-contact-type vital sign sensing device based on the principle of magnetic-induced conductivity. Koo et al. [4] analyzed the effects of the position of a textile-based inductive coil sensor on the measurement of heart rate. In order to assess the capability of the textile-based inductive coil sensor and the repeatability of measured cardiac muscle contractions, they proposed a novel quality index based on the morphology of measured signals acquired via a textile-based inductive coil sensor.

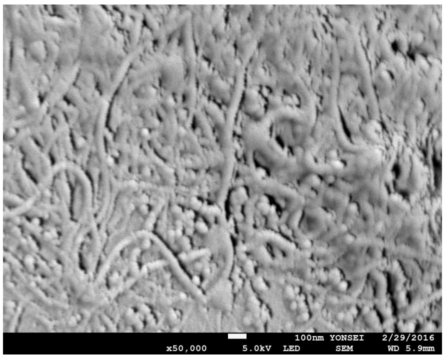
Danish company Danfoss PolyPower A/S has designed a new wearable sports sensor that has the potential to measure everything from stance to force. PolyPower material is a proprietary version of Dielectric Electro Active Polymer (DEAP) technology. The film consists of a patented combination of silicone dielectric material with a corrugated surface covered by a very thin layer of metallic electrodes. As with other types of DEAP, PolyPower material reacts when a voltage is applied. By applying a high voltage, electrostatic pressure causes the film to expand in plane and contract in thickness. The corrugation on the PolyPower material affords it stiffness across the width or length while maintaining flexbility in the perpendicular plane [5]. Dunne et al. [6] developed the 'Posture-monitoring Vest'. Their work evaluated a wearable plastic optical fiber (POF) sensor for monitoring seated spinal posture and compared their results to the method of conventional expert visual analysis; additionally, they developed of a field-deployable posture monitoring system. Technische Universität München (TUM) in Germany has developed 'MiMed Wearable Systems' to measure human movement using accelerometers; these wearables can be used for various purposes by sensing movement and generating data through the eight integrated motion sensors attached to the garments [7]. Friedrich-Alexander Universität (FAU) established the 'Digital Sports Group' with Adidas, Electro Scientific Industries, Inc. (ESI), ASTRUM IT, etc. to organize the 'miLife Research Project'. The group has developed the 'Shimmer system' to sense movement using an accelerometer. The wearable sensor platform and equipment of Shimmer allow for wide-range applicability and simple and effective biophysical and kinematic data capture in real-time [8]. Fraunhofer Institute has developed 'Medical Sensor Systems' to conduct movement analysis. With MEMS accelerometers, it is possible to classify posture and activity as well as generate movement reconstructions [9]. Xsens Technologies B.V. has developed a three-dimensional motion capture system, the 'MVN'. State-of-the-art miniature inertial sensors, biomechanical models and sensor fusion algorithms were employed to fabricate the MVN. The sensor-suit with the MVN inertial sensor set captures various types of movement, including running, jumping, crawling and cartwheels, which is atypical of inertial motion capture technology [10].

3. Experimental Design

3.1 Design of a motion sensor utilizing SWCNT-coated fabrics

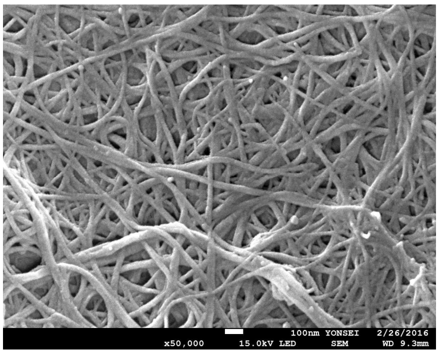
Single-walled carbon nanotubes (SWCNT) are nanometer-diameter cylinders consisting of a single graphene sheet wrapped up to form a tube. These cylindrical carbon molecules have unique properties, which are valuable in the fields of nanotechnology, electronics, optics, and additional fields of materials science and technology [11].

In this study, we first selected two types of highly stretchable knit, nylon-based 'L' knit and polyester-based 'W' knit, to be used as the base layer of the fabric sensor; these knits have been commercialized in the textile market and widely used in various types of active sportwear. as the



×50.000 WD 5.9 ㎚

(a) SWCNT-coated 'L' knit fabric (74 % nylon/26 % spandex)



×50.000 WD 9.3 ㎚

(b) SWCNT-coated 'W' knit fabric (77 % polyester/23 % spandex)

Fig. 1. SEM image of the SWCNT sensor materials

(a) 'W' knit fabric/welding/two-layers/50 x 5 (㎜)

(b) 'L' knit fabric/welding/two-layers/100 x 10 (㎜)

(c) 'W' knit fabric/sewing/one-layer/50 x 10 (㎜)

Fig. 2. SWCNT-coated fabric sensors with varied dimensions and attachment methods

base layer of the fabric sensor. We have coated the two knit fabrics with single-walled carbon nanotubes and post-processed them in various ways to develop a fabric-based human motion detection sensor. A scanning electron microscope (SEM) image of each of the sensor materials is shown in Fig. 1.

In order to identify the sensor requirements, we have selected factors with the ability to impact the performance of the sensor as experimental variables. The selected factors included the fiber composition of the SWCNT-coated base fabrics ('L' knit fabric: 74 % nylon, 26 % spandex/'W' knit fabric: 77 % polyester, 23 % spandex), the method of attachment to the base layer (sewing or welding), the number of layers of the sensor (one layer or two layers), and the width (5㎜ or 10㎜), and the length (50㎜ or 100㎜) of the sensor. By varying these, we have developed a total of 32 types of fabric sensors (Fig. 2).

3.2 Fabric sensor tensile test jig fabrication

A tensile test jig was custom-designed in order to conduct fabricated fabric sensor performance tests. The jig has been designed with a semi-cylindrical holder at one end, around which the fabric sensor is wrapped 180 degrees. The fabric is attached to the opposite end of the experimental jig; thus, the fabric sensor can yield uniform stress distribution across the fabric without being deformed (Fig. 3). The jig facilitates the acquirement of more accurate results during fabric sensor tensile testing because of its ability to maintain a constant width and cross section across the measurement area of fabrics under tension. The system allows sufficient fabric deformation space for wider fabrics.

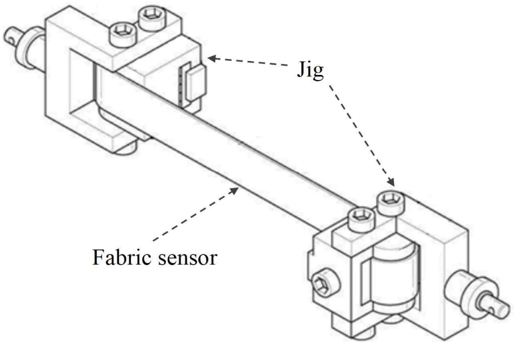


Fig. 3. Fabric sensor test jig (KOREA Patent Application: 10-2015-100215)

3.3 Experiment

The 32 SWCNT-coated fabric sensors, which were variably designed according to the experimental variables in this study, were sequentially clamped to a jig mounted to an INSTRON machine (8874 Axial-Torsion Servohydraulic Fatigue Testing System) and connected to a digital multimeter (Graphtec Data Platform GL7000). The INSTRON tensile machine was used to produce a controlled input movement, while the digital multimeter was used to record responses from the fabric sensors. The amount of voltage change in a fabric sensor as a function of the length was measured as the fabric sensors underwent loading-unloading testing with induced strains of 30 %, 40 %, and 50 % at a frequency of 0.5 Hz (Fig. 4). The experimental data of the fabric sensors were obtained via 10 ms sampling using a Data Logger measurement device. Then, the voltage according to the resistance variation of the sensor was measured by using a 5 V reference voltage and 3.9 kΩ fixed resistance.

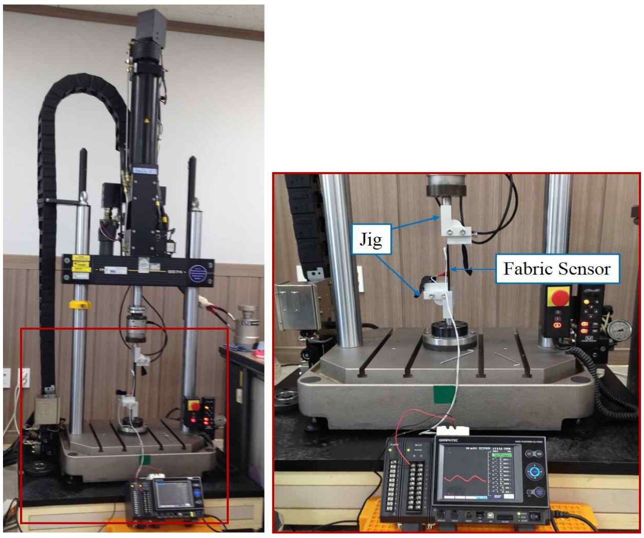


Fig. 4. Fabric sensor testing setup : fabric sensor sample clamped between INSTRON plates and connected to a digital multimeter

Table 1. Composition types of fabric sensors evaluated as suitable for joint motion sensing

Sample No.	Experimental variables	Composition types of fabric sensors
1	Base fabric	‘L’ knit fabric
	Attachment method	sewing
	Number of layers	two layers
	Width×Length (㎜)	5×50
2	Base fabric	‘L’ knit fabric
	Attachment method	sewing
	Number of layers	two layers
	Width×Length (㎜)	5×100
3	Base fabric	‘L’ knit fabric
	Attachment method	sewing
	Number of layers	two layers
	Width×Length (㎜)	10×100
4	Base fabric	‘L’ knit fabric
	Attachment method	welding
	Number of layers	one layer
	Width×Length (㎜)	10×100
5	Base fabric	‘L’ knit fabric
	Attachment method	welding
	Number of layers	two layers
	Width×Length (㎜)	5×50
6	Base fabric	‘L’ knit fabric
	Attachment method	welding
	Number of layers	two layers
	Width×Length (㎜)	5×100
7	Base fabric	‘L’ knit fabric
	Attachment method	welding
	Number of layers	two layers
	Width×Length (㎜)	10×100
8	Base fabric	‘W’ knit fabric
	Attachment method	sewing
	Number of layers	one layer
	Width×Length (㎜)	10×50
9	Base fabric	‘W’ knit fabric
	Attachment method	sewing
	Number of layers	two layers
	Width×Length (㎜)	5×50
10	Base fabric	‘W’ knit fabric
	Attachment method	sewing
	Number of layers	two layers
	Width×Length (㎜)	10×50
11	Base fabric	‘W’ knit fabric
	Attachment method	welding
	Number of layers	one layer
	Width×Length (㎜)	10×100
12	Base fabric	‘W’ knit fabric
	Attachment method	welding
	Number of layers	two layers
	Width×Length (㎜)	5×50
13	Base fabric	‘W’ knit fabric
	Attachment method	welding
	Number of layers	two layers
	Width×Length (㎜)	10×50
14	Base fabric	‘W’ knit fabric
	Attachment method	welding
	Number of layers	two layers
	Width×Length (㎜)	5×100

4. Results and Discussion

4.1 Utilizing strain-voltage curve characteristics to perform a morphological evaluation of fabric sensors

The fabric sensors exhibiting double-peak-type signal or baseline lift of the peak-to-peak voltage (Vp-p) in the voltage waveforms were evaluated as sensors with low sensing accuracy and excluded in subsequent analysis. While most fabric motion sensors are constrained by phenomena such as hysteresis, the constancy of the Vp-p indicates high reliability of the reproducibility of sensor functions. Fig. 5 shows the resistance values of the fabric sensor as a function of the relatively stable strain values.

The results of analyzing the strain-voltage curve characteristics of the 32 property-variant fabric sensors developed and used in this study demonstrated that 14 of the sensors yielded stable voltage values under tension-release conditions. The fabric sensors that were deemed suitable for joint movement sensing are shown in Table 1 according to the fiber composition of the base fabric, the attachment method, number of layers, and sensor width

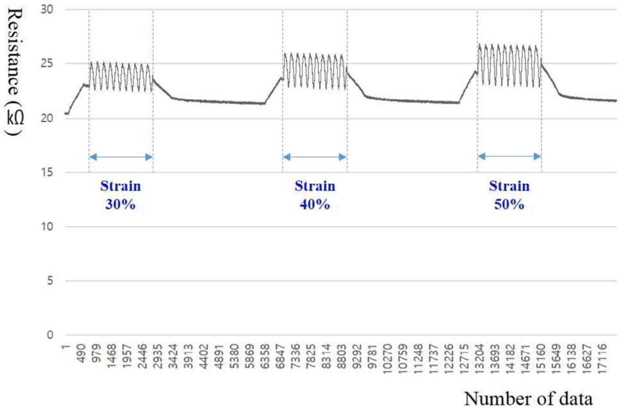
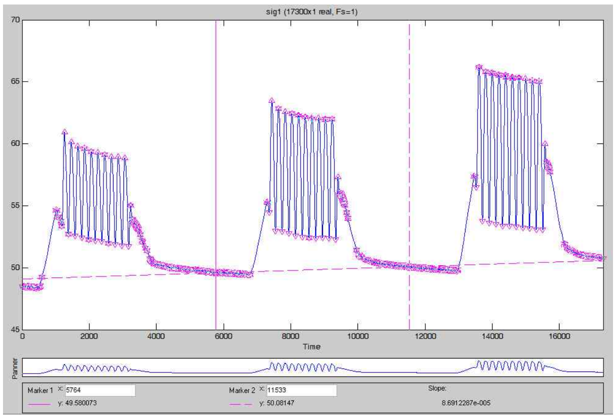


Fig. 5. Resistance value waveforms according to varying levels of strain



Marker 1 x: 5764 y: 49.580073

Marker 2 x: 11533 y: 50.08147

Slope: 8.6912287e-005

Fig. 6. MATLAB signal process

and length.

4.2 Composition requirements of fabric sensors to improve accuracy in movement

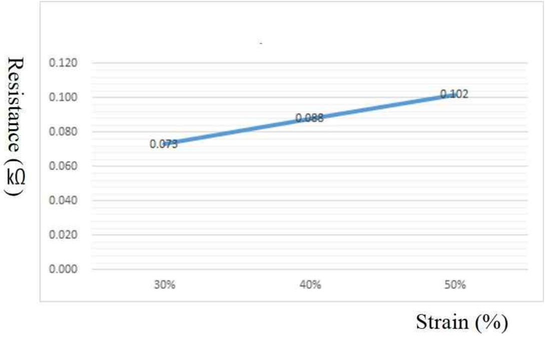
In order to determine the composition requirements of the fabric sensors contributing to improvement of the sensing accuracy, we performed a secondary analysis. We derived the resistance values by converting the obtained voltage data, created a curved graph of resistance variation according to the strain (30 %, 40 %, and 50 %) of each fabric sensor by using the MATLAB Signal Processing Tool, founded peaks and valleys by analyzing inflection points, and analyzed the maximum, minimum, and standard deviations according to the strains of each of the fabric sensors.

Table 2 shows the average maximum, minimum, and standard deviation values for each of the measured resistances from the loading-unloading tests with induced strains of 30 %, 40 %, and 50 % (resistance values were measured 10 times for each strain). The smaller the difference between the maximum and minimum values for each resistance curve under strains of 30 %, 40 %, and 50 %, the higher is the accuracy of the sensor and the more stable is its performance. The resistance value standard deviation resulting from ten measurements was small for each strain.

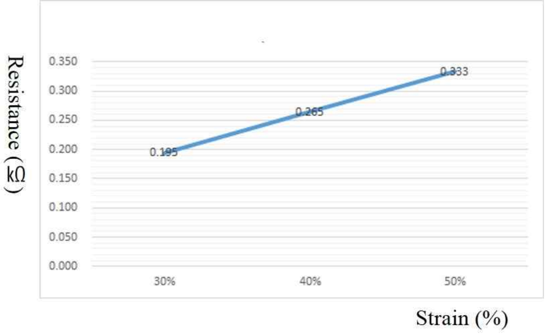
Table 2. Average maximum value, minimum value, and standard deviation of measured fabric sensor resistances

	Average maximum resistance / standard deviation (㏀)			Average minimum resistance / standard deviation (㏀)		
Strain (%) / Sample No.	30	40	50	30	40	50
1	52.545 /0.144	54.297 /0.168	56.317 /0.138	51.399 /0.116	51.913 /0.147	52.412 /0.138
2	59.620 /0.680	61.112 /0.696	64.013 /0.473	51.715 /0.318	52.100 /0.251	52.955 /0.217
3	26.058 /0.108	26.938 /0.110	27.804 /0.217	24.264 /0.124	24.307 /0.082	24.445 /0.102
4	85.410 /0.372	87.436 /0.547	89.578 /0.417	81.534 /0.291	82.044 /0.310	82.715 /0.190
5	45.967 /0.125	46.500 /0.072	47.271 /0.139	44.961 /0.109	45.222 /0.089	45.532 /0.091
6	51.706 /0.126	53.174 /0.084	54.795 /0.079	49.753 /0.064	50.371 /0.056	50.994 /0.038
7	19.893 /0.041	20.223 /0.019	20.691 /0.022	19.395 /0.031	19.551 /0.023	19.713 /0.013
8	13.774 /0.045	13.781 /0.032	15.364 /0.110	13.197 /0.014	13.054 /0.032	13.644 /0.039
9	14.114 /0.057	14.411 /0.052	14.648 /0.051	13.151 /0.049	13.205 /0.045	13.232 /0.045
10	8.933 /0.056	8.860 /0.017	9.347 /0.048	8.221 /0.034	8.014 /0.025	8.286 /0.027
11	24.571 /0.077	24.473 /0.051	26.259 /0.114	22.483 /0.082	22.701 /0.103	22.930 /0.064
12	14.659 /0.021	14.744 /0.012	14.869 /0.004	14.464 /0.020	14.479 /0.014	14.536 /0.007
13	7.722 /0.019	7.741 /0.006	7.764 /0.004	7.649 /0.013	7.653 /0.007	7.662 /0.006
14	17.589 /0.091	18.171 /0.015	18.767 /0.022	16.826 /0.010	17.084 /0.016	17.335 /0.023

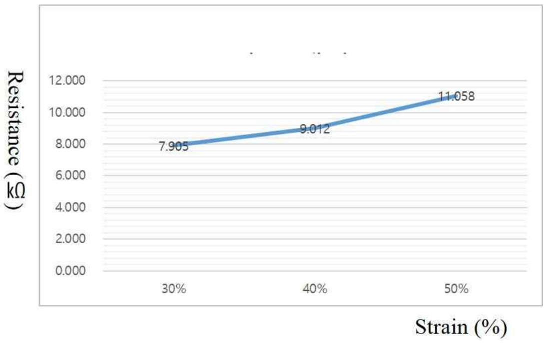
Fig. 7 shows examples of small differences (Fig. 7(a)



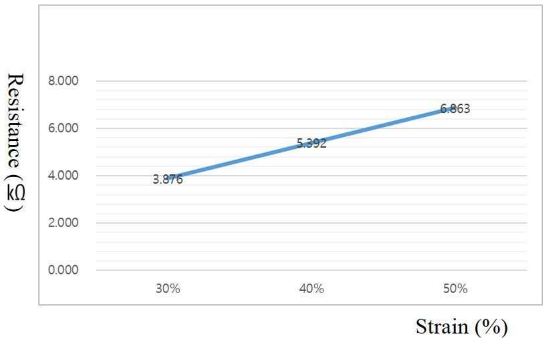
(a) 'W' knit fabric/welding/two layers/10×50 (㎜)



(b) 'W' knit fabric/welding/two layers/5×50 (㎜)



(c) 'L' knit fabric/sewing/two layers/5×100 (㎜)



(d) 'L' knit fabric/welding/one layer/10×100 (㎜)

Fig. 7. Differences in the resistance as a function of the strain on fabric sensors

Table 3. Difference between maximum and minimum resistance values according to strain

Strain (%)	Sample No.	Composition types of fabric sensors	Difference between maximum and minimum resistance (㏀)
30	13	'W' knit fabric/welding/ two layers/10 ㎜×50 ㎜	0.073
	12	'W' knit fabric/welding/ two layers/5 ㎜×50 ㎜	0.195
	7	'L' knit fabric/welding/ two layers/10 ㎜×100 ㎜	0.498
40	13	'W' knit fabric/welding/ two layers/10 ㎜×50 ㎜	0.088
	12	'W' knit fabric/welding/ two layers/5 ㎜×50 ㎜	0.265
	7	'L' knit fabric/welding/ two layers/10 ㎜×100 ㎜	0.627
50	13	'W' knit fabric/welding/ two layers/10 ㎜×50 ㎜	0.102
	12	'W' knit fabric/welding/ two layers/5 ㎜×50 ㎜	0.333
	7	'L' knit fabric/welding/ two layers/10 ㎜×100 ㎜	0.978
Average	13	'W' fabric/welding/ two layers/10 ㎜×50 ㎜	0.088
	12	'W' knit fabric/welding/ two layers/5 ㎜×50 ㎜	0.264
	7	'L' knit fabric/welding/ two layers/10 ㎜×100 ㎜	0.716

and (b)) and relatively large differences (Fig. 7 (c) and (d)) in the measured resistance as a function of the strain on the fabric sensors. As shown, the resistance values increased when the strain was increased from 30 % to 50 %. However, there were no significant differences at each strain level with respect to the linearity and width of variation in the graph. Therefore, the 14 fabric sensors that were developed in this study were deemed to have demonstrated good performance.

These results show that the sensor with the smallest difference between the average maximum and minimum resistance values under strains of 30 %, 40 %, and 50 % is Sample No. 13 ('W' knit fabric/welding/two layers/10×50 (㎜)). Second to Sample No. 13 in terms of the smallest difference between the average maximum and average minimum value is Sample No. 12 ('W' knit fabric/welding/two layers/5×50(㎜)), and then Sample No. 7 ('L' knit fabric/welding/two layers/10×100 (㎜)). As a result, these three samples are determined to yield the highest degree of accuracy. With regard to motion sensing performance, it has been shown that attaching a two-layer sensor via the welding method yielded higher effectiveness and greater influence on performance than the SWCNT-coated base fabric fiber composition or sensor size (Table 3).

4.3 Evaluation of movement-sensing performance of fabric sensor integrated into clothing

Two types of experimental clothing were fabricated by embedding the processed SWCNT-coated fabric. Movement tests (bending and stretching of the arms and legs) were conducted with child subjects wearing the clothing. The values of the voltage outputted by the textile sensor in response to the movement of the arms and legs were recorded.

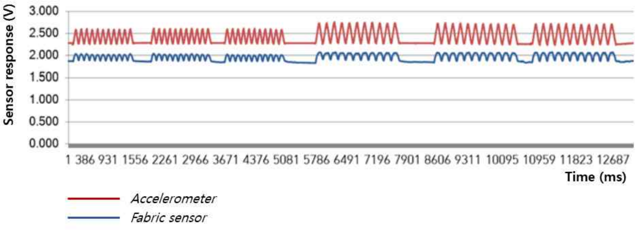


Fig. 8. Signal outputted by flexion-extension motion of the arm

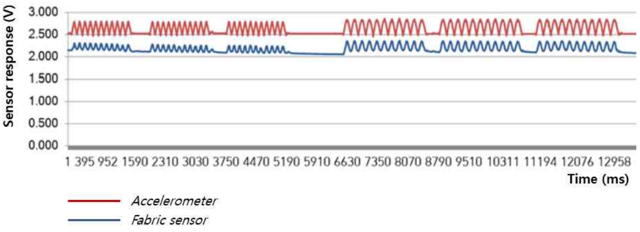


Fig. 9. Signal outputted by flexion-extension motion of the leg

In the experiment, by taking advantage of the Con-Trex MJ, in a controlled situation, the movement test was conducted for three angles - 60°, 90°, and 120° - at a rate of 60 deg/sec. The bending and stretching movement was repeated 10 times for all three angles, and this was considered one set. The voltage output from the joint motion sensor integrated into the garment during three sets of repetitive motions was used as experimental data. In addition, a commercial low-speed acceleration sensor (Low-g Accelerometer) was attached near the fabric sensor to measure and generate reference data simultaneously, to verify the reliability of the fabric motion sensor during the movement of arms and legs. The measurement circuit was set at a reference voltage of 5 V and a fixed resistance of 10 ㏀, and the data output through the fabric sensor at the flexion-extension motion was sampled at intervals of 20 ㎳ via a data logger (GT342).

From the measurements of the flexion and extension motions of the arms and legs using this fabric motion sensor, it was found that the overall signal was uniform and stable, and the agreement with the acceleration sensor was as high as 95.8% (Fig. 8, Fig. 9). The results proved that motion sensing of the human body is possible by utilizing flexible fabric-sensors integrated into clothing.

5. Conclusion

We expect that human body movement can be effectively monitored by integrating the proposed fabric motion sensors into daily or active sportswear, and that smart clothing and wearable sensing systems absent of any large equipment can be implemented in the future.

This study showed the feasibility of utilizing fabric sensors as a wearable human joint motion sensing device. Various types of SWCNT-coated materials were processed, with their performance being analyzed in order to determine the requirements for high motion-sensing accuracy. This study demonstrated that human joint motion can be measured without spatial limitations and interference from everyday activities by integrating the proposed flexible fabric sensors into clothing, as opposed to using heavy and stiff sensors or existing complex systems.

Acknowledgements

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