Structural Development of Flexible Textile-based Thermocouple Temperature Sensor

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Abstract

Textiles are conventionally utilized as the raw materials for making clothing and complementary accessories. To keep abreast of the times, a new direction of integrating textiles into electronic technology has been given in order to develop a temperature sensing device with outstanding built-in flexibility, versality and softness. In this study, a flexible construction of the textile-based thermocouple temperature sensor via an industrial-and-technological based weaving process was designed. The feasible arrangement of the conductive textile materials in the warp and weft directions in related to the temperature sensing ability was studied, in detail, significant linearity was shown in the range of 5-50℃ with different groups of combination of the conductive yarns. More cross-intersections and ‘hot junctions’ resulted from the 3×3 warp-weft arrangement, offering higher stability and accuracy in thermal sensation. Besides, the resistance of thermocouple kept almost constant under different degrees of bending. The relationship between the resistance and the bending flexibility was also investigated over a range of temperature.

Keywords

Conductive yarns, electronic intelligence, flexible, smart textiles, temperature sensor, thermocouple

1. Introduction

Textiles gets in touch with our daily lives for decades. Different kinds of apparel products are made of textiles which can provide the primary needs of daily protection, warmth, and aesthetic images. A new orientation of textiles has been identified and remolded for advanced performances and multifarious functionalities in recent years. Traditional rigid temperature detectors cannot achieve conformal contact with uneven surfaces, which plays a crucial role in the development of flexible and wearable temperature sensors.[1] With the evolution that has been progressed from heavy, hard, and wired sensors into mobile, soft, and flexible devices, simultaneously, textiles have been therefore given a high-tech secondary functionality with the hybridization of sensing components and networks due to the pros of being soft, flexible and light weight.[2-5] These enable textiles to gain considerable attention in the field of electronic technology and different types of textile-based sensors had been studied and developed.

Temperature measurement is a physiological indicator of health pathology. Localized skin temperature monitoring, utilizing sensors that remain concealed within everyday textile garments, could therefore greatly benefit patients and healthcare personnel. Regarding to the role of being a physiological indicator of health, temperature measurement can also be a physical indicator of atmospheres and materials. It can help to monitor the environmental condition as well as the alterations of materials in response to the external changes. A thermocouple temperature sensor is widely acknowledged as an effective device for instant temperature measurement in terms of simple structure, wide temperature range, high accuracy, and effective transmission of output signals. It is also known as an active transducer which generates an electric current without the assistance of an additional power or energy source for operation. Thus, it is convenient, safe, and environmentally friendly in applications. According to the Seebeck Phenomenon introduced in 1821 by Thomas Johann, thermocouples are composed of two dissimilar conductive materials which are joined at one end (i.e. either 'hot' or 'cold end) and connected to form a junction.[6-8] A voltage would be generated between the junctions while there is a potential temperature difference between the two ends. The temperature-dependent voltage would cause a current to flow along the junctions continuously.[9-10]

In the past years, researchers had designed and manufactured the textile-based thermocouples via different methods which include using electro-conductive glues,[11] solderings of metal wires onto fabric substrates,[12] coating conductive polymers by screen printing,[13] sputtering metal electrode stripes,[14] and weaving or embroidering metal wires.[15] However, there are some limitations and drawbacks resulted from these methods. For examples, the conductive properties would be influenced by the amount of electro-conductive glues or metal-filled conductive adhesives applied which precise control of quantity is needed.[16] Flux residues resulted from the method of soldering should be removed so as to avoid corrosion and accumulation of toxic components. For conductive inks screen printing, a textile-based thermocouple was developed by screen printing the conductive poly(3,4-ethylenedioxythiophene), poly(4-styrenesulfonate) (PEDOT-PSS) and polyaniline onto woven cotton fabric. It was found that the adhesion of the conductive materials was relatively low by the print coating method.[17] Besides, the conductivity and the current-carrying capacity would be limited by different materials that are enriched with a layer of monomer. Magnetron sputtering was used to deposit copper and Cu-Ni stripes on polypropylene fabric to form thermocouples.[18] However, the conductivity would be restricted by the scalability of the sputtering disposition and the lift-off of compound films. A research team had used the welding method to incorporate the copper-nickel wire-based thermocouple temperature sensor into firefighters' gloves for monitoring the real-time temperature and to prevent the risk of severe skin burns. However, this method would reduce the flexibility and wear comfort.[19] Weaving or embroidering metal wires across a fabric substrate has become more popular among the above methods. However, the problem for on-body wearing still exists as the metal wires used such as platinum-rhodium alloy, aluminum wires, chromium wires, constantan wires and stainless-steel wires are rather stiff and hard in nature. Therefore, the flexibility of the textile-based thermocouple temperature sensor could not be featured which could not withstand the deformations from external forces.[20] Moreover, some researchers had studied the textile-based sensor with the use of the metal-coated wires. For examples, two dissimilar metal wires, which were chemically deposited with copper (Cu) and constantan (Cn) respectively, were inserted into a woven fabric to form a textile-based heat flux sensor. During this process, copper is partially etched onto the fabric substrate for creating a thermopile Cn-Cu junction knot on the surface of the fabric.[21] Similarly, nickel was plated on the carbon fiber yarn, and then the nickel was partially etched to form a thermopile carbon fiber/nickel-plated carbon fiber junction knot on the surface of the carbon fiber yarn, which was intended to provide energy for the thermopile.[22] Nevertheless, the above examples were made through tedious and complicated processes which would be difficult for large-scale and commercial manufacturing.

Soft, flexible, biocompatible, lightweight, durable, and non-irritating temperature sensors should be developed to satisfy wearable requirements.[23-24] Textiles offer an exceptionally flexible platform to provide sensing functions and comfort to the wearers that owing to a wide range of fibers, yarns, and textiles outside of their protective and aesthetic functions.[25] In order to design a skin compatible temperature sensor for accurate, rapid and comfortable body temperature measurement, it would be important to make a thermocouple with the structural similarity as textiles to the greatest extent. Besides, it should be worn as normal daily clothing and conformed to body curve line. Hence, using conductive textile yarns as well as integrating the yarn-based thermocouples with special weaving parameters is believed to further enhance the stretchability and skin perception.[26-27] In this study, a flexible design of the textile-based thermocouple temperature sensor that makes seamless contact with soft, curved, and dynamically deformed human bodies with an industrial-and-technological based weaving method was proposed. Basically, thermocouple is a type of temperature sensor, which consists of two different thermoelements, allows the generation of a potential difference or voltage based on the thermoelectric phenomenon which is known as "Seebeck". According to Seebeck, if heat energy is applied to the two different conductor ends, a thermal voltage occurs between the end points. The potential difference (V) is calculated as:

$$V = \alpha * \Delta$$

where α denotes the difference in the Seebeck coefficient of thermoelement A and B, and ΔT is the difference between temperatures of hot and cold junctions. Seebeck coefficient is usually measured in μV/K.[28] Rugged, low cost and self-powered properties of thermocouples makes them preferable for having stable reference temperature. Among the metal-based yarns, silver-coated yarns were selected due to their high electrically conductive structure, high biocompatibility, excellent resistance to sterilization conditions, effectiveness on different bacteria and long-term durability of its antibacterial effect.[29-30] The feasibility of incorporating the commercial conductive textile materials into the fabric substrates for developing the textile-based thermocouples was examined. The balance between the temperature sensing ability and the textile stretchability was considered with the application of different types of conductive textile materials, the number of conductive yarns utilized in the warp and weft directions, and the yarn density adjusted of the fabric substrates. The relationship among the resistance, the choice of conductive yarns, the arrangement of construction and the bending degree of the textile-based thermocouple was investigated. It is generally believed that the newly developed textile-based thermocouples could be potentially applied in the advancement of smart textile wearables with temperature monitoring and sensing functionalities such as medical textiles, healthcare clothing and sportswear. Figure 1 shows a conceptual image illustrating the as-developed textile-based temperature sensor for temperature monitoring in medical textiles, healthcare clothing and sportswear.

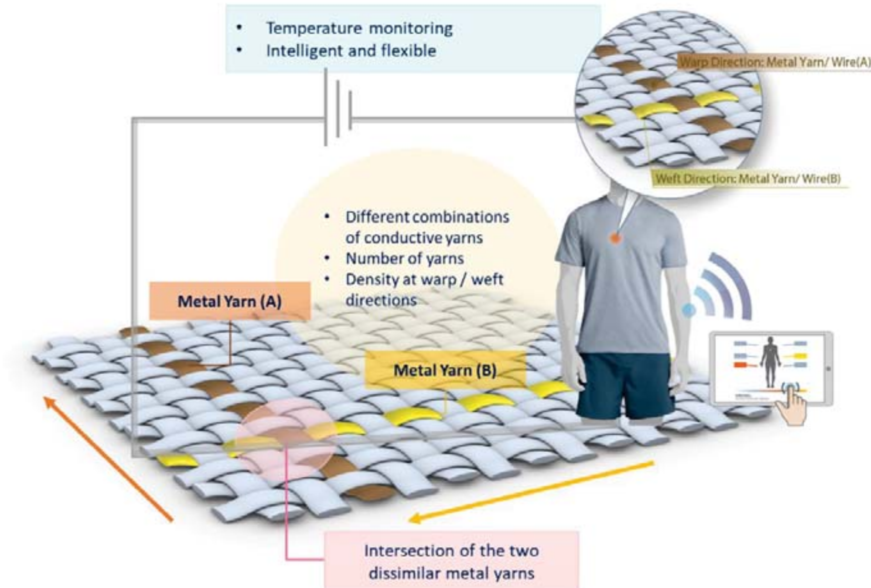

Figure 1 A conceptual image illustrating the as-developed textile-based temperature sensor for temperature monitoring in medical textiles, healthcare clothing and sportswear.

2. Experimental Section

2.1 Materials

Four types of conductive textile materials were used for the experimentation. The Shieldex® silver-plated nylon yarns (Ag-Y) and the Shieldex® silver-plated nylon filaments (Ag-F) were purchased from Statex Produktions-und Vertriebs GmbH. The stainless-steel yarns (St-Steel) were purchased from KOOLON Technologies Co., Ltd. The constantan wires (Cu-Ni) were purchased form Genesis Electric Co., Ltd. The parameters and the resistance (ohms, Ω) of each material were shown in Table 1.

Table 1. The parameters of the textile materials.

No.	Materials	Abbreviations	Types	Resistance (Ω.m)
1	Stainless-steel yarns	St-Steel	316L100F×1	65
2	Shieldex® silver-plated nylon yarns	Ag-Y	235/34×2	65
3	Shieldex® silver-plated nylon filaments	Ag-F	22F/1dtexRD	670
4	Constantan wires	Cu-Ni	Nu80%/Cu20%	60
5	Pure Cotton Fabric	Cotton	Plain Woven	N/A

2.2 Preparation of Textile-based Thermocouples

The specimens of the textile-based thermocouples were designed and produced via weaving technology with a specific arrangement of interlacing the conductive textile materials in the warp and weft directions across a pure cotton fabric substrate. Each interlaced conducting warp and weft formed a “thermoelectric effect” unit. The combinations included 1) Cu-Ni (warp) / Ag-Y (weft); 2) Cu-Ni (warp) / Ag-F (weft); 3) St-Steel (warp) / Cu-Ni (weft); 4) St-Steel (warp) / Ag-Y (weft) ; 5) St-Steel (warp) / Ag-F (weft). The basic plain weave was used as the fabric construction for the thermocouples while the density of yarns in both warp and weft directions was adjusted for further investigation. The groups of measurement were listed in Table 2.

Table 2. Groups of measurement.

No.	**Warp Direction**	**Weft Direction**	**Interlacement of Conductive Yarns**	**Density of Yarns (Warp*Weft)**
1	Cu-Ni	Ag-Y	1×1 / 2×2 / 3×3	36*30 / 36*60
2	Cu-Ni	Ag-F	1×1 / 2×2 / 3×3	36*30 / 36*60
3	St-Steel	Cu-Ni	1×1 / 2×2 / 3×3	36*30 / 36*60
4	St-Steel	Ag-Y	1×1 / 2×2 / 3×3	36*30 / 36*60
5	St-Steel	Ag-F	1×1 / 2×2 / 3×3	36*30 / 36*60

2.3 Investigation and Characterization of the Temperature Sensing Performances

A textile-based thermocouple specimen was firstly placed on a heating plate (JF-956s, Dongguan Chang and Jin Feng Electronic Tool Factory) at a specific and constant temperature. The size of the heating plate was larger than the textile fabric. The warp and weft interlacing point was located at the center (the heating hot junction) of the heating plate. The junction for measurement (i.e. ‘hot’ junction) was further secured with a load for ensuring the full contact between the thermocouple and the heating plate. Another junction (i.e. ‘cold’ junction) was immersed in a semi-frozen bath of distilled water at atmospheric pressure to 0℃ and connected to a Volt-Ohm-Milliammeter (VC85E, Double King Industrial Holdings Co., Ltd.). The change of voltage (ΔU, mV) and the resistance due to the potential temperature difference between the two junctions were measured and recorded. The temperature difference (ΔT) between the two ends was also measured with the use of a dual-channel thermometer (UT320D, Uni-Trend Technology (China) Co., Ltd.) (Figure 2 a).

2.4 Investigation of the Temperature Sensing Applications in Contact with Skin

The wearable textile-based thermocouple specimen was directly in contact with the skin of human subject of different body parts which were the fingertip of the right hand, the dorsal side of the right hand, and the forearm of the right hand respectively. This intersection point between the two dissimilar metal yarns or wires with the contact of skin was tested as the hot junction. The cold junction was immersed in a semi-frozen bath of distilled water at atmospheric pressure to 0℃ and connected to a Volt-Ohm-Milliammeter (VC85E, Double King Industrial Holdings Co., Ltd.). The change of voltage (ΔU, mV) and the resistance due to the potential temperature difference between the two junctions were measured and recorded. The temperature difference (ΔT) between the two ends was also measured with the use of a dual-channel thermometer (UT320D, Uni-Trend Technology (China) Co., Ltd.). The temperature was calculated according to the ΔU-ΔT curve and the corresponding equation y = 0.04571X-0.00668. The results were then compared with a commercial thermocouple sensing device (Figure 2 b).

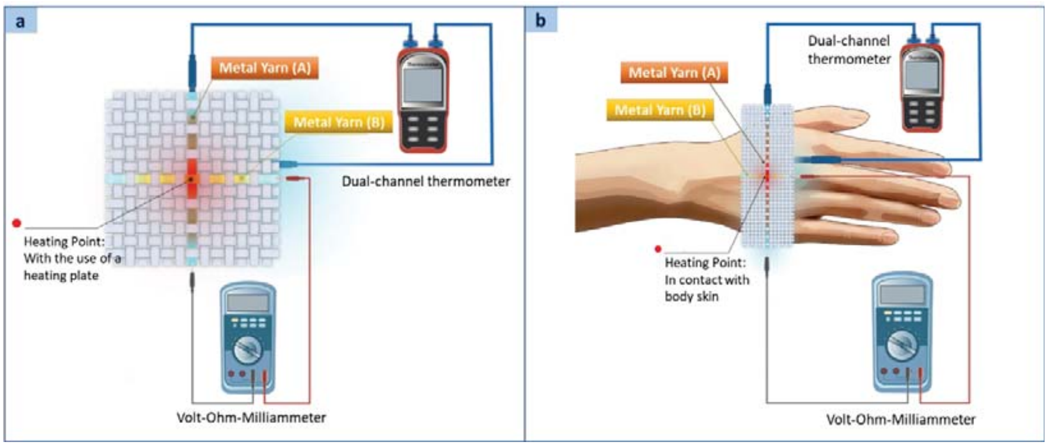

Figure 2 Experimental Set-up of the Investigation of the Temperature Sensing Performances. **(a)** The hot junction was heated with the use of a heating plate; **(b)** the hot junction was in contact with body skin.

3. Results and Discussion

3.1 Morphological Characterization of the Textile-based Thermocouples

The number of yarns and the weaving density used in both the warp and weft directions of different groups of combination were characterized with the use of an optical microscope. The warp sensing yarns and the weft sensing yarns were interlaced in a plain-woven structure. Generally, there was no obvious difference between the 1×1 interlacement under high weft density (36 warps * 60 wefts) and under low weft density (36 warps * 30 wefts) respectively. The higher the interlacement (i.e. 2×2 and 3×3 interlacements), the warp conductive yarns were closely packed in the high weft density structure to ensure that there were as many test points as possible within the same fabric area. The close interlacement of the warp and weft yarns, thereby, increasing the accuracy of the sensor (Figure 3).

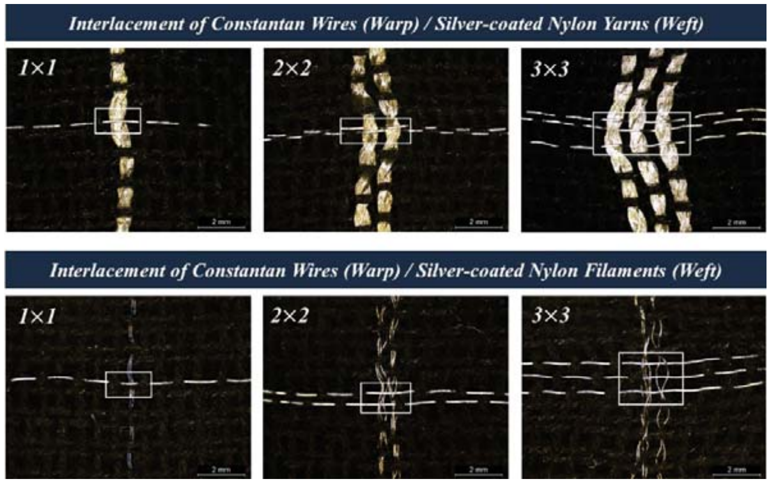

Figure 3 Optical Microscopic Images of the Woven Thermocouples. Different groups of interlacements were applied. The close interlacement of the warp and weft yarns ensured the accuracy of the sensor.

3.2 Investigation and Characterization of the Temperature Sensing Performances

The Seebeck coefficient (S), which is also known as the thermoelectric sensitivity, expresses the change of an output voltage in respect to the change of the junction temperature of a thermocouple (i.e. microvolts per unit of temperature of the Seebeck effect, μV/℃). The thermoelectric sensitivity is temperature dependent and is given by

$$S = \Delta U / \Delta T \quad (1).$$

It characterizes the ability of a thermoelectric material to convert its thermal energy into electrical energy. The thermoelectric performances of the combinations were evaluated based on the equation (1). The higher the Seebeck coefficient, the higher is the sensitivity.[31-33] It was resulted that the Seebeck coefficient of St-Steel / Cu-Ni could up to 49 μV/℃, which was approximate to that of a commercial J-type thermocouple (e.g. iron / constantan) (i.e. 51 μV/℃). This combination exhibited the highest sensitivity and an excellent stability among the other groups. Besides, the combinations of Cu-Ni / Ag-Y and Cu-Ni / Ag-F were resulted with significant Seebeck coefficients and were in line with that of the commercial T-type thermocouples (e.g. copper / constantan) (i.e. 40 μV/℃), which were 42 μV/℃ and 45 μV/℃ respectively. It was because the Seebeck coefficients of both copper (Cu) and silver (Ag) were basically the same and platinum was used as the reference metal. Therefore, Ag could be used as the thermoelement when pairing with Cu-Ni wires to form a similar T-type thermocouple.[34-35] Besides, constantan has a large negative Seebeck coefficient value (-35) at 0 degree Celsius relative to platinum, while the stainless-steel and the silver are both positive, thus, excellent temperature sensitivity could be given when pairing up with Cu-Ni wires. Furthermore, there was a relationship between the Seebeck coefficient of a thermocouple (S_{AB}) and the absolute Seebeck coefficients of the two hot electrode materials A and B (i.e. S_A and S_B) and the relationship was characterized by the equation[36-37]

$$S_{AB} = S_A - S_B \quad (2).$$

Since the individual Seebeck coefficient of the stainless-steel yarns and the silver-plated yarns was very close to each other and the resistivity between the two materials was quite high, thus, the Seebeck coefficients resulted from the combinations of St-Steel / Ag-Y and St-Steel / Ag-F were respectively low. As a consequence, the thermoelectric effect was relatively poorer. The resulted Seebeck coefficients of the textile-based thermocouples with different groups of combinations could be seen from Table 3. and Figure 4.

Table 3. The Seebeck Coefficient of Different Groups of Arrangement.

Materials	**Seebeck coefficient (µV/°C)**			
	St-Steel	Ag-Y	Ag-F	Cu-Ni
St-Steel	—	3.02	4.00	49.34
Ag-Y		—	—	41.95
Ag-F			—	45.31
Cu-Ni				—

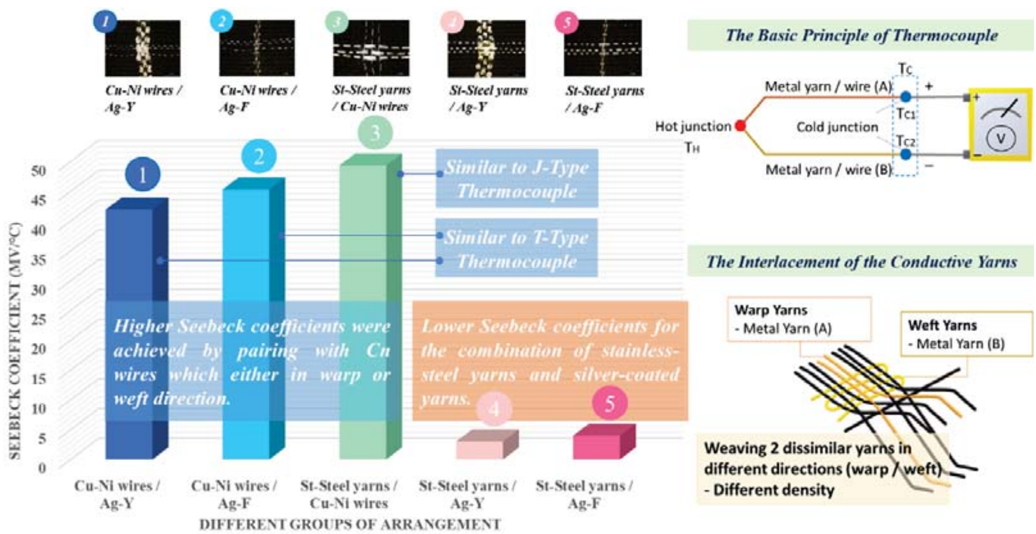

Figure 4 The Seebeck Coefficients of the Textile-based Thermocouples with Different Groups of Combinations. Higher Seebeck coefficients were achieved by pairing with constantan wires which in either warp or weft direction.

According to Figure 5 (a), the *ΔU-ΔT* curves were obtained by using the first-order polynomial with the equation

$$U = B(\Delta T) + C \quad (3)$$

when U represents the thermoelectric voltage (mU); ΔT represents the temperature difference between the hot junction and the cold junction (℃). The ΔU-ΔT curves of the specimens with different groups of combination nearly showed an linear relationship with an increase of the temperature difference in the range of 5-50℃. This linear characteristic between the thermoelectric voltage in response to temperature difference and over a range of temperature was applicable in the basis of forming a thermocouple with the above groups of arrangement. Comparing the results of ΔU-ΔT, the steepest slope was obtained by using Cu-Ni / St-Steel, followed by Cu-Ni / Ag-F, Cu-Ni / Ag-Y, St-Steel / Ag-F, and St-Steel / Ag-Y in descending order. The results indicated that the highest thermoelectric voltage could be achieved by using Cu-Ni / St-Steel. Besides, the steepness of the slopes shown by using St-Steel / Ag-F, and St-Steel / Ag-Y was found to be the lowest which was consistent with the results shown in Figure 4. Furthermore, the fitting degree between the model and the actual measurement could be accurately reflected by the value of R^2. The maximum R^2 value of Cu-Ni / St-Steel was 0.99, followed by the combination of Cu-Ni / Ag-Y and Cu-Ni / Ag-F, which were all greater than 0.99. The values of St-Steel / Ag-F and St-Steel / Ag-Y were smaller than the others.

Apart from the voltage difference corresponded to the temperature difference, the interrelationship between the Seebeck coefficient (S) and temperature difference was determined in Figure 5 (b). It could be observed that the curves of all specimens were nearly appeared as straight lines with little variations. The Seebeck coefficients of all groups of arrangement were resulted with less than 1μV/°C between the range 5℃ and 50℃ respectively, which would be promising for the measurements in this temperature range. Based on the results achieved, several combinations of using Cu-Ni wires could exhibit better performances in providing the highest possible thermoelectric voltage, excellent sensitivity and linearity over the range of temperature from 5℃ to 50℃. Considering the design of a highly flexible and soft textile-based thermocouple, the combination of Cu-Ni / Ag-F was applied for further investigation and development due to the significant thermoelectric performances of Cu-Ni wires and the outstanding textile features of nylon filaments for offering both the strength and resilience in the application of wearables.

After the preliminary study of the groups of arrangement, the promising material combination (i.e. Cu-Ni / Ag-F) of the textile-based thermocouples was selected with the alteration of the warp-weft density and the weaving construction so as to optimize the temperature sensing performances. The ΔU-ΔT curves of Cu-Ni / Ag-F with different warp-weft density under heating and cooling cycles were shown in Figure 6 (a). A better linear relationship in the range of 0-50℃ could be obtained with higher weft density, and the value of R^2 would be close to 1 which could represent a good fitness of model. It might be due to the situation that the two dissimilar conductive materials at the junctions for measurement were closer in contact with a more compact weft structure which could enhance the stability in testing. As shown in Figure 6 (b), linear relationships between ΔU and ΔT could be shown for the specimens with different arrangements of the number of conductive yarns used in the warp and weft directions. It indicated that the as-developed textile-based temperature sensors could be successfully used in the simplest structure (1×1 configuration), which ensures its applicability to the greatest extent. The maximum R^2 value was achieved with the application of the 3×3 warp-weft arrangement when comparing with the 1×1 and 2×2 arrangements. Furthermore, a higher degree of the goodness-of-fit as well as the coincidence of the heating and cooling curves in the temperature range of 5-50℃ were resulted. These indicated that the 3×3 warp-weft arrangement, which means 3 warp sensing yarns and 3 weft sensing yarns were interlaced in a plain-woven structure, could provide a more stable sensing ability and higher accuracy due to the increased number of tested areas and the cross-intersections.[38] According to Ohm's Law, electric current is directly proportional to the electromotive force (emf). An emf is produced when the junction is heated. As a result, more efficient flow of electrons could be induced with the increasing number of 'hot junctions' and the electromotive force. The accuracy for body temperature measurement was hence increased. The coincidence could further verify the good thermoelectric characteristics of the textile-based thermocouples with the utilization of the Cu-Ni / Ag-F - 3×3 warp-weft arrangement.

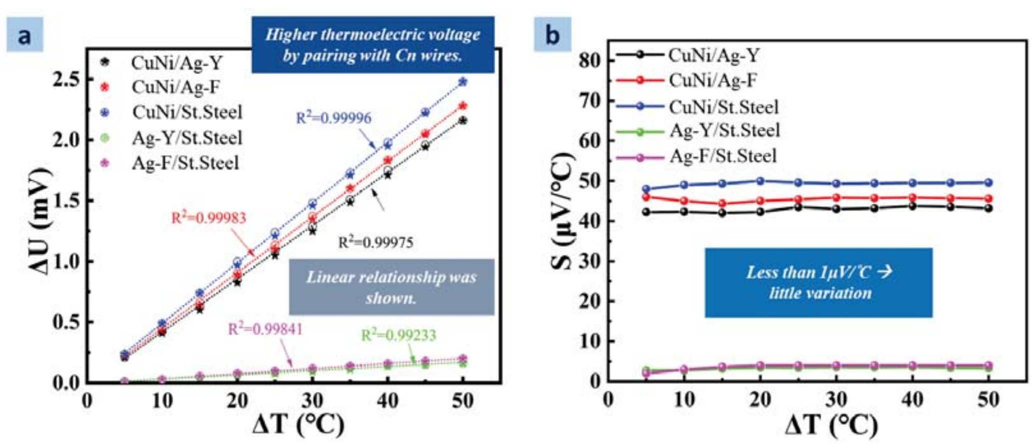

Figure 5 (a) The ΔU-ΔT curves of different combinations of conductive textiles yarns; **(b)** the interrelationship between the Seebeck coefficient (S) and temperature difference of different combinations of conductive textile yarns.

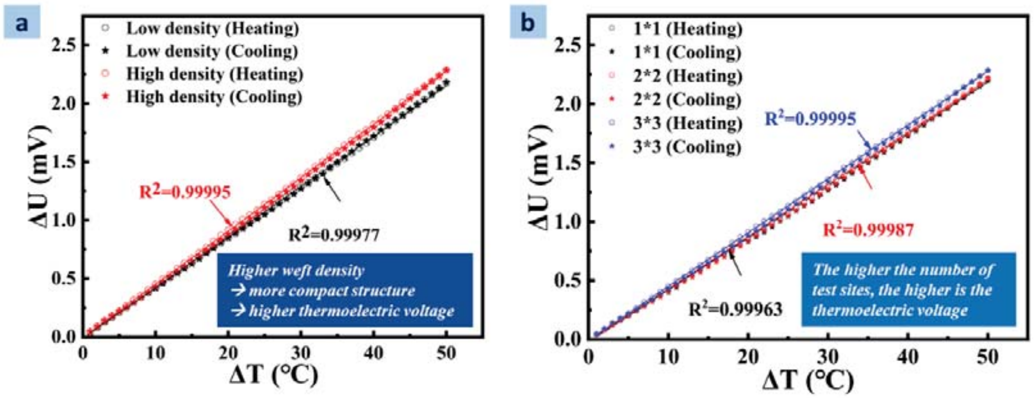

Figure 6 (a) The *ΔU-ΔT* curves of Cu-Ni/Ag-F with different warp-weft density under heating and cooling cycles; (b) the interrelationship between *ΔU* and *ΔT* with the different number of conductive yarns used in the warp and weft directions of the Cu-Ni/Ag-F specimens.

The stability of the CuN-i / Ag-F thermocouple was further examined and characterized. According to Figure 7 (a), the change of voltage at a constant temperature of T = 50℃ for every 5 minutes was recorded. It was shown that the curve was similar to a straight line which indicated that the Cu-Ni / Ag-F thermocouple was highly stable in a long-term duration at a constant temperature. In Figure 7 (b), each curve of the heating and cooling cycles coincided with one another which suggested that the fluctuation of *ΔU* was very small under different number of heating and cooling cycles, and significant temperature cycling stability was resulted. After multiple heating-cooling cycles, the numerical changes of *ΔU* and *ΔT* were negligible under the same conditions, which proved that the as-developed textile-based temperature sensor has good stability. The six curves in Figure 7 (b) almost overlap, proving that six curves have the same slope, thus the Seebeck coefficient is consistent.

Generally, the conductive resistance and flexibility are inversely proportional to textile-based sensor made of the same yarn. As shown in Figure 7 (c), the as-developed textile-based temperature sensor was bent with different degrees of bending radius. The smaller the bending radius, the higher the degree of bending. Within the bending radius of 0.5-5.0 cm, the resistance of the sensor remains almost constant, which proves that the as-developed textile-based temperature sensor has good flexibility. The R/R_0, where R_0 means the resistance of the as-developed textile-based temperature sensor in flat, while the R represents the resistance of sensor in different degrees of bending radius. The R/R_0 of the specimen with the bending radius r = 0.5 cm (i.e. the highest degree of bending) was 0.99 while that of the specimen with the bending radius r = 5 cm (i.e. the lowest degree of bending) was 1.00. The variation between the highest and the lowest degree of bending was less than 0.01 which verified the proposed thermocouple could be developed with excellent flexibility. Furthermore, the resistance did not change whether the fabric was folded or curled (i.e. shown by the changes of bending radius). It indicated that there was no open circuit caused by folding or curling which the basic conditions for the formation of thermocouple were still valid. Therefore, it could be predicted that the as-developed textile-based temperature sensor can work stably in the case of deformation and stretching.

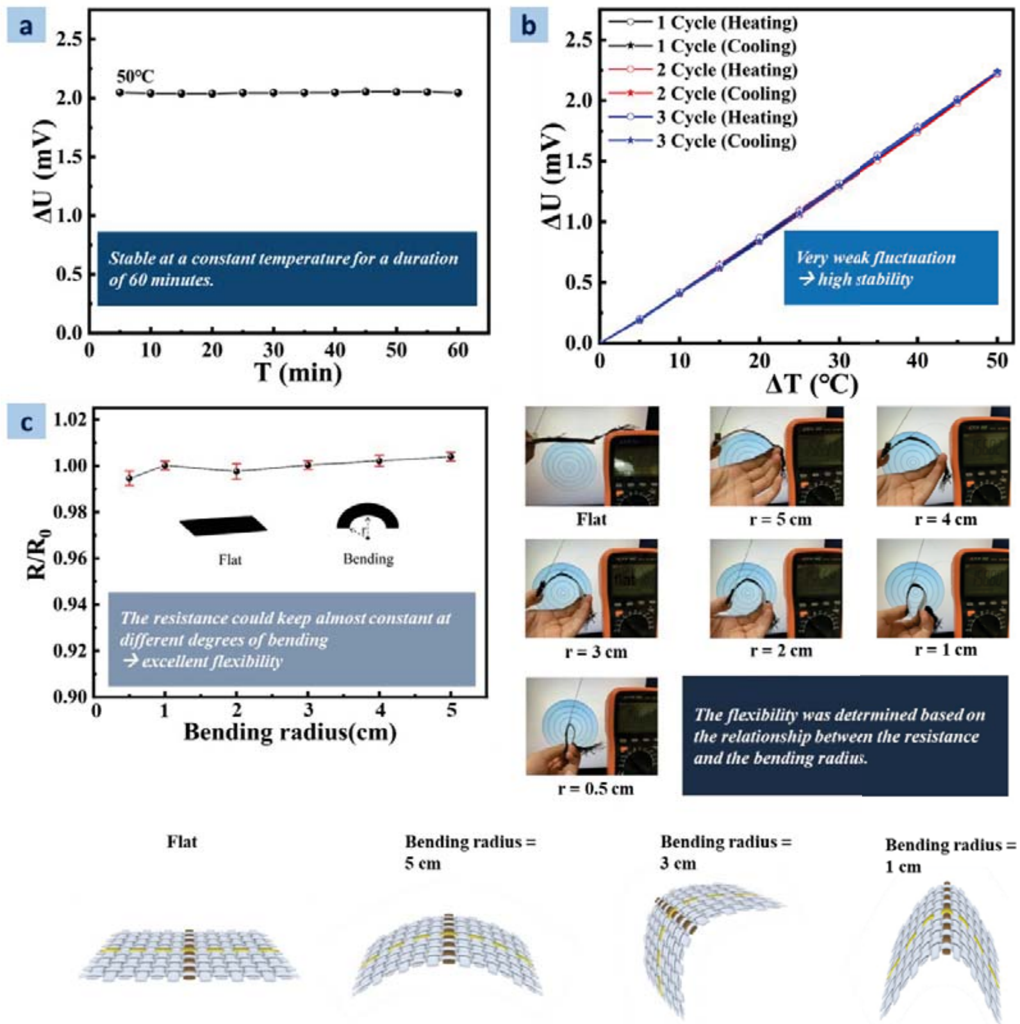

Figure 7 (a) The change of voltage at a constant temperature of T = 50℃; **(b)** the *ΔU-ΔT* curves under different number of heating and cooling cycles; **(c)** the relationship between R/R_0 and bending radius.

3.3 Investigation of the Temperature Sensing Applications in Contact with Skin

The surface temperature of human skin was measured with the use of the proposed textile-based temperature sensor specimen. Fingertip of the right hand, the dorsal side of the right hand, and the forearm of the right hand were chosen as the testing points for the hot junctions, respectively, due to the accuracy of technical measurement. A medium, which was close to 0℃, was used as the reference cold junction. The thermoelectric voltage was calculated based on the curve of y = 0.04571x - 0.00668 after fitting where 0.04571 represents the slope while 0.00668 was used as the fitting model. The data received were compared with the Type K commercial thermocouple and the results were shown in Figure 8. Type K thermocouple was chosen for comparison as it could function with a wide range of temperature and in different atmospheres as well as offering reliable and rapid responses which is suitable for body temperature measurement under different conditions. It was discovered that the temperature recorded from the testing fingertip, the dorsal side of the hand, and the forearm of the subject were 34.60℃, 33.62℃ and 34.92℃ respectively with the utilization of the proposed textile-based temperature sensor while the results of Type K commercial thermocouple were 34.40℃, 33.70℃ and 34.80℃ respectively. It was believed that the proposed textile-based temperature sensor could be potentially used in daily wear for versatile cutaneous temperature measurement and thermal sensation estimation. Various types of small textile wearables such as wrist bands and rings could be designed for monitoring the cutaneous temperature along the artery regions.

Figure 8 The Temperature Measurement of Human Skin Surface with the use of the Proposed Textile-based Temperature Sensor Specimen. Fingertip of the right hand, the dorsal side of the right hand, and the forearm of the right hand were chosen as the testing points for the hot junctions, respectively.

4. Current Applications and Future Perspectives

Temperature monitoring is an essential indicator for daily healthcare. Advanced flexible textile-based temperature sensor could make seamless contact with soft, curved, and dynamically deformed human bodies, as well as offering a real-time, comfortable, and skin compatible on-body temperature sensing system, therefore potentially initiating continuous, long-term monitoring of health conditions. As textile materials were used as the basis of the proposed sensor, a wide range of wearables could be created for different healthcare and therapeutic purposes with the body temperature profile and distribution. Additionally, metal-coated yarns are flexible, lightweight, conformable, and can be woven or knitted into various textile structures for facile integration of sensors within the fabric structure. These fabrics can be cut, sewn, stretched, crumpled, and manipulated in ways where hard metals, carbon and plastics cannot be used. The flexibility of the proposed textile-based temperature sensor is believed to impel the production of medical garments and sportswear which allows an ease of movement while monitoring the temperature. For home healthcare applications, real-time personal tracking of body temperature could be provided by wearing the clothing or the wearables with the integration of the textile-based thermocouple. This could assist doctors, medical practitioners, healthcare providers in detecting early critical physiological status and health conditions of patients, elderly, infirm and babies. For sportswear applications, the skin temperature could be measured and the body core temperature could be estimated instantly when performing exercise. The thermo-physiological response, the heat production in muscles and body heat balance could be hence monitored during intermittent high tensity exercise. The risk of having hyperthermia could be avoided.[39-42] Regarding the healthcare monitoring, during the times of epidemics, body temperature is known as an important indicator for the early detection of infectious diseases. The proposed textile-based temperature sensor is thought to be a promising future application which could help to quickly measure the elevated body temperature whenever and wherever in order to reduce the spread of infection via fever screening.

Furthermore, clothing preservation would be another concern for providing a favorable storing condition so as to reduce the risk of self-destruction of garments. The high-end fashion, wedding gowns and uniforms should be kept at an optimum temperature to prevent the fading of color because of temperature fluctuations. In addition to clothing conservation, the textile relics or historic artifacts are easily damaged or structural altered by the changes of external factors such as temperature and humidity as they are originated from natural resources which are thus extremely sensitive to environmental variations. The temperature for storage should be maintained below 23 ℃ as high temperature may fasten the rate of decay of the textile materials and the chemically unstable natural colorants and may shorten the half-life of the textile relics. Keeping the textile artifacts in good condition would be necessary for restoration. This proposed flexible textile-based temperature sensor could be “integrated” into the relics to “feel” the temperature, to monitor the actual state of textile relics (Figure 9).

For the future realization of the sensor, the obtained data can be connected to flexible integrated chips, which in turn wirelessly transferred data to a Bluetooth-enabled smartphone, with a custom-developed application downloaded. The washability of as-developed textile-based temperature sensor will be further investigated to meet the commercial application requirements.

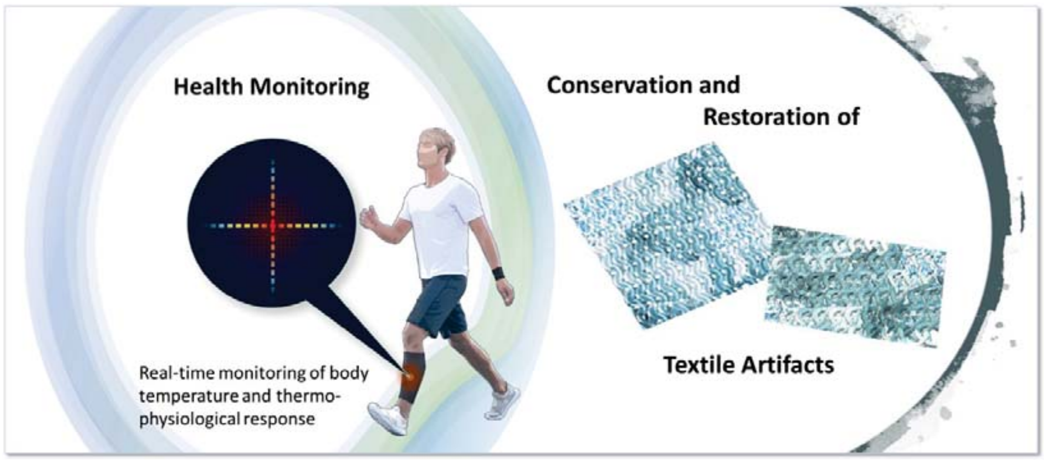

Figure 9 The Potential Applications of the Proposed Textile-based Thermocouple Temperature Sensor.

5. Conclusion

In conclusion, the proposed textile-based thermocouples were prepared by interlacing different number of conductive textile materials in the warp and weft directions. Through observing the structural morphology of the thermocouples, the conductive yarns in the warp direction would become more closely packed in the high weft density construction. According to the results of thermoelectric voltage in response to change of temperature, significant linearity was shown in the range of 5-50℃ with different groups of combination of the conductive yarns. The highest thermoelectric voltage, sensitivity and linearity were resulted by pairing with Cu-Ni wires. To integrate both the pros of having the greatest thermal sensing performance and the bendable properties, the combination of Cu-Ni / Ag-F was studied. More significant linearity was achieved with higher weft density in the range of 0-50℃ because the junctions between the two dissimilar conductive yarns were closer in contact with one another. Maximum R^2 value and higher degree of coincidence of the heating and cooling cycles were obtained with the construction of 3×3 warp-weft arrangement. It may be due to the phenomenon that more cross-intersections and 'hot junctions' were resulted from the 3×3 warp-weft arrangement which could offer a higher stability and accuracy in thermal sensation. The simplest woven structure of 1×1 configuration could be applied for the as-developed textile-based temperature sensor. Good stability was achieved after multiple heating-cooling cycles. Besides, the resistance of the Cu-Ni / Ag-F thermocouple kept almost constant under different degrees of bending. Further investigating the temperature sensing performance when in contact with the fingertip, the dorsal side of hand, and the forearm, the results received from the proposed textile-based thermocouple were similar with that from the Type K commercial thermocouple which verifying the accuracy and versatility of the proposed thermocouple for commercialization and industrialization.

Declaration of conflicting interests

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References

[1] Descent, P., Izquierdo, R., & Fayomi, C. (2018, May). Printing of temperature and humidity sensors on flexible substrates for biomedical applications. In 2018 IEEE International Symposium on Circuits and Systems (ISCAS) (pp. 1-4). IEEE.

[2] Wang, L., Wang, L., Zhang, Y., Pan, J., Li, S., Sun, X., Zhang, B., & Peng, H. (2018). Weaving sensing fibers into electrochemical fabric for real-time health monitoring. Advanced Functional Materials, 28(42), 1804456.

[3] Heo, J. S., Eom, J., Kim, Y. H., & Park, S. K. (2018). Recent progress of textile-based wearable electronics: a comprehensive review of materials, devices, and applications. Small, 14(3), 1703034.

[4] Bosowski, P., Hoerr, M., Mecnika, V., Gries, T., & Jockenhövel, S. (2015). Design and manufacture of textile-based sensors. In Electronic Textiles (pp. 75-107). Woodhead Publishing.

[5] Wang, L., Fu, X., He, J., Shi, X., Chen, T., Chen, P., Wang, B, & Peng, H. (2020). Application challenges in fiber and textile electronics. Advanced Materials, 32(5), 1901971.

[6] Göpel, W., Hesse, J., & Zemel, J. N. (Eds.). (1990). Sensors: Thermal sensors (Vol. 4). VCH.

[7] Nicholas, J. V., & White, D. R. (2002). Traceable temperatures: an introduction to temperature measurement and calibration.

[8] Michalski, L., Eckersdorf, K., Kucharski, J., & McGhee, J. (2002). Temperature measurement.

[9] Lee, H. S. (2010). Thermal design: heat sinks, thermoelectrics, heat pipes, compact heat exchangers, and solar cells. John Wiley & Sons.

[10] Kasap, S. (2001). Thermoelectric effects in metals: thermocouples. Canada: Department of Electrical Engineering University of Saskatchewan, pp. 1–11.

[11] Ziegler, S., & Frydrysiak, M. (2009). Initial research into the structure and working conditions of textile thermocouples. Fibres Text. East. Eur, 17, 84-88.

[12] Mrugala, D., Ziegler, F., Kostelnik, J., & Lang, W. (2012). Temperature sensor measurement system for firefighter gloves. Procedia Engineering, 47, 611-614.

[13] Seeberg, T. M., Røyset, A., Jahren, S., & Strisland, F. (2011, August). Printed organic conductive polymers thermocouples in textile and smart clothing applications. In 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 3278-3281). IEEE.

[14] Depla, D., Segers, S., Leroy, W., Van Hove, T., & Van Parys, M. (2011). Smart textiles: an explorative study of the use of magnetron sputter deposition. Textile Research Journal, 81(17), 1808-1817.

[15] Takatera, M., Uchiyama, E., Zhu, C., Kim, K. O., & Ishizawa, H. (2017, October). Effect of air gap on apparent temperature of body wearing various sizes of T-shirt. In IOP Conference Series: Materials Science and Engineering (Vol. 254, No. 18, p. 182012). IOP Publishing.

[16] Gomatam, R., & Mittal, K. L. (2008). Electrically Conductive Adhesives. CRC Press.

[17] Seeberg, T. M., Røyset, A., Jahren, S., & Strisland, F. (2011, August). Printed organic conductive polymers thermocouples in textile and smart clothing applications. In 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 3278-3281). IEEE.

[18] Depla, D., Segers, S., Leroy, W., Van Hove, T., & Van Parys, M. (2011). Smart textiles: an explorative study of the use of magnetron sputter deposition. Textile Research Journal, 81(17), 1808-1817.

[19] Mrugala, D., Ziegler, F., Kostelnik, J., & Lang, W. (2012). Temperature sensor measurement system for firefighter gloves. Procedia Engineering, 47, 611-614.

[20] Caldwell, F. R. (1962). Thermocouple materials. Temperature, Its Measurement and Control in Science and Industry, (2), 81-134.

[21] Gidik, H., Bedek, G., Dupont, D., & Codau, C. (2015). Impact of the textile substrate on the heat transfer of a textile heat flux sensor. Sensors and Actuators A: Physical, 230, 25-32.

[22] Hardianto, H., Malengier, B., De Mey, G., Van Langenhove, L., & Hertleer, C. (2019). Textile yarn thermocouples for use in fabrics. Journal of Engineered Fibers and Fabrics, 14, 1558925019836092.

[23] Li, Q., Zhang, L. N., Tao, X. M., & Ding, X. (2017). Review of flexible temperature sensing networks for wearable physiological monitoring. Advanced healthcare materials, 6(12), 1601371.

[24] Dias, T. (Ed.). (2015). Electronic textiles: Smart fabrics and wearable technology. Woodhead Publishing.

[25] Park, S., & Jayaraman, S. (2003). Smart textiles: Wearable electronic systems. MRS bulletin, 28(8), 585-591.

[26] Ziegler, S., & Frydrysiak, M. (2009). Initial research into the structure and working conditions of textile thermocouples. Fibres Text. East. Eur, 17, 84-88.

[27] Information Resources Management Association. (2018). Wearable technologies: Concepts, methodologies, tools, and applications. IGI Global.

[28] Arman Kuzubasoglu, B.; Kursun Bahadir, S. (2020). Sensors and Actuators A: Physical, 315, 112282.

[29] Pollini, M., Russo, M., Licciulli, A., Sannino, A., & Maffezzoli, A. (2009). Characterization of antibacterial silver coated yarns. Journal of Materials Science: Materials in Medicine, 20(11), 2361-2366.

[30] Huang, Q., & Zhu, Y. (2019). Printing conductive nanomaterials for flexible and stretchable electronics: A review of materials, processes, and applications. Advanced Materials Technologies, 4(5), 1800546.

[31] Lee, H. S. (2010). Thermal design: heat sinks, thermoelectrics, heat pipes, compact heat exchangers, and solar cells. John Wiley & Sons.

[32] Bentley, R. E. (Ed.). (1998). Handbook of temperature measurement Vol. 3: The theory and practice of thermoelectric thermometry (Vol. 3). Springer Science & Business Media.

[33] Webster, J. G. (Ed.). (1999). The Measurement, Instrumentation, and Sensors: Handbook. Springer Science & Business Media.

[34] Jung, W. (2005). Op Amp applications handbook. Newnes.

[35] Chan, A. Y. (2016). Biomedical device technology: principles and design. Charles C Thomas Publisher.

[36] Lee, H. S. (2010). Thermal design: heat sinks, thermoelectrics, heat pipes, compact heat exchangers, and solar cells. John Wiley & Sons.

[37] Pollock, D. D. (1991). Thermocouples: theory and properties. CRC press.

[38] Tian, B., Liu, Z., Wang, C., Liu, Y., Zhang, Z., Lin, Q., & Jiang, Z. (2020). Flexible four-point conjugate thin film thermocouples with high reliability and sensitivity. Review of Scientific Instruments, 91(4), 045004.

[39] Dias, T. (2020). Electronically active textiles. MDPI.

[40] Koncar, V. (Ed.). (2016). Smart textiles and their applications. Woodhead Publishing.

[41] Dias, T. (Ed.). (2015). Electronic textiles: Smart fabrics and wearable technology. Woodhead Publishing.

[42] Shishoo, R. (Ed.). (2015). Textiles for sportswear. Elsevier.