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Development of a flexible wearable thermal textile accessory for winter sports

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Abstract

In pursuit of a healthy lifestyle, people are paying more attention to sports activities, even in winter. They are thus seeking high function and maximum comfort to improve their performance. However, cold weather may result in a higher risk of injuries. It is of prime importance to perform warm-up, which can increase body temperature to relieve muscle stiffness and allow improvement of performance. Unfortunately, the traditional approach of wearing multiple thick layers of clothing to keep warm can prevent the easy movement of the body. Therefore, the integration of flexible textile and wearable thermal technology has become a major research initiative in both sports and textile fields. Current attempts by high-tech start-ups and wearable textile enterprises are not able to overcome the hurdle of transforming wearable technology into a fashionable and marketable product. Hence, this paper introduces a design-driven method to develop a flexible wearable thermal textile accessory for winter sports usage. The relationships between thermal textiles, electrical resistance, thermal performance, stretchability, energy consumption, and function stability were evaluated to optimize the thermal textile fabrication. Then, a prototype was produced and its specification was defined. These enable the realization of mass production and provide a blueprint for the future development of wearable textiles.

Keywords

Wearable electronics, thermal textiles, design-driven method, winter sports

In the light of improved living standards and advanced technology, requirements for advanced functional textile and apparel products have increased significantly. Hence, people are no longer satisfied with the current thick and multi-layer fabrics to keep warm in winter. When it comes to sportswear, people are seeking highly functional fabrics that can provide maximum comfort to improve their performance. In particular, people are engaging in more sports activities, even in winter, in pursuit of a healthier lifestyle. Literature review shows that the market for sportswear is expanding rapidly. According to global market research by Global Industry Analysts, Inc., by 2024 the global market for sports or fitness apparel is predicted to reach US$231.7 billion.[1] Researchers and marketers are thus encouraged to compete for market share by fulfilling the high-performance demand and upgrading functions. However, in contrast to normal sports activities, winter sports may carry a higher risk of injuries due to the cold weather. When the exposure time exceeds 30 min, at a temperature below 5°C and wind speed above 5 mph, outdoor exercises are warranted.[2–13] Previous studies have also pointed out the importance of thermoregulation on athletic performance and safety.[14],[15] Environmental heat stress reduces power output during exercise.[15–17] Sufficient warm-up is needed to improve body core and skin temperature to maintain training performance, as this helps to relieve muscle stiffness and improve athletes' response. Hence, taking proper measures to keep warm not only enables body comfort, but also prevents injury.

Multi-layer wearing is the most common approach against cold weather. However, its cumbersome and bulky nature hinders body movements and adversely affects sporting activities. Also, passive insulation prevents the dissipation of body heat and eventually causes a feeling of exhaustion for wearers. The wearer can indeed remove an outer layer of clothing during exercise; however, the wearer may then have to carry the outer layer of clothing while simultaneously doing strenuous activity. This not only impedes mobility, but also depletes the wearer's energy significantly.[18–23]

Currently, wearable electronic thermal apparel challenges the traditional understanding of clothing and provides a new direction for both the textile and sports industry. The potential market for wearable electronics is huge, yet most of the available products are accessories such as watches. Well-integrated textile electronics are rarely found due to the lack of efficient transformation between technology and product design.[24-31] Therefore, the acceptance rate is still very low, and they cannot be seamlessly applied to daily wear. For example, the most widely used heating technology in clothing adopts a USB heating plastic film with rough electrical wires. The heating plastic film is rigid, non-foldable, stiff, non-breathable, and non-washable, and is usually attached by sewing. This adversely affects the comfort level as well as the appearance of the clothing, and eventually reduces its usability. Additionally, most of these products on the market are made of carbon fiber and fabricated as non-woven fabrics. The advantages of the heating sheet made using non-woven fabric are low cost and convenient assembly. However, the disadvantages include rigid nature, extra additions, wire link function elements, and power supply system. Therefore, it is suggested that light, thin, flexible, and soft thermal-protective sportswear should be developed to meet consumers' expectations, especially for the sportswear market. Besides, a design-driven method is expected to be a solution for the low acceptance.

This study introduces an industrial-based design method to develop a wearable electrical thermal textile for winter sports usage. This prototype combines soft silver-coated conductive yarns (SCCYs), elastic nylon yarn, and polyester yarn featuring fast response, electrical-thermal comfort, lightweight, flexibility, and so on. Also, the relationships between thermal textile's electrical resistance, thermal performance, stretchability, energy consumption, and function stability were investigated to optimize the thermal textile fabrication. Afterward, a prototype and its specification sheet were developed to instruct mass production. This research can facilitate the transformation of technology into a practical product and provide various possibilities for future research and development.

Experiment design

The experiment design was targeted on production-oriented purposes to accelerate the process of transfer from research and development to mass production. Technical textiles usually emphasize functionality, and thus are usually developed from an engineering point of view, whereas general textiles focus on aesthetics. Different perspectives contribute greatly to the results, and in fact the research design involves practical and theoretical work in parallel strands. The major difference between the disciplines of design and engineering lies in the methodology in which quantitative and qualitative considerations are integrated.[32-40] To ensure integration and marketability, the design flowchart as shown in Figure 1(a) is used as the foundation for the development procedures. It combines both technical product engineering and textile design, and can be easily understood by enterprises from different fields. Figure 1(b) shows the experiment design flowchart issued for research engineering technical terms. The theoretical engineering work involves investigation of elastic and resistance values, and knitting conductive circuit formation to enable heat stability under different levels of extension.

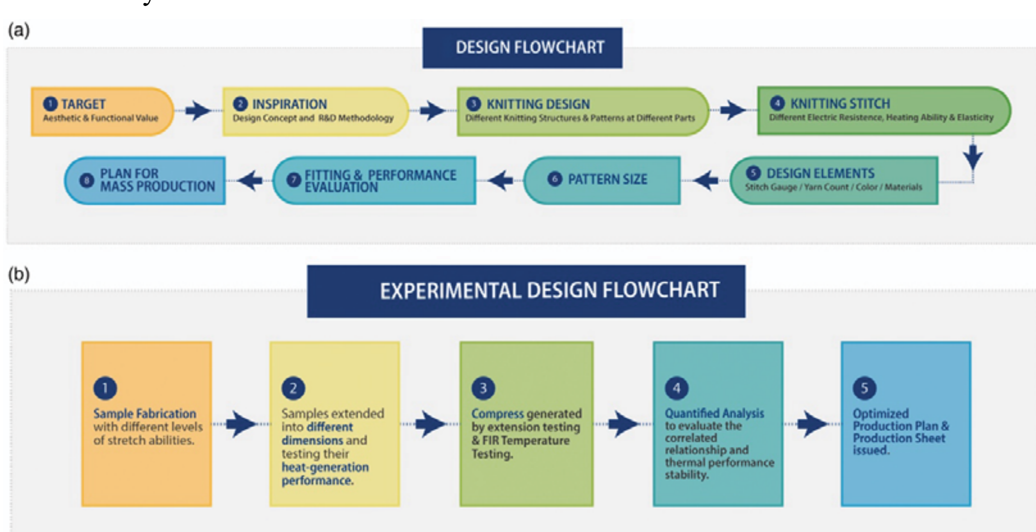

Figure 1. (a) Knitting products design procedures; (b) Experiment Design Flowchart.

Considering the scenario of sports activities, flexible electrically conductive and thermal-function fabric should maintain a stable heating performance under different stretching conditions. Therefore, this research revealed the relationship between the fabric's heating performance and its different levels of extensions in considering optimization of the production methodology. This is the key to adopt the proposed research technology in the real application scenario.[41-45] Meanwhile, mass production techniques and aesthetic value are essential factors to be considered. After confirming the feasibility of the proposed thermal fabrication methodology, a kneecap guard prototype was developed and its production sheet issued. This prototype sets an example to illustrate the research routine to final consumers. Thus, a production sheet is issued and functions as a bridge.

Selection of materials

With advances in spinning, synthetic chemistry, and electrical engineering technology, light, flexible, and highly conductive fibers and yarns are commercially available on the market. There are three main categories: (1) carbon fiber/yarn, (2) metal or metallic oxide fiber/yarns, and (3) metal/metallic oxide-coated conductive synthetic yarns. Carbon fiber has the problem of being brittle and may stick to human skin, causing skin problems or toxicity, while 100% metal yarn has the limitations of being non-elastic, heavy, and poor to handle, and protrudes from the fabric causing discomfort or even injury. Hence, to fulfill the aforementioned requirements, metal/metallic oxide-coated conductive synthetic yarns are preferred due to their soft, flexible, elastic, and highly conductive characteristics. Among various coating materials, the silver particle-coated layer exhibits excellent stable electrically conductive property. The conductive thermal fabric can thus become lighter, softer, more flexible and elastic, can tightly fit with the body curve, evenly distribute the loaded pressure and distort, and swing in large angles with various body movements. Meanwhile, with different wt.% of silver particles added, SCCY products can be produced with different preferred linear electrical conductivities. Further, this kind of conductive yarn can withstand more than 10 times of washing while maintaining stable conductivity. To form a complete conductive circuit in one piece of fabric,[4], [6–48] referring to the previous conductive knitted fabric-forming technologies which develop areas of electrodes and thermal areas with significant resistance value gap, two SCCYs available on the market with a huge resistance gap, SCCY A and SCCY B, were selected. They had the highest resistance (SCCY A, with the resistance of 677 Ω) and lowest resistance (SCCY B, with the resistance of 9.8 Ω), and could form the thermal area and electrodes. The details of yarn are listed in Table 1; the scanning electron microscopy (SEM) images show the different structures of SCCY A and

SCCY B and the coated layer of silver particles on core nylon filaments, as well as the materials for the proposed fabric and prototype development.

Materials	Details
SCCYs	SCCY A: High conductive resistance to form Thermal Area (2 lines)  Yarn Count (tex): 2.2 R/cm (Ω/cm): 68.6 SCCY B: Low conductive resistance to form Conductive Path (1 line)  Yarn Count (tex): 47 R/cm (Ω/cm): 1.0
1. Elastic Nylon Yarn	Different number of elastic yarns laid in (from 0 to 2, 40D nylon elastic yarns)
2. Polyester Yarn	20D, one yarn
3. Space Fabric	Volume Space fabric for tube development

Table 1. Materials utilized for sample development

Production method

As flexibility and extensibility are required for sportswear, a knitted structure was selected due to its excellent extension property. When forming the knitting loops, elastic yarns can be embedded to generate strong force against extension force, maintain dimensional stability, and fit the body curve. Moreover, to satisfy the requirement of thin thermal fabric for both athletes and normal consumers, the high gauge (18G) circular knitting method was selected instead of flat knitting technology. Plain stitch structure was also determined to maximize reduction on the fabric thickness.

The thermal fabric was divided into three parts: top, middle, and bottom. The top and bottom parts were fabricated by SCCY B as electrodes, while the middle part was fabricated by SCCY A, elastic yarns and polyester yarn as thermal area. A demonstration is shown in Figures 2(b) and (c). For mass production, a uniform size has to fit different figure sizes and the size expansions caused by different movement postures and maintain stability. Thus, in this paper, the influence of extending of stretch on performance stability of the thermal fabric was investigated. A uniform size of thermal fabric knitted with plain stitch by 18G circular machine was developed and sheathed onto different tubes with three levels of radius to bear three degrees of stretch.

Figure 2. (a) Different samples sheathed on tubes with different sizes; (b) the fabrication of samples on the circular knitting machine and the method of applying electricity on the proposed thermal fabric; and (c) the magnified photos of the micro inner structure of the thermal circular knitting fabric.

There are two independent variables: (1) numbers of elastic nylon yarn laid-in in the heating area; and (2) radius size of the inner tube to sheath on the thermal fabrics. These two factors generate different levels of compression force (pressure) from the elastic fabric to the inner tube surface and fluctuate the electrical resistance. These affect the heating temperature directly. Hence, the dependent variables were: (1) pressure from fabric to the inner tube surface, (2) electrical resistance (R) of the thermal fabric, (3) final heating temperatures (T_{max}), and (4) power consumption.

Furthermore, the implications of these dependent variables were analyzed to determine the requirements for the proposed sportswear, the kneecap guard's design and development, in terms of elasticity, flexibility, inner pressure, electrical resistance, heating temperature, and power efficiency.

Equipment

The following types of equipment are listed in Table 2, including sample fabrication, measuring, and data collection.

Sample-making equipment	18G circle knitting machine 
Power supply	DX6005DS digital DC power supply
Temperature recording	FLIR infrared camera 
Pressure sensor	Pedar Pliance Systems with a single pressure sensor (ø10 mm, with 78 mm^2 sensing area, 2–200 KPa testing range) 

Table 2. Equipment utilized for sample development and measuring and evaluation

Sample fabrication

Circular thermal fabric with different elasticities

After several trials, thermal areas composed of two lines of SCCY A and one line of polyester yarn exhibited appropriate electrical resistance with T_{max} in a comfort zone under a safe power supply (4.5 V). With more elastic yarns laid-in, internal strain generated against external extension was higher. Accordingly, the sample fabricating parameters were decided and are listed in Table 3. There were three kinds of thermal fabric samples with three levels of elasticities (with 0 line, 1 line, and 2 lines of elastic yarns embedded, respectively). Each sample had three pieces to repeat the testing for three times to obtain the average.

	Electrode Circle No.[#]	Electrode Material	Thermal Area Circle No.[@]	Thermal Area Materials		
Sample 1 (non-elastic)	35	SCCY A *1	100	SCCY B * 2	Polyester Yarn * 1	
Sample 2 (40D*1)	35	SCCY A *1	100	SCCY B * 2	Polyester Yarn * 1	40D nylon elastic yarn *1
Sample 3 (40D*2)	35	SCCY A *1	100	SCCY B * 2	Polyester Yarn * 1	40D nylon elastic yarn *2

[#]Electrode Circle No. refers to the lines of loops in the weft direction formed by SCCY B in the electrode area.
[@]Thermal Area Circle No. refers to the lines of loops in the weft direction formed by SCCY A in the heating area.

Table 3. Fabrication parameters for sample development

Inner tubes with different radius sizes

To mimic the size variance of limbs and different levels of extensions, three tubes were made in different sizes, as listed in Table 4. The circular thermal fabrics were sheared onto these tubes, to mimic how circular thermal fabrics with different elasticities would respond to different levels of extension. Sheathed on larger tubes, larger extension was generated and larger contact pressure loaded onto the inner tube surface, as shown in Figure 2(a). However, larger tubes had a larger heat dissipative area. Thus, these nine settings of mimics, as listed in Table 4, could be utilized to investigate the influences of two independent variables on fabrics' resistances and their thermal performance. When testing the heat generation process, the power supply was maintained for 20 min so that a thermal balance status between the fabric and its environment could be achieved. During the experiment, the temperature was recorded every 5 min.

	Sample 1 sheathed on	Sample 2 sheathed on	Sample 3 sheathed on
Tube 1 (Radius: 2.50 cm)	Non elastic yarn (small)	40D * 1 Elastic nylon yarn (small)	40D * 2 Elastic nylon yarn (small)
Tube 2 (Radius: 3.75 cm)	Non elastic yarn (mid)	40D * 1 Elastic nylon yarn (mid)	40D * 2 Elastic nylon yarn (mid)
Tube 3 (Radius: 5.00 cm)	Non elastic yarn (big)	40D * 1 Elastic nylon yarn (big)	40D * 2 Elastic nylon yarn (big)

Table 4. Samples sheathed on tubes with different radius

Measurement and testing

Different pressures loaded on the inner tube surface were not only generated by various numbers of elastic nylon yarn laid-in, but also by shearing those circular samples on tubes with different radius, as shown in Figure 3(a). The pressure sensor was inserted to test the pressure (*P*) toward the inner tubes. This model mimicked the situation of subjects wearing the proposed sportswear on their limbs. A direct electrical energy source (DC 4.5 V, DX6005DS Digital DC Power Supply) was provided to ensure all the swatches reached sufficient T_{max} for athletes against a chill environment. The test on each point was repeated three times and the mean value was calculated and recorded.

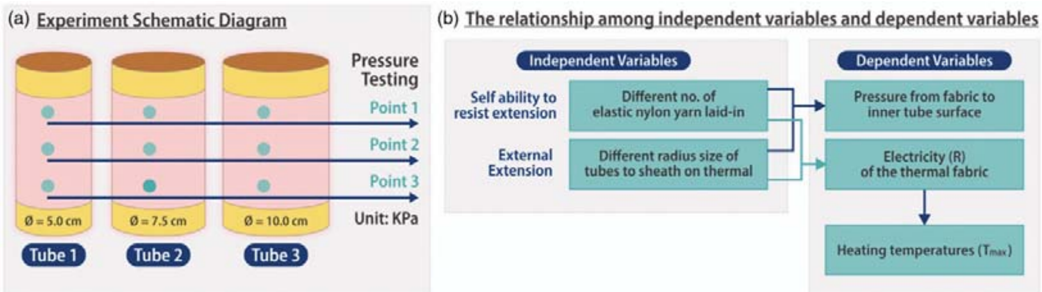

Figure 3. (a) Testing of thermal fabric samples (with 0, 1, or 2 elastic yarns laid-in) on tubes with three different radii and under different strain conditions, (b) testing schematic diagram.

The electrical resistance of the fabric was also investigated. Two ends of the conductive paths were ironed with a circle of the metal film and clamped by stainless steel. The equivalent resistances were measured at around the pre-tension of 0.5gf/tex, and by a Keithley 2010 multimeter. Three samples were taken for each type of fabric. An insulating plate was placed below the stainless-steel plate for isolation.

Results and discussion

Referring to the testing schematic diagram shown in Figure 3(b), comparisons of pressure and electrical resistance were made by (1) samples with the same number of elastic yarns laid-in but sheathed onto different tubes, and (2) samples with different numbers of elastic yarns laid-in but sheathed onto the same tubes. These would affect the targeted heating temperature. Detailed information and analysis about each dependent variable and their influence on the final choice is elaborated in the following sections.

Weight and thickness

The weight of the samples was tested by electronic balance AY210 equipment with a readability of 0.1 mg, while the thickness of the fabrics was tested under the pressure of 4 gf/cm^2 by RMES equipment. In addition, the most common kneecap LP support product available on the market was selected for comparison. The results are shown in Table 5. Comparing the weight per unit area of these four samples, it was found there was a slight difference among the non-elastic, 40D*1 and 40D*2 samples, while the weight of the product purchased from the market was relatively very high, three times of the weight of sample 3 (40D*2). Therefore, the proposed thermal textile technology could offer a light and convenient solution for wearable thermal sportswear or accessory design. Moreover, the thickness of these four samples varied greatly. However, the largest thickness difference of sample 1 (non-elastic), sample 2 (40D*1), and sample 3 (40D*2) was 1.26 mm, which is hardly noticeable when wearing on the limb, especially in an extended condition. In addition, due to its knitted structure, the thermal fabric is soft and elastic. Therefore, the comfort or convenience of the proposed technology would not be degraded. Furthermore, the thickness of the product selected from the market was approximately four times that of sample 1 (non-elastic) and 3.5 times of sample 2 (40D*1). Hence, the current product on the market was bulky and might restrict motion. Obviously, this technology offered a more advanced replacement.

	Sample 1 (non-elastic)	Sample 2 (40D*1)	Sample 3 (40D*2)	Product from the market
Weight (g/cm2)	0.030	0.035	0.040	0.120
Thickness (mm)	0.70	0.82	1.96	2.82

Table 5. Results of sample weight and thickness in resting status

Pressure testing

The contact pressure of exerting the fabric onto tubes was measured using pressure sensors with a force-to-voltage system. When there was no elastic nylon yarn laid-in or sheared on a small tube (r 2.5 cm), the contact pressure was insignificant. Based on the chart shown in Figure 4(a), the pattern of how contact pressure varied among samples with different lines of elastic yarns laid-in was analyzed. With the increase in tube radius, the contact pressure loaded onto the tube surface linearly increased accordingly. In particular, the speed of the contact pressure generated by the thermal fabric with two lines of elastic yarns laid-in increased faster than the samples of one line or no line of elastic yarn laid-in. Moreover, under the same level of extension, the thermal fabric with more elastic yarns laid-in showed that the contact pressure polynomial increased more rapidly. The thermal sample with two elastic yarns laid-in generated the maximum range of contact pressure increases, which varied from 0 to 1.98 KPa.

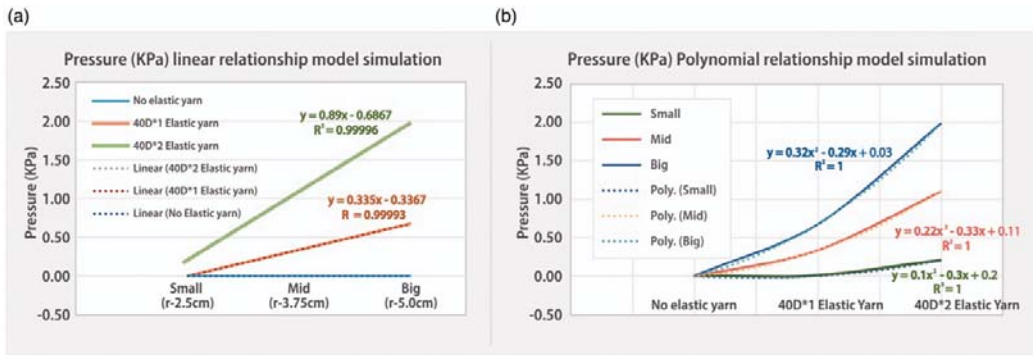

Figure 4. Contact pressure changes with the (a) size of the radius (R) and (b) a number of elastic yarns laid-in.

Increasing the elasticity of the fabrics enhanced their compression capability. Considering physical mechanics, size variance of the knee joint, the pressure of wearing tight sports leggings, and bending of the knee joints from 0° to 90° (that occurs in different gestures), the contact pressure at different parts around the knee joint were measured. The maximum variance of the contact pressure around the knee joint ranged from 1.3 to 2.0 KPa. When shearing the thermal sample 40*2 elastic yarns onto different tubes, the variance of the contact pressure increased from 0 KPa to 2.0 KPa, which stimulated contact pressure fluctuation generated around the knee joint when doing different exercises. In addition, the averaged contact pressure of multiple testing points varied from 0.7 to 1.3 KPa.

When designing a professional compression sports kneecap guard, high contact pressure enables the close fit that prevents slip-off during strenuous exercises. Moreover, the compressive contact pressure can provide extra support to help reduce pain and swelling, and thus provide support and stabilization to reduce the risk of injuries. With more elastic yarns laid into the thermal area of fabrication, higher pressure can be generated to provide this kind of compressional and thermal protection. Therefore, more lines of elastic yarns can be selected for these advantages when considering the design.

T_{max} testing: Thermal performance

The results suggested that T_{max} increased with heating time and tended to be stable after 20 min. The T_{max} was recorded and is shown in Figure 5(a). The thermal performance comparison could be made regarding the following two terms: (1) samples with the same elasticity (with the same lines of elastic yarns laid-in) but sheathed onto different tubes, and (2) samples with different elasticity (with different lines of elastic yarn laid-in) but sheathed on the same tube. Combining these two directions of compression, the comprehensive influence of both elasticity and extension could be analyzed, and the weight of each variance could also be compared.

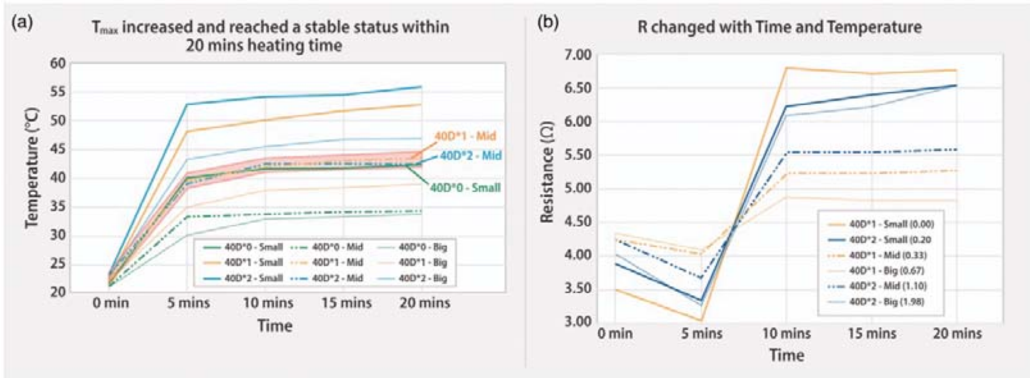

Figure 5. (a) T_{max} increased and reached a stable status within 20-min heating time with 4.5 V power supply; (b) resistance changed as the heating time passed.

It was found that with more lines of elastic yarns laid-in, the higher elasticity of the fabric, the faster response of the fabric, and the more rapid increase of its heating temperature, and thus a higher T_{max}could be achieved. Specifically, it took 5 min for the non-elastic yarn sample sheared on the small tube to reach 40°C, while it took approximately half this time (2.5 min) for the 40D*2 samples to reach the same temperature. Furthermore, with the highest elasticity constrained in the highest-density condition, its temperature increase was the fastest.

What is more, it was found that the T_{max} was lower with the same elasticity samples (with the same lines of elastic yarns laid-in) sheared onto the larger tube. This was related to the expanded heat dissipation areas. Under extensive extension, the electrical resistance of the thermal fabric also changed accordingly. The electrical resistance was a critical factor to determine the temperature-raising speed and the target T_{max}. Thus, changing patterns of electrical resistance could be analyzed by different fabric elastic properties and different levels of extension.

Furthermore, referring to the temperature highlighted in the orange area in Figure 5(a), the raising speeds of the temperature of three samples (non-elastic fabric sheared on the small tube, 40D*1 fabric sheared on the mid tube, 40D*2 fabric sheared on the mid tube) and their variances with time were approximately the same. This indicated that when thermal fabric extended to a larger size, the T_{max}-lowering negative effect was negated by inserting elastic yarns. This finding offered a solution for the proposed sportswear and accessory design against various extensions brought about by performing different motions. The temperature-raised speed and T_{max} could be maintained in a stable range.

Therefore, considering the lightness, flexibility, pressure support, and rapid thermal functions, multiple lines of elastic yarns are suggested to be applied to the proposed thermal sportswear design.

Resistance (R)

R versus stretching

According to Joule's first law, the relationship between the heat generated and current flowing through a conductor is expressed as:

$$Q_{heat} = I^2 \times R \times t \tag{1}$$

where Q_{heat} is the amount of heat generated (w); *I* is the electrical current flowing through a conductor; hence, it is the thermal area of the fabric (A); *R* is the amount of electrical resistance present in the thermal area (Ω), and *t* is the amount of time that this occurs (s). In addition, according to Ohm's Law, the relationship between current, voltage, and resistance is expressed as:

$$I = V \div R \tag{2}$$

where *I* is the current, *V* is the voltage and *R* is the electrical resistance. If equation (2) substitutes into equation (1), the following equation is formed:

$$Q_{heat} = V^2 \div R \times t \tag{3}$$

When *R* is smaller with constant *t* and *V*, there is a higher speed of Q_{heat} generation and thus contributes to a higher temperature. Combining the previous T_{max} testing results, it was found that *R*could be decreased by adding elastic yarns into the thermal fabric. Nevertheless, when stretched into different larger sizes, the *R* of the thermal area varied. The change of *R* of each square unit of conductive knitted loops under different extension levels is expressed as:

$$\Delta\text{R } \% = \frac{\Delta\left(\frac{R'}{S'}\right)}{\left(\frac{R_0}{S}\right)} \times 100\% \tag{4}$$

When sheared onto different tubes, *R* changed and the change in terms of percentage is shown in Table 6 and Figure 7. It showed that the Δ*R*% of 40D*2 was the most predictable, and most likely to be a linear change. Thus, 40D*2 was more appropriate to be adopted for elastic thermal equipment production. Furthermore, the microphotographs of these three groups of samples were taken and recorded in Figure 6(b).

	40D*0 Small	40D*0 Mid	40D*0 Big	40D*1 Small	40D*1 Mid	40D*1 Big	40D*2 Small	40D*2 Mid	40D*2 Big
R (Ω)	4.64	3.49	3.88	4.5	4.33	4.25	4.02	4.25	4.02
R/S (Ω /cm^2)	0.296	0.191	0.128	0.222	0.184	0.135	0.247	0.180	0.128

Table 6. The comparison of R at different levels of extension normalized by the size of fabric

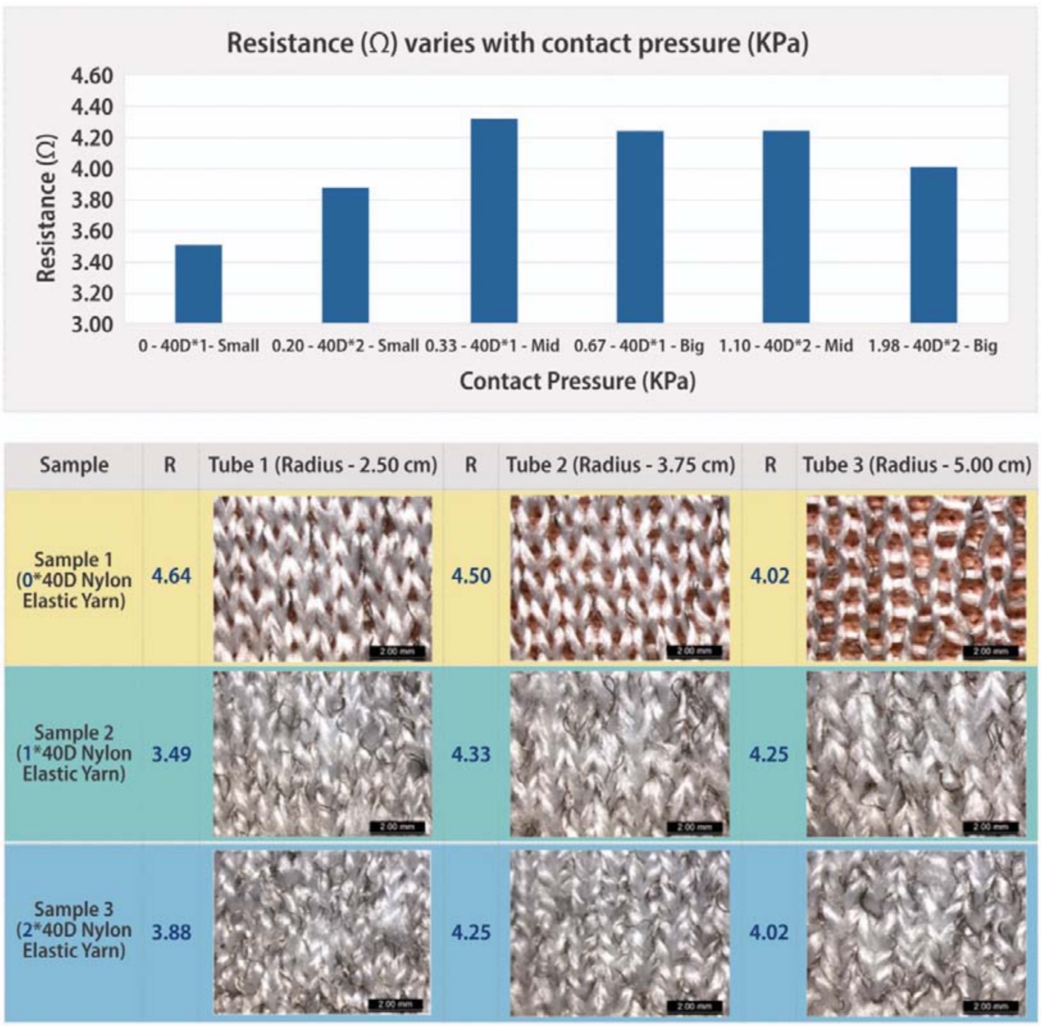

Figure 6. Analyzing the relationship among different levels of extension, elasticities, and electrical resistance: (a) R (with 4.5 V power supplied) varies with samples with different elasticities and under different levels of extension; (b) the morphology of the allocation of SCCY A in the knitting fabrics under different levels of extension.

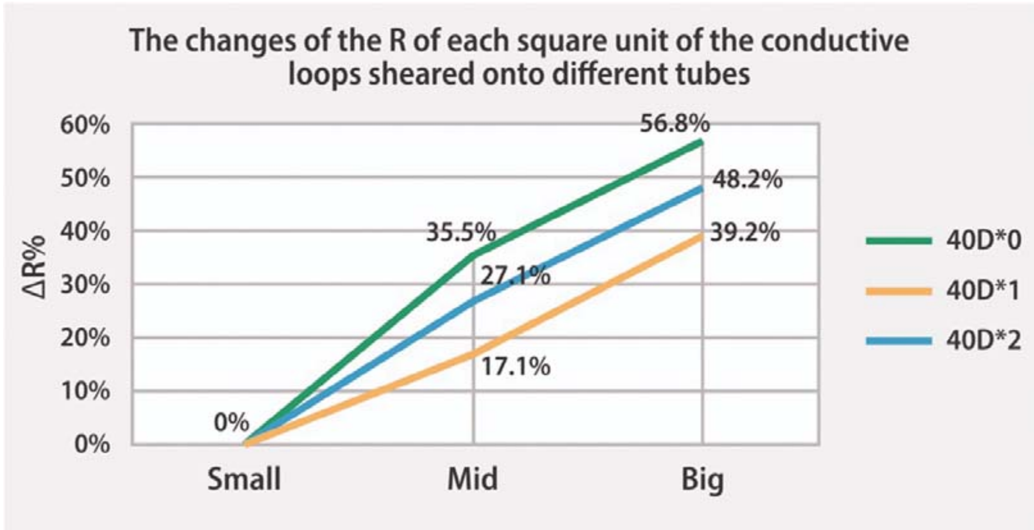

Figure 7. The changes of resistance of each square unit of the conductive loops sheared onto different tubes.

In the first row, the SCCY A laid-in each loop of the thermal area in sample 1 (non-elastic) was partly connected to the SCCY A laid in the loops on the two sides. When sample 1 (non-elastic) stretched to a larger size, each loop and SCCY A yarn was also stretched, so that more SCCY A yarns in loops were directly connected to the ones in the loops on their two sides. This explained the phenomenon that when stretching sample 1, *R* decreases. However, the speed of this decrease in *R* was smaller than the increase of speed of heat dissipation caused by the stretched larger area.

In the second row, due to the one line of 40D elastic yarn laid-in, the loop structure in the thermal knitting area was denser. Hence, more SCCY A in each loop of the thermal area in Sample 2 (40D*1) was connected to the SCCY A yarns in the loops on the two sides. In this way, when stretching sample 2 into a larger size, the loop structure became loose again, and the resistance increased accordingly because of having fewer SCCY A yarns connected to each other. However, due to the embedding of the elastic yarns, the fabric became denser. Thus, more air was still trapped inside the fabric structure and less thermal convection and conduction dissipation occurred. Therefore, T_{max} of sample 2 was still higher than that of sample 1.

In the third row, when more lines of elastic yarns are laid-in, the resistance of sample 3 (40D*2) slightly raised, compared with sample 2, because more lines of elastic yarns partly separated the connection of SCCY A yarns. However, this slightly increasing *R* could be eliminated by stretching the knitting fabric into a larger size. Hence, when sample 3 was sheared to the large tube, its resistance decreased again.

Therefore, even it had a large heat-dissipation area, and its T_{max} was still higher than those of 40D*1 and 40D*2 sheared on mid tubes.

Combining these three findings, to derive the benefits of contact pressure support and countervail the influence from stretching on increasing resistance, the production plan of thermal fabric with two lines of 40D elastic yarns laid-in was suggested.

R versus raising temperature (T)

As shown in Figure 5(a), the heating temperature increased gradually and tended to be stable after 20 min. However, this heating temperature would influence *R*, and this relationship can be expressed in the following equation:

$$\rho(T) = \rho_0\left[1 + \alpha(T - T_0)\right] \tag{5}$$

whereρ is the resistivity of the conductor material; is the temperature coefficient of resistivity, the parameter is an empirical parameter fitted from measurement data; T_0 is a fixed reference temperature (usually room temperature), and ρ_0 is the resistivity at temperature T_0.

Thus, the relationship between *R*, time, and the rising temperature is shown in Figure 5(b). At the first 5 min, the temperature increased rapidly, while *R* slightly dropped. Afterward, the temperature increased slowly and became stable, while *R* increased rapidly and then was maintained in a stable range. This finding suggested that in the initial stage, with the rising temperature, yarn and loop might expand and thus the loop structure might become denser. SCCY A yarns, having more connection points internally, led to the dropping of *R* and increasing of temperature. Therefore, when laying conductive yarns into fabrication, their resistance changing pattern was more complicated than the normal strict conductive wires or conductors. Through the tests, mimicking different application scenarios, in this research, the optimized balance status could be obtained from thermal fabrics with two lines of elastic yarn laid-in as it could achieve a higher T_{max} and a smaller *R* variance range, compared with other samples.

Power (P)

Associating the power (rate of work) *P* of each thermal fabric under different extension levels and its T_{max}, the energy utilization efficiency could be obtained. However, the heat dissipation (Q_{dis}) area of each tube to shear on was different, and it follows Fourier's law:

$$Q_{dis} \propto S\left[\frac{d(T-T_0)}{dx}\right]dt \quad (6)$$

where ρ is the heat dissipation amount (w); S is the dissipation surface area (cm^2); T is the surface temperature, while T_0 is the environmental temperature (°C); and dx is a certain coordinate point on the object surface.

Thus, taking the variance S into consideration to compare the power utilization efficiency of each fabric sample, ∂ as the power efficiency index is used to conduct the comparison, and its expression is listed as equation 7 below, and the ∂ of each fabric was calculated, with the results listed in Table 7.

	Non – Small (0.00)	Non – Mid (0.00)	Non – Big (0.00)	40D*1 – Small (0.00)	40D*1 – Mid (0.33)	40D*1 – Big (0.67)	40D*2 – Small (0.20)	40D*2 – Mid (1.10)	40D*2 – Big (1.98)
∂ (cm2•°C/w)	115.7	164.7	275.4	208.7	236.6	367.1	221.6	262.8	660.5

Table 7. Comparing P in terms of contact pressure and heating temperature

When reaching the stable status at 20 min:

$$\partial \cdot Q_{heat} = Q_{dis}$$

$$Q_{heat} = I^2 \cdot R \cdot dt = P \cdot dt$$

Thus: $\partial \cdot P \propto S \cdot (T_{max} - T_0)$

$$\partial \propto \frac{S \cdot (T_{max} - T_0)}{P} \quad (7)$$

It was found that when the same fabric extended into a larger area, the efficiency index (∂) was higher. Moreover, comparing fabrics with different levels of elasticity extended into the same area, the ∂ of the fabric with higher elasticity was higher, especially the ∂ of sample 40D*2 sheared on the large tube, which was significantly higher than the others. This result indicated that when drafting the prototype design and production plan, the thermal fabric with higher elasticity (with more elastic yarns laid-in) is preferred.

Mimicking wearing scenario

In randomly selected female subjects (with an average height of 160 cm, weight of 50 kg, normal wearing size of S), the average radius of their knee, gained by measuring the width of the knee (mean: 33 cm) and then calculating the approximate radius, was approximately 5.2 cm. Therefore, the samples wrapped on the large tube 3 could directly mimic the wearing scenarios. First, the heating performance was reviewed and recorded using a FLIR infrared camera, and is shown in Figure 8. With 4.5 V power supplied, the electrical thermal fabric with two lines of elastic yarns embedded had the highest heating temperature and achieved the highest energy-utilizing efficiency. However, as its T_{max} already reached 47.0°C, it tended to cause an over-heating safety problem. Driven by safety concerns and pursuing a more energy-saving heating mode, a lower power (3.0 V) was provided to control the heating temperature in a safe and comfortable range. Under this lower voltage power supply, the different heating performances of these samples were recorded. In particular, the samples with two lines of elastic yarns embedded performed the best, reaching a T_{max} of 32.4°C, which was very close to the human skin temperature in the proposed thermal zone. Therefore, for wearing on the limbs as thermal sports equipment or accessory and for guarding against the chill outside during physical training conditions, this design is suggested as an optimized prototype production plan. To further demonstrate the effectiveness of the proposed technology in a final utilization and facilitate this optimized research result into actual industrial production, an electrical-thermal sports kneecap guard was custom designed and developed.

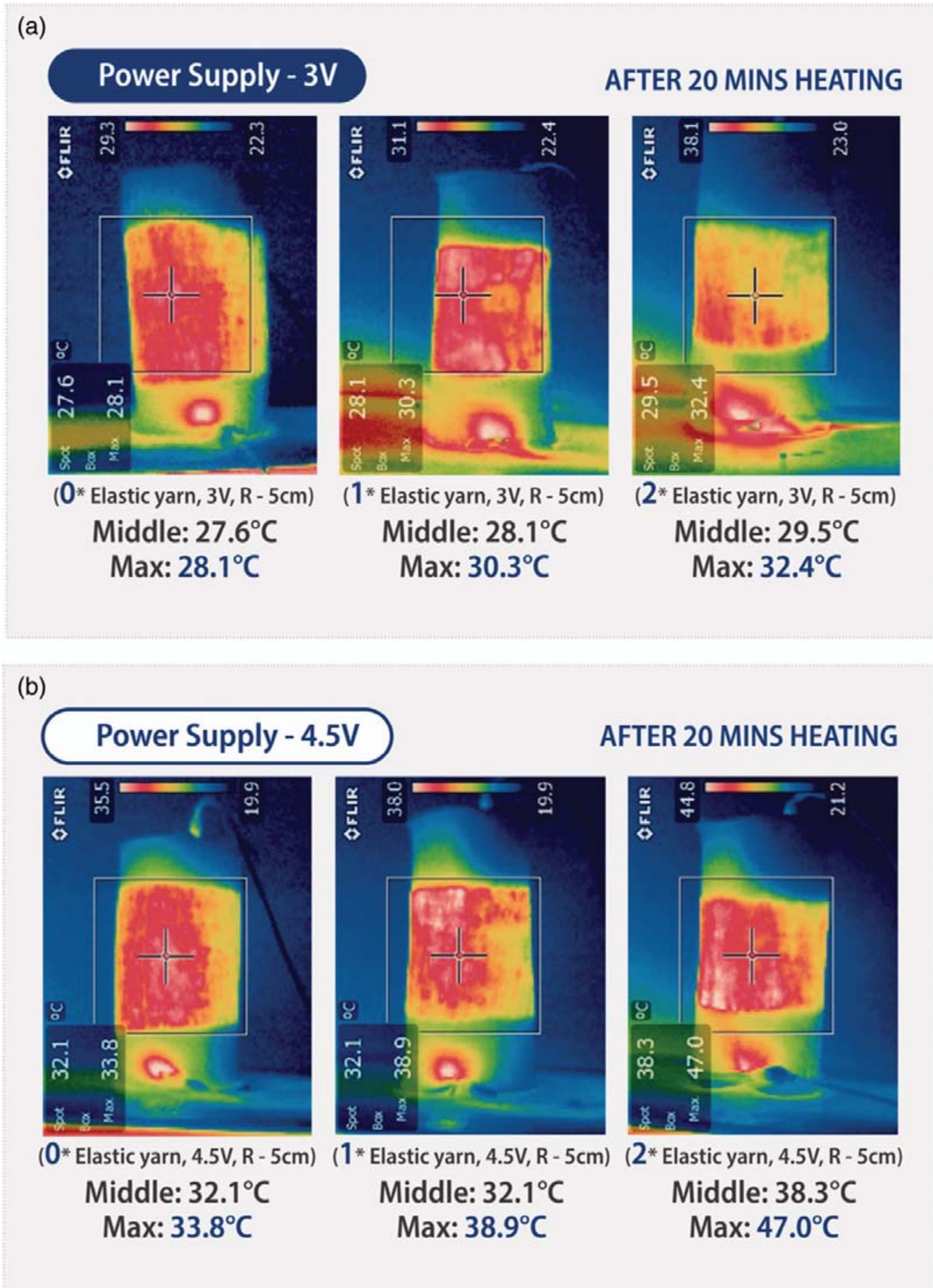

Figure 8. Mimicking a wearing scenario: (a) heating for 20 min with 3.0 V power supplied; (b) heating for 20 min with 4.5 V power supplied.

Prototype development

Based on the previous findings in terms of (1) safety support offered by higher contact pressure; (2) faster thermal response and higher T_{max} thermal protection against the chill condition offered by higher elasticity (with two lines of 40D elastic yarns laid-in); (3) higher energy utilization efficiency offered by higher elasticity (with two lines of 40D elastic yarns laid-in), the lasting time could be extended when using the same power supply. Thermal fabric with two lines of elastic yarn laid-in, which has a higher elastic property, is recommended for the proposed thermal sportswear and accessory design. This proposal can offer a flexible, light, fast-response, and high-efficiency thermal solution.

A prototype, which acts as a kneecap guard and an elbow guard as shown in Figure 9, was developed based on the proposed technology. It can be worn for different occasions, such as racing, skiing, and hockey competitions, with the considerations of warmth, thinness, flexibility, lightness, and avoiding extra stretch. Cylinder knit products are elastic in nature. Two lines of elastic yarns and two lines of SCCY were selected to knit together with a line of polyester yarn to form the targeted thermal fabric. It could thus enhance the thermal effect with lower energy consumption. This thermal fabric was filmed onto the back side of normal elastic fabric, with the most widely used thin plain structure for making tight sportswear design. The heating inner layer and the testing cylinder had the same circuit. The thermal area was designed at the center to accelerate the blood flush to the muscles around the knee or elbow. Moreover, the outer layer was made of stretch sports fabric. Sports always involve a large extent of stretch. Hence, a special polyurethane (PU) pattern was filmed onto the front side to avoid overstretching. The two layers of fabric are merged by a V-shaped line. Additionally, electrically generated heat might be lost to the environment. Therefore, to enhance heating efficiency, an extra layer may be added on top of the thermal fabric. The positive and negative poles are woven by lead-point wires and guided on both sides of the knee pad, and the battery was connected with conductive buttons. The battery was contained in the battery pocket of the knee pad. Figure 10 shows how the electric circuit was arranged and connected to the power supplier.

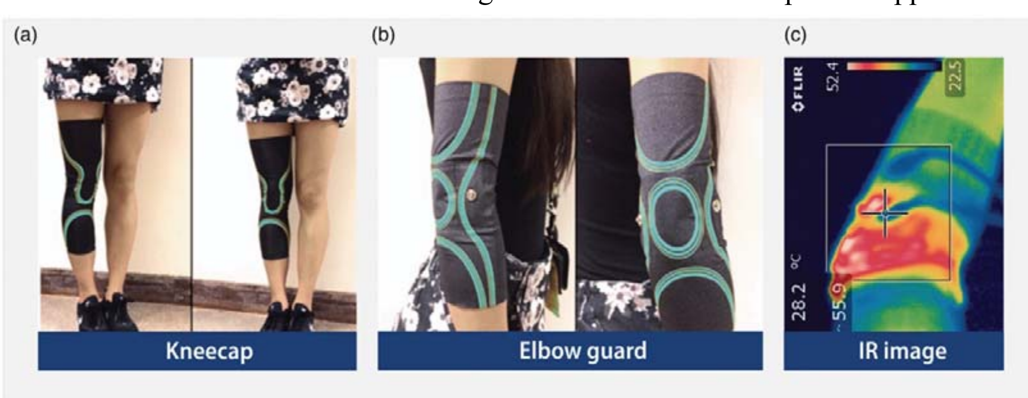

Figure 9. The prototype can be used as: (a) a kneecap guard and (b) an elbow guard, by

adopting the proposed technology; (c) heating performance shown by FLIR infrared camera.

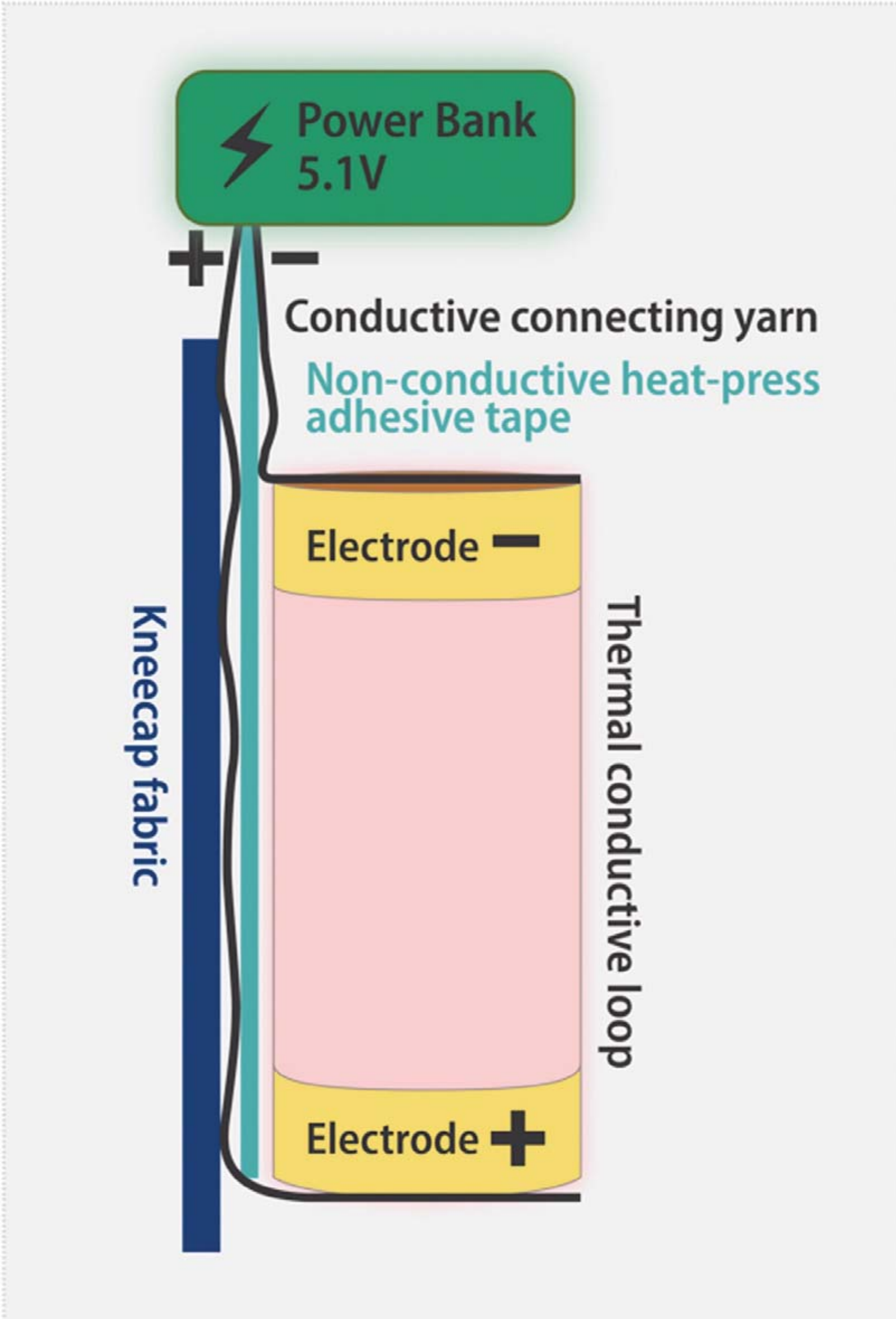

Figure 10. Arrangement and connection of electric circuit.

Furthermore, through a special pattern design and combination of PU materials in different colors, aesthetic products can be developed catering to different consumer preferences. Therefore, this prototype can facilitate the transfer of the proposed technology into a practical application. Most importantly, the specification sheet of this prototype can be developed, as shown in Figure 11, which can help to facilitate mass production.

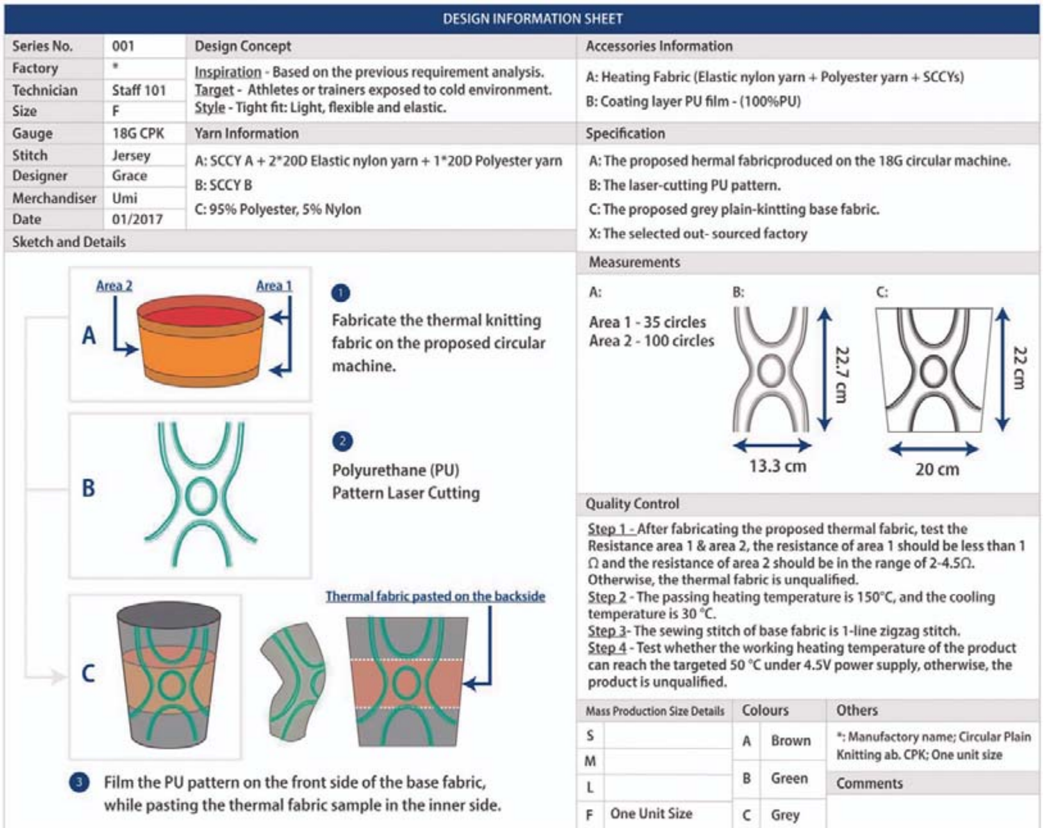

Figure 11. Specification sheet for prototype development.

Conclusion

With different lines of elastic yarns laid-in (different elasticities) and sheathed onto tubes of different sizes (different levels of extensions), the resulting values for electrical resistance, response speed, thermal effect, energy consumption, as well as the inner relationships among these parameters, were investigated. It was found that with two lines of elastic yarns, the proposed thermal fabric could have a faster response, better thermal effect, lower energy consumption, and more stable support provided by higher contact pressure. Furthermore, when the thermal fabric was stretched gradually, the heating temperature dropped, while with two lines of elastic yarns laid-in, this drop was negated. To apply this finding to a practical application, following the same knitting sample development method, *R* and thermal effect can be predicted once the contact pressure is known. This not only saves time and resources for research and development, but also ensures the accomplishment of the product requirement.

The prototype developed can be used as a kneecap guard or an elbow guard, and can be utilized on different occasions. A specification sheet was drawn up accordingly to instruct mass production. This can positively promote the transfer of the proposed research textile technology into a practical industrial application. It may offer a comfortable, light, flexible, thermal product for athletes, and reduce injuries related to cold climate. Additionally, this design integrated two separate fields—electrical engineering and textile science—and contributed to a new direction for product development. This design research methodology is thus illustrated in the flowchart shown in Figure 12 to promote the transfer of wearable electrical-thermal technology into a real application.

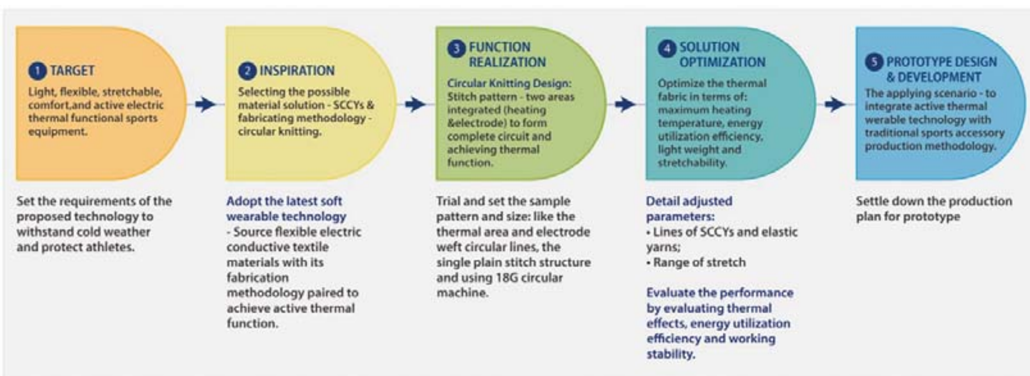

Figure 12. Design research flowchart of light and flexible electrical-thermal technology and customization for certain prototype R&D, with every key point elaborated.

Further possibilities

In addition to the example of a kneecap guard, the proposed technology and thermal model can also be applied to other sportswear developments, such as outerwear, sports socks, sports gloves, leggings, shorts, tanks, and so on. This shows the potential to increase the growth of the industry in a market that is attracting new manufacturers. Moreover, the power supply system, crucial for this kind of wearable thermal textile product, needs to be as small and light as possible. Therefore, the perfect coordination between textile and battery should be further studied. In general, the future is promising for this wearable thermal textile technology.

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