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Changes in characteristics of silver conductive fabrics owing to perspiration and washing

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The original appearance and physical properties of smart clothing as well as the electrical properties of the conductive fabric applied, despite utilization and the management environment, need to be maintained. Previous research has only investigated the washability and functional changes of smart textiles according to the environment from the perspective of sensors and fabric material; however, they have not comprehensively considered actual usage conditions. In this study, changes in the appearance, color, chemical components, wettability, and electrical properties of silver-coated conductive knitted fabrics due to exposure to perspiration and washing were investigated based on the manufacturing methods of conductive fabrics. The conductive knitted fabric exposed to perspiration exhibited the most prominent color change, and the surface became rough and hydrophilic as AgCl and AgO were formed through a chemical reaction between perspiration and silver. In contrast, the conductivity of the fabric was enhanced by the release of Ag^+ ions *via* perspiration. After washing, the silver layer on the surface of the conductive knitted fabric peeled off due to the interference and friction between the fabrics caused by the mechanical force generated during the cleaning process. There was no obvious chemical change, but the contact angle decreased as the nano-roughness decreased owing to the removal of silver particles. The conductivity slightly increased after washing but did not show a significant difference at 10% elongation. Finally, as the frequency of exposure to perspiration and washing increased, the silver layer coating the fiber or fabric surface peeled off and was damaged, resulting in a significant color change. Additionally, the chemical composition of the silver layer was significantly altered by perspiration and water and became hydrophilic. Surface resistance also increased linearly as the frequency of exposure to perspiration and washing increased. In terms of hand value, softness and smoothness decreased, and warmness increased after several cycles. Under all conditions, the conductive fabric with silver-coated yarn maintained a more optimized appearance and electrical properties than the silver-coated fabric according to the manufacturing method. Therefore, conductive yarn is more suitable for manufacturing conductive knitted fabrics for smart clothing in terms of durability. Additionally, specific management plans based on the actual use and environment of smart clothing using conductive knitted fabric are urgently needed.

1. Introduction

The demand for smart textiles is rapidly growing. The sportswear industry is one of the first industries to utilize this growing smart textile technology. There are several smart textile products from major sportswear brands, most of which are experiencing exponential growth.[1] Smart sportswear refers to wearable e-textile products or smart clothing designed to be worn on or close to the body.[2,3] This could potentially drastically change the way athletes are trained and monitored physiologically, ultimately improving their performance during games.[1,4,5]

Numerous studies on e-textile prototypes are underway, and a few products are available in laboratories worldwide; however, these products have limitations. Reliability is a major hurdle to their commercial launch.[6] If e-textile products are completely integrated into a fabric structure, they must be washable and reusable to gain market acceptance in the market and attract customers.[7] This means that similar to fabrics without an integrated system, smart clothing must be washable or cleanable, as they can get stained during use.[2,8] Smart sportswear, which is currently the most commercially available, is exposed to mechanical and chemical environmental changes owing to the intense physical activity of the wearers, and undergoes frequent washing and drying to remove the consequent high amount of perspiration and body odor. Even so, the

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performance and appearance of smart clothing should not deteriorate or change because of perspiration by athletes during physical activity or due to management procedures such as washing, drying, and storage.

Silver-coated nylon yarn is the most commonly used smart textile material for wearable e-textile products. Although silver-coated nylon yarns exhibit excellent electronic properties, they are easily damaged and susceptible to environmental factors such as moisture and perspiration, and can be relatively easily corroded.[7–9] During the life cycle of smart clothing with a silver-coated conductive fabric, silver may undergo various chemical changes that can limit its conductivity in the air and moisture in its environment, perspiration from the human body, or the washing process.[5,10] Therefore, identifying the moisture- and perspiration-induced changes and ensuring the corrosion resistance of silver-coated fabrics are important for applications such as smart sportswear in wet environments and during contact with perspiration.[7]

Currently, the change in electrical resistance is measured through repeated washing to evaluate the performance and reliability of functional implementation of smart textiles. There are several standard test methods for washing smart textiles. In this study, samples were washed using the general washing methods specified in ISO 6330, and the reliability of the electrical properties was evaluated by measuring the surface resistance using the methods specified in AATCC 76 or AATCC 84. However, because basic information on the general wearing environment for smart clothing is lacking, washing evaluation is mostly based on the conclusion drawn by researchers.[2] Gaubert et al.[11] evaluated the effect of washing on silver-plated textile electrodes. Evaluation of the appearance and function of the smart electrode after washing showed that liquid detergent had less effect on the electrode performance than powder detergent. In addition, bleach oxidizes and destroys the silver layer, maximizing the effect of mechanical friction during washing. Previous studies suggested that the silver-plated nylon electrode loses its conductivity owing to necessitates the identification of suitable washing conditions. Chui et al.[7] simulated the actual environment of silver-coated nylon fibers or fabrics and evaluated their functional stability according to environmental conditions. In particular, a washing and drying environment is created during clothing production. When the adhesion between the fibers and silver particles was attenuated, the silver layer on the fiber surface peeled off, even after washing 10 times, causing damage to the appearance and poor performance.

However, most previous studies on changes in the physical properties and functions of smart fabrics based on the actual wearing environment by monitoring physical activity, to which smart clothing is applied, are related to perspiration. Tajin et al.[9] manufactured a smart antenna from silver-coated nylon yarn, and evaluated the performance of the smart antenna according to perspiration, washing, and drying conditions to apply it to clothing. They found that it was difficult to maintain the performance of silver because the resistance increased owing to changes in the chemical composition caused by perspiration and friction during washing. Therefore, based on

these results, researchers have proposed further research to improve the durability of antenna performance in a dynamic environment. Yan et al.[12] observed the chemical changes in fabrics coated with silver upon exposure to an artificial perspiration solution. They mixed salt, acid, and alkali by adjusting the pH of artificial perspiration and immersed fabric in this solution to evaluate the consequent changes in silver ion release, surface shape change, and chemical composition. Their results showed that the release behaviour of the silver particles varied according to the pH of the solution, and the environmental and human risk increased with the release of silver ions in an environment with high ionicity. These results can be applied to silver-based smart fabrics.

Previous studies have only investigated the washability and functional changes of smart textiles according to the environment from the perspective of sensors and fabric material. However, they have not comprehensively considered actual usage conditions. Smart clothing is in close proximity to the human body; therefore, chemical and physical changes can affect the human body. In particular, it is necessary to consider the chemical changes in smart textiles caused by sebum and perspiration from the human body. Additionally, clothing products must undergo essential management processes such as washing and drying. Therefore, it is necessary to accurately understand the changes in conductive materials by mimicking the actual wearing and management environment of smart clothing and observing the changes in physical properties and functionality when they are repeatedly exposed to perspiration and washing. Furthermore, it is necessary to identify acceptable changes in physical properties and appearance by comparing and analysing these results with changes in general textile materials, and propose practical usage and management methods.

The purpose of this study was to analyze and compare changes in the physical, chemical, and electrical properties of smart fabrics and common fabrics applied to representative smart clothing products owing to repeated exposure to perspiration and washing. In this study, changes in the appearance, color, chemical composition, electrical properties, and tactile properties of conductive knitted fabrics with silver coatings and common knitted fabrics were examined and compared in relation to changes in chemical and physical environments such as perspiration and washing. This was aimed at elucidating the behavior of smart textiles under each environmental condition and acquiring basic data to ensure product quality reliability and develop management measures for future commercialization by comprehensively exploring the scope and environment of smart textiles.
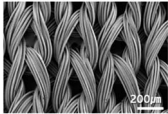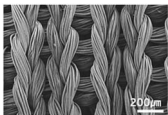
2. Experimental section

2.1. Materials

Five fabrics were prepared as listed in Table 1. Conductive fabrics were prepared in two forms: two fabrics were dip-coated with a silver solution in the fabric state, and one fabric was dip-coated with a silver solution in the yarn state and knitted with nylon yarns. Notably, common knitted fabrics are prepared

Table 1 Prepared conductive and common knitted fabrics

	Composition (finishing)	Weight (g m^{-2})	Thickness (mm)	Gauge (wale × course)	Appearance (mag. ×150)
C1	100% nylon (silver coating fabric)	100	0.15	24 × 47	
C2	85% nylon, 15% spandex (silver coating fabric)	200	0.28	76 × 115	
C3	55% silver-coated nylon, 45% nylon	175	0.20	54 × 57	
K1	56% PTT, 44% polyester	209	0.25	58 × 31	
K2	80% nylon, 20% spandex	204	0.21	74 × 49	

using two types of knitted fabrics based on polyester and nylon, which are primarily used in sports and fitness wear. The structures of all the fabrics were tricot-warp knitted fabrics.

2.2. Test procedure

2.2.1. Immersion in perspiration fluid. Perspiration powder (ISO W 04 Powder A, pH 5.5, Test Fabrics) was used as the repa-ration fluid, and consisted of L-histidine monohydrochloride monohydrate, sodium chloride, and sodium dihydrogen phos-phate dihydrate. To prepare the perspiration fluid, 7.7 g of perspiration powder was dispersed in 1 L of distilled water. The fabric was subjected to the color fastness test using the perspira-tion standard method (KS K ISO 105-E04), where it was immersed in the prepared perspiration fluid for 15 min to fully absorb it. To remove any excess perspiration fluid from the fabric, it was placed between two perforated acrylic plates (30 × 30 × 5 cm) and sub-jected to 5 kg of pressure for 30 min. After immersion, the samples were dried at room temperature for 24 h.

2.2.2. Washing process. The fabric samples were immersed in perspiration fluid, and 14 pieces of IEC 60456 pillowcases were placed in a front-loading washer (24 kg, DC68-03055A-04, Samsung Electronics, Republic of Korea) to adjust to a 4 kg load. The detergent was added by dispersing 49.25 g of the IEC 60456 reference detergent A* detergent powder in 800 mL of distilled water. Washing was performed in the standard cycle (washing for 16 min, rinsing for 25 min, and dehydrating for 20 min), and the temperature of the washing water was set to 40 °C. After washing, the samples were dried at room temperature for 24 h.

2.2.3. Immersion in perspiration fluid and washing process. After immersion in the perspiration fluid using the method described above, the samples were dried at room temperature for 24 h and subsequently washed. After washing, the samples were dried at room temperature for another 24 h. This process was repeated one, five, and ten times. In all conditions, the sample size was prepared as 10 × 10 cm, except for the condition involving ten washes with perspiration fluid immersion, where an additional sample measuring 30 × 30 cm was prepared to measure the hand value.

As shown in Table 2, the experimental conditions included the untreated condition, immersion in perspiration fluid only, washing only, and controlling the number of immersions in perspiration fluid and washes.

2.3. Characterization

2.3.1. Appearance. The surface morphologies of the conductive knitted fabrics were observed using a field-emission scanning electron microscope (FE-SEM, Merlin Compact, Zeiss, Germany) after perspiration or washing. To prevent the samples from charging, their surfaces were coated with a layer of plat-inum using a sputter coater (108 Auto, Cressington Scientific Instrument Ltd, UK), with the current maintained at 10 mA for 200 s.

2.3.2. Chemical properties. The chemical compositions of the sample surfaces before and after exposure to the perspira-tion fluid were characterized using an energy-dispersive X-ray microanalysis system (EDX, Ultradry, Thermo Scientific, USA) coupled with FE-SEM.

Table 2 Experimental conditions according to perspiration fluid and washing process

	Frequency of immersion in perspiration fluid	Frequency of washing	Cods
Untreated	—	—	UT
Immersion in perspiration fluid	1	—	P1
Washing	—	1	W1
Immersion in perspiration fluid and washing	1	1	P1W1
	5	5	P5W5
	10	10	P10W10

Furthermore, the overall chemical composition of the sample and the chemical properties and bonding state of Ag for each treatment were examined using an X-ray photoelectron spectrometer (Versaprobe III, PHI, USA). To analyze the quantity of Ag, the binding energy was measured from 0 to 1000 eV. Additionally, CasaXPS software (Casa Software Ltd, Version 2.3.25) was used to fit the peaks for analysis of the chemical bonds of Ag.

A contact angle analyzer (Theta Lite Optical Tensiometer, KSV Instruments, Finland) was used to evaluate the hydrophobic or hydrophilic properties of the conductive knitted fabrics after exposure to perspiration fluid or washing. The samples were attached to a slide glass using a 3 M tape, and a 3.5 ± 0.3 μL drop of deionized water was deposited on the surface to be investigated. The contact angle of the water droplet was recorded 1 s after deposition. Ten different sites on each sample were measured, and the average value was calculated.

2.3.3. Conductivity. The sheet surface resistivities of the conductive knitted fabrics were measured using a DC milliohm meter (GOM-804, GW INSTEK, Taiwan) in accordance with AATCC 76-1995. The final surface resistivity was obtained by averaging five measurements taken at different positions.

The linear electrical resistance of the conductive fabric was also measured using a DC milliohm meter. The fabric samples measured 10×10 cm in the wale and course directions. The sample was supported at a distance of 1 cm using two alligator clips, and the initial resistance value was measured. Subsequently, the sample was stretched to observe the change in resistance based on the elongation rate. The fabric resistance was tested at 10% elongation in the wale and course directions, respectively. Three samples were tested, and the average electrical resistance was calculated. Additionally, the percentage change in fabric resistance, tested at 10% elongations, was calculated as shown in eqn (1) below.

$$\text{Change of fabric resistance} = \frac{R_e}{R_o} \times 100 \qquad (1)$$

where R_o is the value of the fabric resistance without elongations (Ω m^{-2}), R_e is the value of the fabric resistance with 10% elongation in the wale or course directions of the samples (Ω m^{-2}).

2.3.4. Color difference (ΔE). The L^*, a^*, and b^* values were measured using a spectrophotometer (CM-2600d, Konica Minolta Sensing Korea Co., Ltd, Republic of Korea) to analyze the color change of the conductive and common knitted fabrics

through immersion in perspiration and washing processes. To compare the color difference with the untreated fabric, the untreated fabric was designated as the target, and the L^*, a^*, and b^* values of the sample were measured for each condition. The color difference (ΔE) was calculated using eqn (2). Three samples were tested, and four measurements were taken for each sample. The average value was derived from the 12 measurement values obtained from all three samples.

$$\Delta E = \sqrt{\left(\text{dL}^*\right)^2 + \left(\text{da}^*\right)^2 + \left(\text{db}^*\right)^2} \qquad (2)$$

dL* = sample L^* − target L^*(UT), da* = sample a^* − target a^*(UT), db* = sample b^* − target b^*(UT).

3. Results and discussions

3.1. Changes in characteristics of conductive fabrics due to perspiration

3.1.1. Appearance. Clothing is closest to the human body, and thus directly exposed to secretions such as perspiration. Therefore, considering the exposure of clothing material to perspiration, it is most important to maintain durability without changing its appearance and functionality. In particular, perspiration from a healthy person during exercise is slightly acidic with a pH of 4.5–6.5; therefore, conductive fabrics applied to sportwear must exhibit durability in acidic solutions.[13] Changes in the appearance of conductive fabrics due to the reaction of silver with perspiration were investigated using a simulated perspiration solution. After immersing the conductive fabrics and common knitted fabrics once in an acidic perspiration solution and drying them, the fabric surfaces were observed using FE-SEM, and the color change was measured.

Fig. 1 shows FE-SEM images of each sample before and after immersion in the perspiration solution. In the conductive fabrics shown in Fig. 1a–c, there are numerous grains on the surface of the fibers, which may have resulted from the formation of salts upon exposure to acidic perspiration. The conductive fabric used in this study was coated with Ag in the yarn or fabric state. Acidic perspiration can result in a fast release rate and a significant release of silver.[12] Silver can be corroded by a NaCl solution because a few Ag$^+$ cations on the surface of the silver coating and Cl$^-$ in the NaCl aqueous solution form AgCl, and AgCl continues to react with Cl$^-$ anions in the NaCl aqueous solution and forms [AgCl$_2$]$^-$ complexes, which lead to the dissolution of silver.[7] Additionally, when Ag
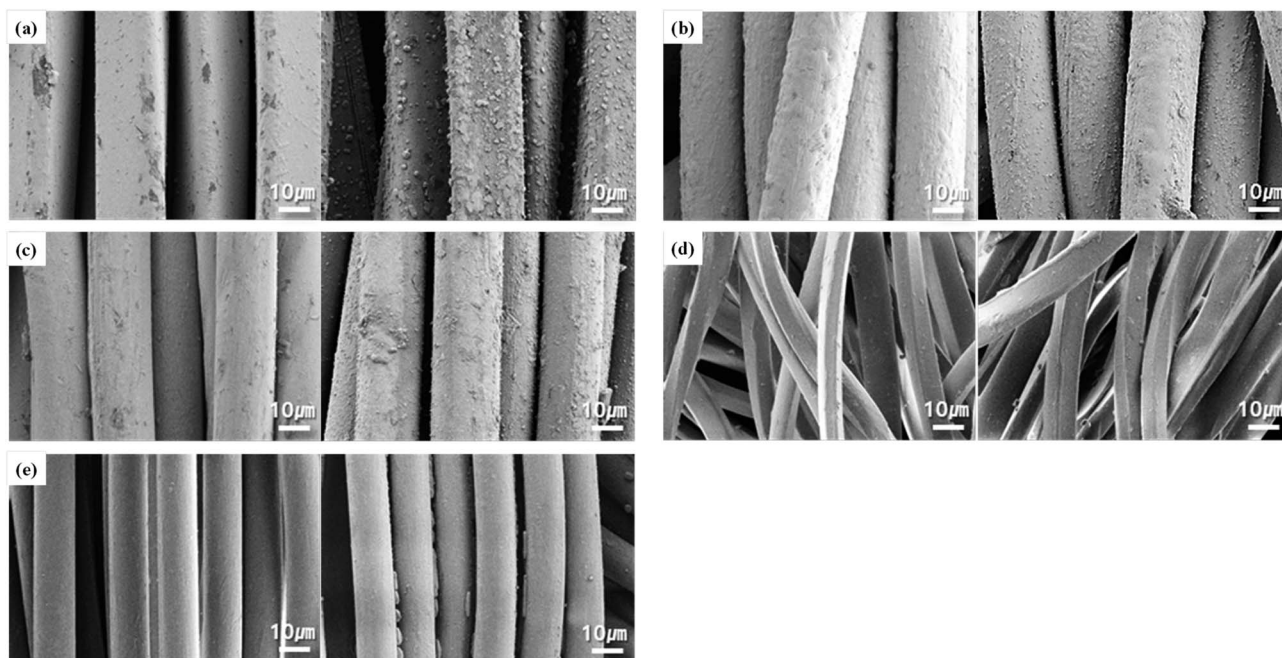
Fig. 1   FE-SEM images (×3000) of the fabric surface before and after immersion in perspiration solution: (a) C1; (b) C2; (c) C3; (d) K1; (e) K2.

reacts with salt, it undergoes a double substitution reaction to form an insoluble precipitate.[14] Therefore, the substance observed on the fiber surface in Fig. 1a–c is a precipitate. To confirm the formation of these grain components by the reaction of the conductive knitted fabric with perspiration, a quantitative analysis of the surface elements was performed using EDX, and the results are shown in Fig. 2. EDX analysis of the grains created on the surface of the conductive fibers showed the presence of C, O, Ag, Cl, and Si. C and O were detected in the fibers, and a large amount of Ag was confirmed owing to the silver coating. Si was used as a crosslinking agent to attach silver to the fiber surface. Na and Cl were not included in the fiber or silver coating agent. Therefore, they were obtained through perspiration. The Na detected in C1 and C3 (Fig. 2a and c) resulted from the recrystallization of substances that did not react or were removed after immersion in the perspiration solution into NaCl. Additionally, Cl is confirmed where silver and grains are gathered on the fiber surface. Therefore, EDX analysis confirmed that the chemical change from silver to AgCl and $AgCl_2$ was due to perspiration. Chui et al.[7] observed white grains of the same shape on the surfaces of silver-coated nylon yarns immersed in a 0.5% NaCl solution. Particularly, the conductive fabric of C1 showed a larger and clearer formation of deposits than that of C2 despite the use of the same coating method involving post-coating in a silver bath in fabric state. This is because the space between the loops in C1 is larger, resulting in a lower density than the other conductive fabrics, which is more advantageous for salt formation through the permeation of perspiration. The degree of perspiration penetration into the pores between fabrics, yarns, and fibers depends on the porosity of the weaving or knitting method. This leads to a difference in tortuosity, which affects the flow of fluid

and may cause variation in water absorption between yarns and fibers.[15] In the case of C3, which is a mixture of conductive yarns and nylon yarns, the silver content is low compared to that of C1 and C2; therefore, the grains formed by the reaction with perspiration are relatively small.

In contrast, no change was observed on the fiber surface in knitted fabrics (d) and (e). This is because the common knitted
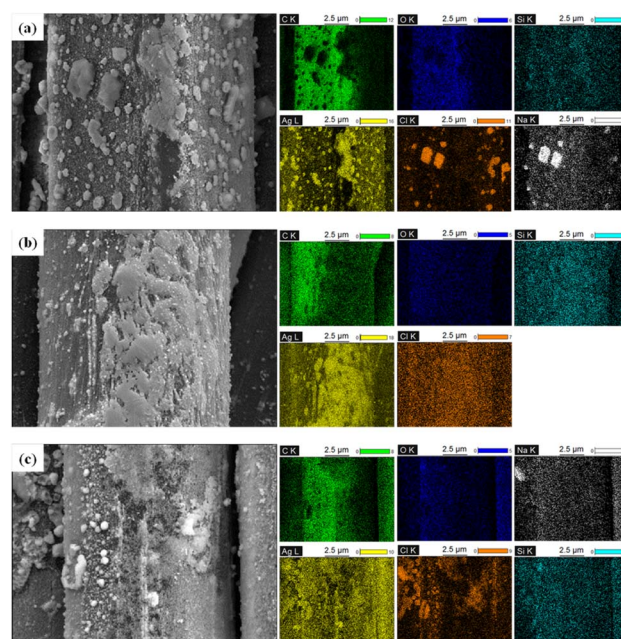

Fig. 2   FE-SEM images (×10 000) and EDX mapping images of grains on the conductive knitted fabrics after exposure to the perspiration: (a) C1; (b) C2; (c) C3.

fabric does not contain substances that can chemically react with perspiration. In the case of the K2 sample, some solid materials were observed in the space between the fibers, which corresponded to the solidification of perspiration. K2 is composed of filamentous nylon fibers, allowing capillaries to be form between the fibers. Perspiration fluid is absorbed and transferred into the fabric through these capillaries. The perspiration fluid excessively adsorbed on the surface of the fiber solidified and were not removed during the drying process. When conductive fabrics and common knitted fabrics were exposed to perspiration, the color difference that may occur due to a chemical reaction with perspiration was analyzed by observing the appearance and calculating ΔE. The results are as shown in Fig. 3 and Table 3.

As a result of the observation, the color change of the conductive fabric due to exposure to perspiration could be confirmed with the naked eye, while the common knitted fabric showed a similar color, as shown in Fig. 2. According to Table 3, the L^* values of all samples decreased and became somewhat darker, and the a^* and b^* values increased, resulting in stronger red and yellow colors. The results indicated a brownish tendency. Overall, the color change of the conductive fabrics was more pronounced after immersion in perspiration than that after immersion of common knitted fabrics in perspiration. When the fabric is immersed in water, its surface becomes negatively charged. Acidic perspiration provides a good binding force with these negatively charged fabrics, allowing them to penetrate the fibers more easily.[16] Therefore, the more the perspiration penetrates the fibers, the more active the reaction with the silver deposited on the surface of the conductive fabrics, resulting in a distinct color change.

Among the conductive fabrics, especially C2 showed a significant color change after immersion in perspiration, and the ΔE value was also the highest. Compared with C1, which was coated with silver using the same method, the color change of C2 was notable. This was because the silver particles were highly reactive to acidic perspiration, and the spandex yarns blended in C2 were very vulnerable to perspiration. Spandex fibers are composed of urethane groups (–NH–CO–O–) and thus have many amino groups (–NH$_2$). Therefore, spandex can be dyed using acid dyes.[17] Based on this dyeability, spandex cause a color change through a reaction with acidic perspiration. In contrast, C3 exhibited the lowest color change and excellent durability. This is because C3 was not entirely coated with silver

Table 3 Color difference of the fabric according to exposure to perspiration

		L^*	a^*	b^*	ΔE
C1	Before	54.93 ± 0.57	0.73 ± 0.07	4.90 ± 0.32	4.94 ± 1.94
	After	51.09 ± 1.90	1.96 ± 0.20	7.64 ± 0.74	
C2	Before	56.56 ± 1.23	-0.09 ± 0.22	5.42 ± 0.24	9.65 ± 0.72
	After	55.40 ± 1.53	4.03 ± 0.10	13.77 ± 1.00	
C3	Before	60.98 ± 0.76	0.50 ± 0.10	5.28 ± 0.29	1.97 ± 0.54
	After	59.77 ± 0.88	1.24 ± 0.18	6.53 ± 0.34	
K1	Before	91.30 ± 0.23	6.81 ± 0.08	-17.98 ± 0.45	0.71 ± 0.46
	After	91.22 ± 0.17	6.72 ± 0.08	-17.81 ± 0.43	
K2	Before	92.08 ± 0.58	3.74 ± 0.06	-14.63 ± 0.55	1.67 ± 0.58
	After	91.35 ± 0.30	3.59 ± 0.18	-13.41 ± 0.68	

in the fabric state but was composed of 55% silver-coated nylon yarns and 45% normal nylon. Conductive yarns coated in the yarn state form a more uniform silver layer and stably bond with the fibers compared to conductive fabrics coated in the fabric state.[18,19] Additionally, because the amount of silver exposed to the surface is small, chemical reactions or changes due to perspiration may be relatively small.

However, the color change due to exposure of common knitted fabrics to perspiration was difficult to distinguish with the naked eye, and the ΔE value was relatively low. C3, which showed the lowest color change among the conductive fabrics, exhibited an ΔE value similar to that of K2. That is, as it is difficult to distinguish this level of color difference with the naked eye, C3 may be suggested as the most suitable for use in clothing among conductive fabrics in terms of appearance changes.

3.1.2. Chemical properties. XPS was performed to analyze the chemical composition of the conductive fabrics after exposure to perspiration. Table 4 presents the atomic concentrations of C, O, Cl, and Ag detected on the conductive fabric surfaces before and after exposure to perspiration. The small amount of detected Cl in the untreated samples of C1 and C2 is presumed to originate from the components of the medium used in the silver coating process. In all three conductive fabrics, the concentrations of C and Ag decreased, while those of O and Cl increased after exposure to perspiration. This change can be attributed to the oxidation of silver on the fabric surface or its reaction with the NaCl in the perspiration solution, resulting in the formation of AgCl. These characteristics were more pronounced in C1 and C2, which were coated with silver in the fabric state. However, in the case of C3, the change was
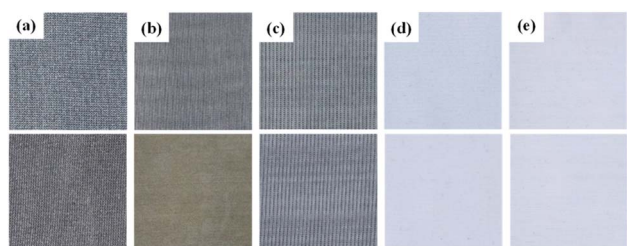

Fig. 3 Appearance of the fabrics following exposure to perspiration: (a) C1; (b) C2; (c) C3; (d) K1; (e) K2.

Table 4 The atomic concentration of the fabric according to exposure to perspiration

Composition	C1 Before	C1 After	C2 Before	C2 After	C3 Before	C3 After
C12	55.43	52.20	53.71	51.98	68.76	69.26
O12	16.27	25.99	19.70	29.75	29.28	28.65
Cl2p	1.39	2.11	0.88	1.85	0.00	0.29
Ag3d	26.91	19.70	25.71	16.42	1.96	1.80

relatively small owing to the lower silver content exposed on the surface. This was because C3 was coated with silver in the yarn state and then interknitted with the nylon yarn, resulting in a smaller change compared to C1 and C2.

Fig. 4 shows the XPS spectrum of Ag 3d for each conductive knitted fabric sample. The Ag $3d_{5/2}$ and Ag $3d_{3/2}$ core-level binding energies for all conductive fabrics appear at 368 and 374 eV, respectively, in good agreement with bulk Ag, indicating that Ag is bound to the fabric surface.[20,21] These two bands shift to lower energies in all three samples after exposure to perspiration. This shift is caused by electron transfer from the silver layer to the perspiration solution. The binding energy of the higher ionic state of Ag is lower than that of zero-valent Ag because of shifts in the initial state potential of the ionic charge and the lattice potential.[20] Additionally, new peaks appear at approximately 367 and 373 eV after perspiration, particularly for C1 and C3. The peaks at 368 and 374 eV can be assigned to the Ag 3d peaks of metallic Ag, whereas those at 367 and 373 eV can be ascribed to the Ag 3d peaks of Ag^+ in AgCl.[22,23]

In contrast, according to the contact angle measurement results in Table 5, the common knitted fabrics (K1 and K2) were immediately absorbed as soon as the water droplets fell and exhibited hydrophilic properties. PTT, nylon, and polyester are naturally hydrophobic fibers by nature.[24] However, the density of the common knitted fabrics used in this study was quite low, and water easily penetrated through capillary action. Conversely, the conductive knitted fabrics (C1, C2, and C3) exhibited

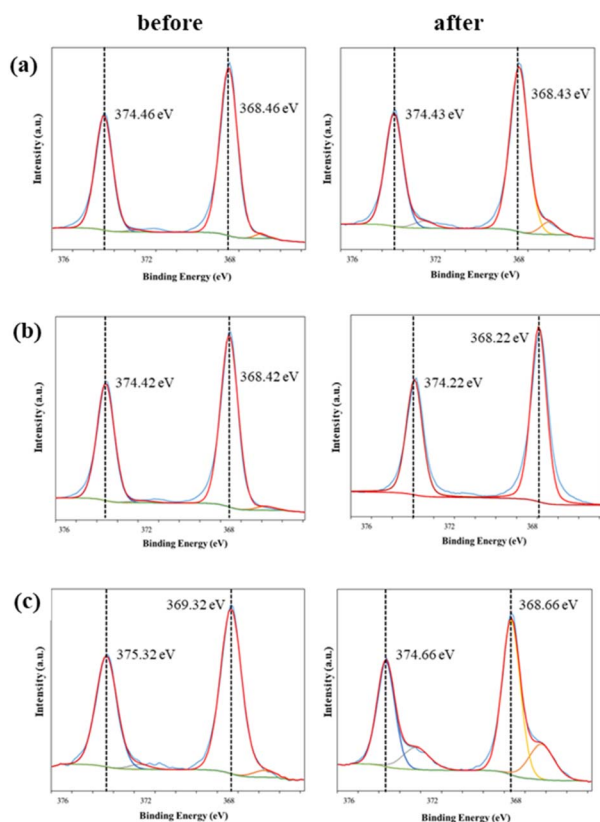**Fig. 4** Ag 3d XPS spectra of the conductive fabrics according to exposure to perspiration: (a) C1, (b) C2, and (c) C3.

Table 5 Contact angle of the fabric according to exposure to perspiration

	C1	C2	C3	K1	K2
Before	123.5 ± 4.3	135.1 ± 5.3	143.1 ± 3.8	0.0 ± 0.0	0.0 ± 0.0
After	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

hydrophobicity at approximately 130° by reducing the contact angle area between water and fibers, as well as voids on the fabric surface due to the micro–nano dual roughness caused by the yarn and silver coating.[24,25] After exposure to perspiration, all the samples became hydrophilic, with a contact angle of 0°. As metal oxides are capable of strong hydrogen bonding, their surfaces are typically completely wetted by water.[26] Additionally, artificial perspiration absorbed into the fabric forms a heterogeneous solid surface, leading to the absorption of water droplets.[25] Therefore, the oxidation and chemical changes in silver following exposure to perspiration can be confirmed through the contact angle measurements.

3.1.3. Conductivity. Changes in the electrical properties of the conductive fabrics upon exposure to perspiration were investigated, specifically focusing on changes in surface resistance and linear resistance with respect to elongation. Table 6 presents the surface resistance values of the conductive fabrics before and after exposure to perspiration, measured in the wale and course directions. The surface resistance decreased in all samples after exposure to perspiration, indicating an improvement in electrical properties.

Silver is highly soluble in acidic solutions. Yan et al.[12] reported that when silver nanoparticle-coated nano fabric was immersed in an acidic artificial perspiration solution, a significant number of Ag^+ ions was detected as silver was released. These dissolved Ag^+ ions react with NaCl during perspiration, forming AgCl. However, as the conductive fabric used in this study had a compact silver coating, the silver coating became more apparent even with a small amount of silver dissolved through perspiration. This phenomenon was the main reason underlying the decrease in surface resistance.[7] The effect was more pronounced in the wale direction, as the electron flow in this direction is smoother and more networked owing to the arrangement of loops. Conversely, the course direction in the warp-knitted fabric introduced contact resistance.[11]

Table 6 Surface resistance of the conductive fabrics according to exposure to perspiration

		Wale ($\Omega \ m^{-2}$)	Course ($\Omega \ m^{-2}$)	Average ($\Omega \ m^{-2}$)
C1	Before	0.39 ± 0.06	0.38 ± 0.04	0.38 ± 0.05
	After	0.27 ± 0.04	0.38 ± 0.04	0.32 ± 0.07
	Change%	**44%**	**0%**	**19%**
C2	Before	0.35 ± 0.06	0.35 ± 0.05	0.35 ± 0.05
	After	0.31 ± 0.05	0.30 ± 0.05	0.31 ± 0.04
	Change%	**13%**	**17%**	**13%**
C3	Before	0.36 ± 0.06	0.46 ± 0.07	0.41 ± 0.08
	After	0.27 ± 0.04	0.42 ± 0.04	0.35 ± 0.08
	Change%	**33%**	**10%**	**17%**

Meanwhile, no difference was observed between the C1 or C2 samples, both of which were coated with silver on the fabric surface after knitting, and the C3 sample, which was knitted after applying a conductive yarn with a silver coating. The reason behind this lack of difference is that the silver layer exposed on the yarn or fabric surface chemically reacts with perspiration, regardless of the coating method.

Fig. 5 shows the linear resistance values of the conductive fabrics before and after perspiration, which were measured in their original and elongated states. All samples showed lower linear resistance, regardless of the direction, when elongated by 10% compared to the original state. However, in the case of C2, a higher linear resistance was observed when stretching in the course direction because the spandex fiber was inserted. Owing to their structural characteristics, knitted fabrics have excellent stretchability.[27] Spandex, contrastingly, is elastic because the soft segment is deformed by an external force owing to its polymer structure composed of soft and hard segments.[28,29] Therefore, the linear resistance increased as the silver layer on the surface was partially damaged, as the fiber, and not the fabric structure, was stretched during elongation in the course direction.

Conversely, the linear resistance of each sample decreased or remained the same after exposure to perspiration, and there was no significant difference from before exposure to perspiration at 10% elongation. As observed in the surface resistance results mentioned above, Ag^+ ions were eluted as perspiration and silver reacted, which made the compact silver layer clearer and improved conductivity. This trend was more clearly observed for C2. In the case of C2, the effect of the reaction between silver and perspiration was more pronounced, and the conductivity improved five times before and after exposure to perspiration in the elongation state. Meanwhile, the effect of Ag^+ ions caused by perspiration appeared to be relatively small in the other samples because the electrons flowed smoothly owing to the shortened electron transport distance as the loop expanded during elongation.[30]

3.2. Changes in characteristics of conductive fabrics by washing

3.2.1. Appearance. Washing is an essential process for comfortable and hygienic clothing. It involves the application of various complex forces using water and detergents to clothing materials. Therefore, the durability of washing is a major factor in determining the lifespan of clothing. According to Zaman et al.,[31] a washing cycle can be broken down into four damaging actions with possible interactions and interdependencies: mechanical stress (abrasion, flexion, and hydrodynamic flow), thermal stress (temperature), water stress, and chemical influence (detergent). In particular, it is important to not only consider changes in the appearance of conductive fabrics due to washing but also the deterioration of functions such as electrical conductivity. Checking these changes according to the washing of conductive fabrics is essential.

Fig. 6 displays SEM images of changes in the fiber surface after washing. In the case of conductive fabrics C1 and C2, which were coated with silver, the fiber surface was scratched, the silver-coated layer peeled off after washing, and damage to the fiber surface was evident. This is because the entire fabric was post-coated with silver, and the silver layer was removed owing to interference and friction between the fabrics caused by the mechanical force generated during the washing process. The mechanical force transmitted to the fabric during washing includes a large-scale force, which causes movement of the entire fabric; a medium-scale force, which is transmitted between yarns; and a small-scale force, which is transmitted between the fibers and causes damage to the fiber surface.[32] Therefore, the fabric is damaged by the friction between the fabric and the frictional force caused by the fall that occurs when the fabric rises from the drum by centrifugal force and then falls into in the drum-washing machine.

However, in the case of C3, the damage to the fiber surface was the least among the conductive fabrics. This indicates that the conductive fabric in C3 is made of silver-coated yarn and nylon yarn, and the area exposed to mechanical force from the washing machine is smaller compared to C1 and C2, which are
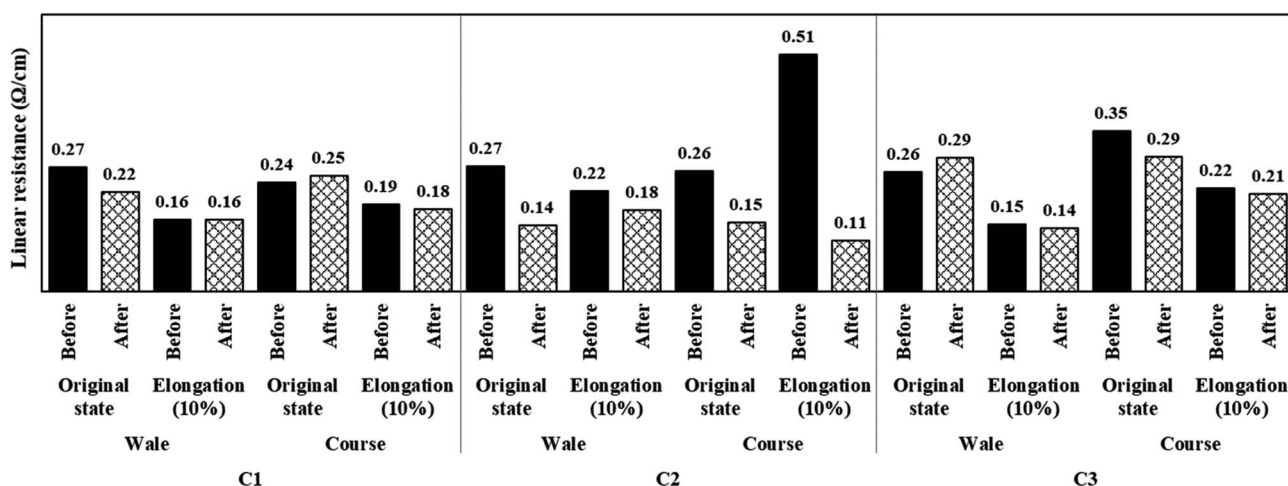

Fig. 5 Linear resistance in original and elongation state according to exposure to perspiration.
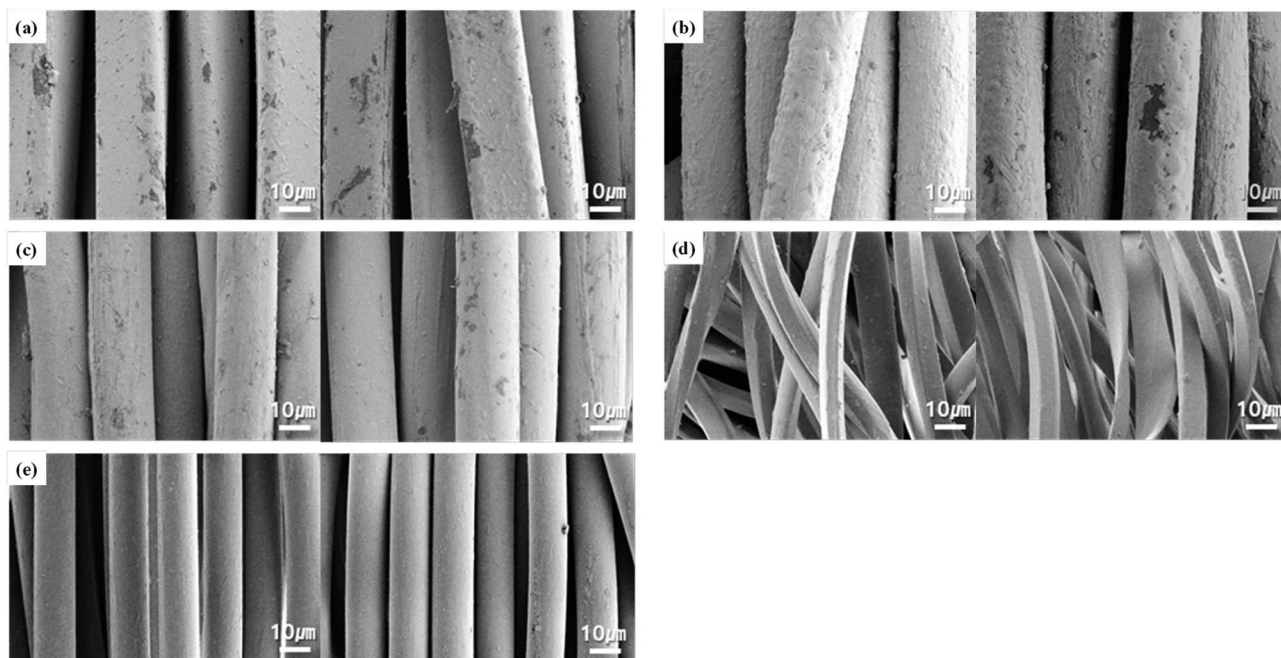
Fig. 6 FE-SEM (×3000) of the fabric surface before and after washing: (a) C1; (b) C2; (c) C3; (d) K1; (e) K2.

coated with silver in the fabric state.[33] Additionally, yarn is more flexible to mechanical forces than the fabric, resulting in less damage during washing. No damage to the fiber surface was observed in the common knitted fabrics, as shown in Fig. 6d and e. This is because the mechanical force was not sufficient to cause damage to the surface of the fabric after only one washing cycle.

Fig. 7 and Table 7 show the results of observations on the changes in appearance and the color difference between the conductive fabrics and common knitted fabrics before and after washing. In all the samples, there was no significant change in appearance after one washing cycle. The L^*, a^*, and b^* values decreased slightly, resulting in a decrease in brightness and a stronger bluish color. However, the color change was not significant. C2, which exhibited a significant color change when exposed to perspiration among the conductive fabrics, was not significantly affected by washing alone. Thus, it was confirmed that silver had some durability against washing, as there were no significant physical and chemical changes with respect to washing. However, desorption of some silver particles was observed even after one washing. If repeated washing occurs, desorption of the coating adsorbed on the surface is induced, leading to a potential decrease in conductivity.

3.2.2. Chemical properties. An XPS analysis was performed to determine the chemical composition of the conductive fabrics after washing. Table 8 presents the atomic concentrations of C, O, Cl, and Ag detected on the conductive fabric surfaces before and after washing. In C1 and C2, the concentrations of C and O increased, while the concentrations of Cl and Ag decreased after washing. This occurred because the coated silver layer detached from the fabric surface due to friction and dynamic behavior during the washing process. Benn and Westerhoff[34] discovered that ionic and particulate Ag could be released from conductive textiles when exposed to shaking water. In the case of C3, the concentration of Ag increased after washing. This can be attributed to the Ag particles separating from the conductive yarn during the washing process and adhering to a wider area on the fabric
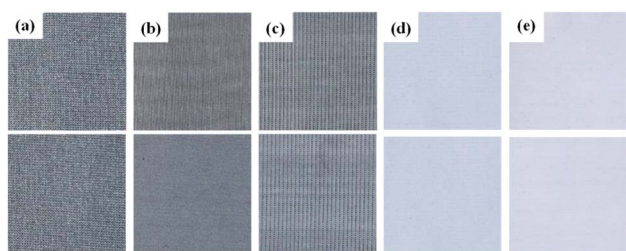

Fig. 7 Appearance of the fabric according to washing: (a) C1; (b) C2; (c) C3; (d) K1; (e) K2.

Table 7 Color difference of the fabric according to washing

		L^*	a^*	b^*	ΔE
C1	Before	54.93 ± 0.57	0.73 ± 0.07	4.90 ± 0.32	1.23 ± 0.46
	After	54.47 ± 0.88	0.57 ± 0.06	4.10 ± 0.17	
C2	Before	56.56 ± 1.23	-0.09 ± 0.22	5.42 ± 0.24	1.30 ± 0.60
	After	55.60 ± 0.73	0.04 ± 0.23	4.77 ± 0.17	
C3	Before	60.98 ± 0.76	0.50 ± 0.10	5.28 ± 0.29	1.81 ± 0.44
	After	61.76 ± 0.69	0.65 ± 0.06	3.86 ± 0.23	
K1	Before	91.30 ± 0.23	6.81 ± 0.08	-17.98 ± 0.45	0.85 ± 0.59
	After	91.19 ± 0.11	6.86 ± 0.12	-18.63 ± 0.33	
K2	Before	92.08 ± 0.58	3.74 ± 0.06	-14.63 ± 0.55	0.95 ± 0.44
	After	91.33 ± 0.17	3.52 ± 0.18	-14.11 ± 0.56	

Table 8 The atomic concentration of the fabric according to washing

Composition	C1		C2		C3	
	Before	After	Before	After	Before	After
C12	55.43	64.23	53.71	60.97	68.76	72.17
O12	16.27	17.08	19.70	19.24	29.28	24.25
Cl2p	1.39	0.97	0.88	0.85	0.00	0.00
Ag3d	26.91	17.72	25.71	18.94	1.96	3.57

surface, resulting in a higher Ag content within the measuring range.

Fig. 8 shows the XPS spectrum of Ag 3d for each conductive knitted fabric after washing. The binding bands representing Ag $3d_{5/2}$ and Ag $3d_{3/2}$ shift to lower energies after washing. This shift is the result of the slight oxidation of silver due to the detergent and water used during washing. The binding energies of AgO and Ag_2O are 367.4 eV and 367.8 eV, respectively.[35] In contrast, since no new peak was observed after washing, there was little change in the silver components, such as AgCl.

The detachment of the silver particles from the fiber surface after washing was also confirmed by the contact angle results. As shown in Table 9, the contact angles of all silver-coated conductive knitted fabrics decreased after washing. This is the result of the oxidation of silver, increased reactivity with water, and loss of nano-roughness due to the silver particles falling off.[24]
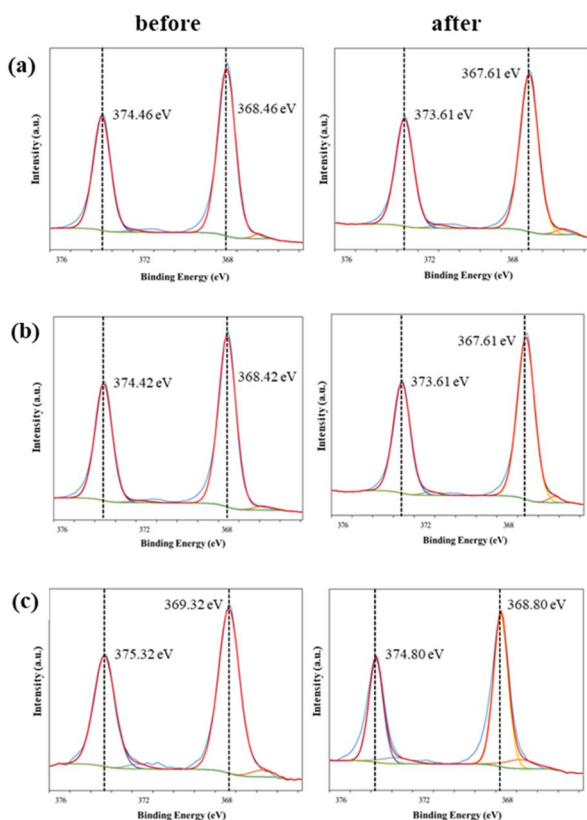

Fig. 8 Ag 3d XPS spectra of the conductive fabrics according to exposure to washing: (a) C1, (b) C2, and (c) C3.

3.2.3. Conductivity. The changes in the electrical properties of the conductive fabrics after washing were investigated in terms of surface resistance and linear resistance changes according to elongation.

Table 10 lists the surface resistance values of the conductive fabrics before and after washing measured in the wale and course directions, respectively. After washing, the surface resistance of all the samples increased, regardless of the wale and course direction. As confirmed by the FE-SEM image, this was because the silver layer on the surface of the conductive fabric was damaged owing to mechanical friction between the fabric and the drum wall of the washing machine during the washing process.[31] However, the change in conductivity after washing showed a trend similar to the change following exposure to perspiration, regardless of the coating method.

Fig. 9 shows the linear resistance values of the conductive fabrics before and after washing measured in their original and elongated states. The linear resistance of each sample increased or remained constant after washing. The largest change was observed in the C1 sample, which showed a linear resistance increase of approximately 20% or more with just one washing process in both the course and wale directions. This was because the silver coating layer on the fabric surface was partially damaged during the washing process. C2 was also coated using the same method as C1, but in the case of C2, owing to a higher gauge than C1, the pores were small and the adhesion between the silver layer and the fiber was large; therefore, the effect of washing on the mechanical behavior was relatively small. On the other hand, there was no significant difference from before washing at 10% elongation. As the loop was stretched owing to elongation, the electron movement path was shortened, and the electron flow was smoothed. In this process, damage to the silver layer due to washing did not have a significant effect on the linear resistance.

3.3. Changes in characteristics of conductive fabrics after repeated exposure to perspiration and washing

3.3.1. Appearance. To simulate the actual usage environment of smart clothing, changes in the appearance of conductive fabrics and common knitted fabrics after repeated exposure to perspiration and washing were investigated. Fig. 10 shows the results of observing the appearance of the samples after repeated immersion in the perspiration solution and washing cycles 1, 5, and 10.

In the case of conductive fabrics, the silver layer on the fiber surface was peeled off and damaged upon repeated exposure to perspiration and washing. A single cycle of exposure to perspiration and washing did not significantly damage the silver coating layer; however, after five cycles, the silver coating peeled

Table 9 Contact angle of the fabric according to washing

	C1	C2	C3	K1	K2
Before	123.5 ± 4.3	135.1 ± 5.3	143.1 ± 3.8	0.0 ± 0.0	0.0 ± 0.0
After	119.2 ± 2.7	116.0 ± 7.2	136.3 ± 10.7	0.0 ± 0.0	0.0 ± 0.0

Table 10 Surface resistance of the conductive fabrics according to washing

		Wale (Ω m^{-2})	Course (Ω m^{-2})	Average (Ω m^{-2})
C1	Before	0.39 ± 0.06	0.38 ± 0.04	0.38 ± 0.05
	After	0.47 ± 0.06	0.51 ± 0.08	0.49 ± 0.07
	Change%	**−17%**	**−25%**	**−22%**
C2	Before	0.35 ± 0.06	0.35 ± 0.05	0.35 ± 0.05
	After	0.44 ± 0.2	0.41 ± 0.09	0.43 ± 0.12
	Change%	**−20%**	**−15%**	**−19%**
C3	Before	0.36 ± 0.06	0.46 ± 0.07	0.41 ± 0.08
	After	0.52 ± 0.23	0.50 ± 0.11	0.51 ± 0.15
	Change	**−31%**	**−8%**	**−20%**

off or cracked, as shown in Fig. 10a–c, and was completely peeled off after 10 cycles, thus exposing the nylon fiber surface. In particular, compared to C3, which was coated with silver in the yarn state, C1, and C2, which were post-coated with silver in the fabric state, showed relatively greater damage from repeated exposure to perspiration and washing. This is because the coating layer on the fiber surface was loosened as the silver was oxidized owing to exposure to perspiration, and the mechanical force generated during the washing process was transferred to the fabric, causing movements such as tension, bending, and elongation in the fabric.[12,32] In the case of the fabric coated entirely with silver, all the yarns in the fabric were bent and stretched simultaneously, and the outermost surface-coated material fell off, causing more damage. However, in the case of C3, because the fiber was coated with silver, the fiber was flexible even when the entire fabric moved, resulting in relatively less damage and high durability.

In the common knitted fabrics K1 and K2, no change was observed on the surface of the fibers even after repeated exposure to perspiration and washing cycles because there was no separately treated material in the state of the fibers of the fabrics.

Fig. 11 and 12 show photographs and graphs of the color difference values of conductive fabrics and common knitted fabrics according to the frequency of exposure to perspiration and washing, respectively.

As shown in Fig. 11, a color change was observed in the conductive fabric as the frequency of exposure to perspiration and washing increased. C2 exhibited the largest color change and numerous stains on its surface. C1 and C3 also turned yellow and became more stained as the number of repetitions increased. Among the conductive fabrics, C3 exhibits the smallest color change. In the case of the common knitted fabrics, no color change was observed with the naked eye after repeated perspiration and washing.

According to the results in Fig. 12, the color difference increased compared to the untreated fabric as the frequency of exposure to perspiration and washing increased under all fabric conditions. The color differences according to repeated treatments were large, in the order of C2, C1, K2, C3, and K1. Among the conductive fabrics, C2, which was most vulnerable to perspiration, showed the highest color difference, whereas C3 showed minimal color change. This is because the effect of perspiration exceeded that of washing. In the results of the above examination, the fabric coated with silver in the fabric state showed the lowest durability when exposed to perspiration solution. Therefore, repeated exposure to perspiration caused a large color change as it caused continuous damage to the conductive fabric surface. In contrast, in the case of the common knitted fabrics, no color change was observed with the naked eye, but when compared through color difference values K2 showed a higher color difference value than C3, which is a conductive fabric. K2 has luster because it is thin, very flexible, and had a smooth surface, owing to the uniform arrangement of the fibers. Therefore, as the surface was worn by repeated washing cycles, the luster decreased, the L^* value decreased, and the overall color difference of K2 was higher than that of K1 or C3.[36]

Therefore, in terms of appearance, C3 exhibited optimal durability upon subjection to repeated exposure to perspiration and washing.
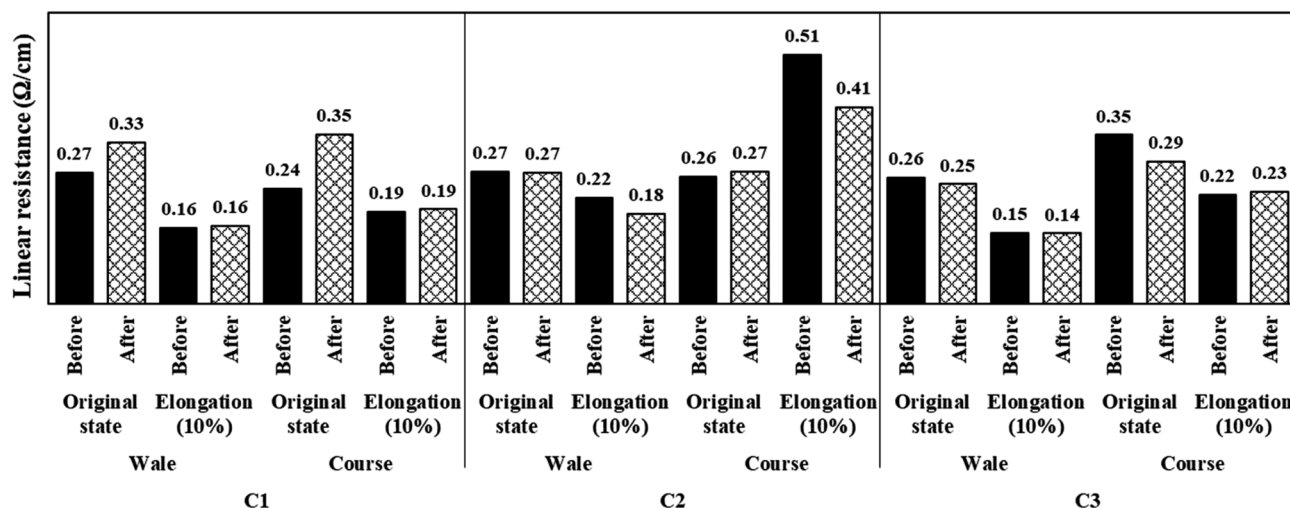
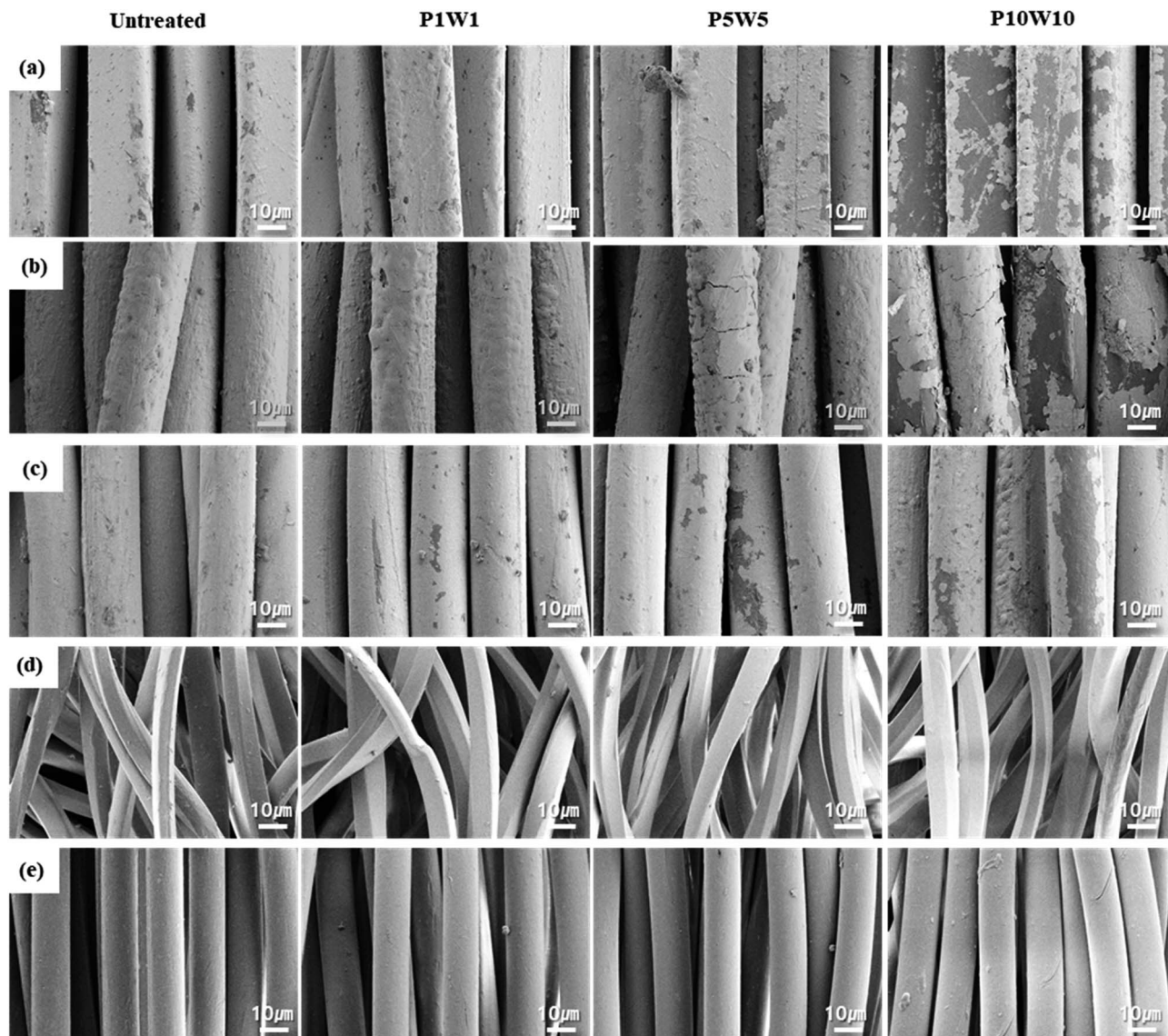**Fig. 9** Linear resistance in original and elongation state according to washing.

Fig. 10   FE-SEM (×3000) of the fabric surface according to repeating exposure of perspiration and washing: (a) C1; (b) C2; (c) C3; (d) K1; (e) K2.

3.3.2.   Chemical properties. The chemical changes in the conductive knitted fabrics due to repeated exposure to perspiration and washing were analyzed using XPS. Table 11 lists the atomic concentrations of C, O, Cl, and Ag detected on the surface of the conductive fabric before and after a single cycle of exposure to perspiration and washing. The increase in C and decrease in Ag after exposure to perspiration and washing are consistent with the results above. It was confirmed that silver particles were eliminated from the surface of the fabric and AgCl was formed through the reaction between silver and perspiration. However, in Fig. 13, which shows the XPS spectrum of Ag 3d for each conductive knitted fabric, the formation of a new peak is very prominent in the case of C3. The peaks at 367.6 eV and 373.4 eV are assigned to the Ag 3d peaks inside AgCl and AgO.[22,35] Silver nanoparticles are oxidized to dissolved ionic forms when subjected to prolonged exposure to water.[34] Therefore, the silver on the surface of the conductive knitted

fabric was chemically changed owing to the continuous reaction between perspiration and water. As a result, C3, which had a relatively small amount of silver compared to the other two samples, showed a clearer chemical structure change in the XPS spectrum.

Fig. 14 shows the change in the contact angles of the conductive knitted fabrics according to the frequency of exposure to perspiration and washing cycles. The contact angles of the untreated sample and the 1, 5, and 10 cycles of exposure to perspiration and washings were 123.5°, 108.8°, 117.2°, and 122.7° for C1 and 135.1°, 107.4°, 114.7°, and 126.0° for C2. In C1 and C2, the contact angle decreased after a single cycle of exposure to perspiration and washing, and recovered to the level of the untreated sample upon increasing the number of cycles. This was because water penetration by capillary action on the fabric surface increased as the nano-roughness of the fabric was damaged by the loss of silver particles after a single
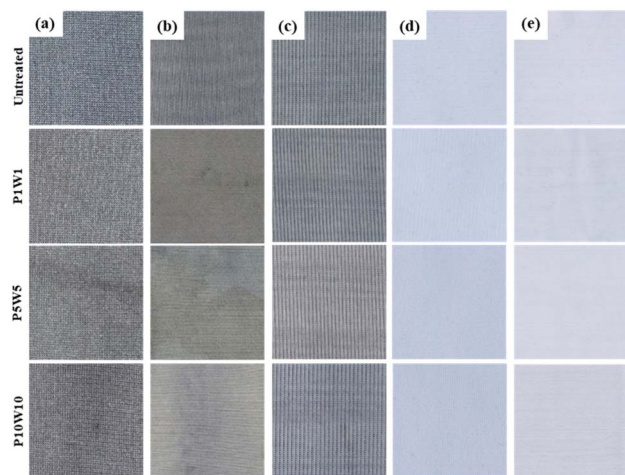
Fig. 11 Appearance of the fabric according to repeating exposure to perspiration and washing: (a) C1; (b) C2; (c) C3; (d) K1; (e) K2.
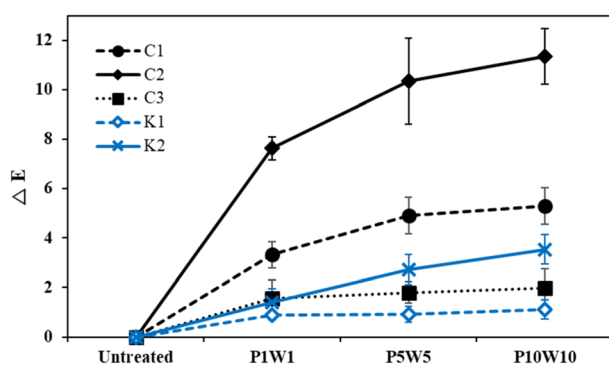

Fig. 12 Color differences of the fabric according to repeating exposure to perspiration and washing.

Table 11 The atomic concentration of the fabric according to repeating exposure to perspiration and washing

Composition	C1		C2		C3	
	Before	After	Before	After	Before	After
C12	55.43	63.04	53.71	59.17	68.76	67.26
O12	16.27	19.33	19.70	19.00	29.28	27.05
Cl2p	1.39	0.91	0.88	1.28	0.00	0.75
Ag3d	26.91	16.72	25.71	20.55	1.96	4.94

Fig. 13 Ag 3d XPS spectra of the conductive fabrics according to exposure to perspiration and washing: (a) C1, (b) C2, and (c) C3.

Fig. 14 Water contact angle of the fabric according to repeating exposure to perspiration and washing.

cycle of exposure to perspiration and washing.[24] However, as the silver layer peeled off from the fiber surface owing to friction between fabrics during repeated washing, the fabric surface became rough and the contact angle increased. In contrast, the contact angles of untreated and 1, 5, and 10 times of treatment for C3 were 143.1°, 123.7°, 120.2°, and 0.0°. The oxidation and desorption of silver due to exposure to perspiration and washing increased its affinity to water molecules and wicking by capillary action. However, unlike other samples, the silver-coated conductive yarn was half-inserted into the fabric, so
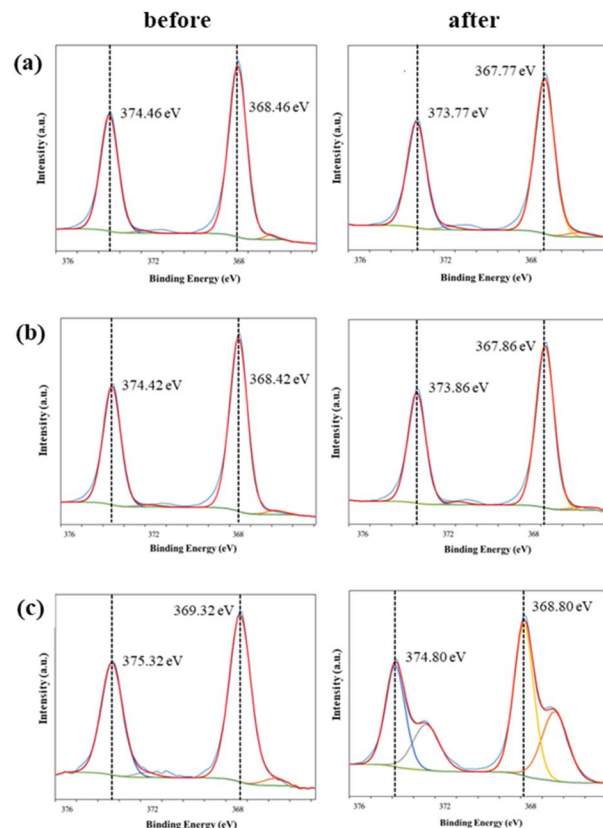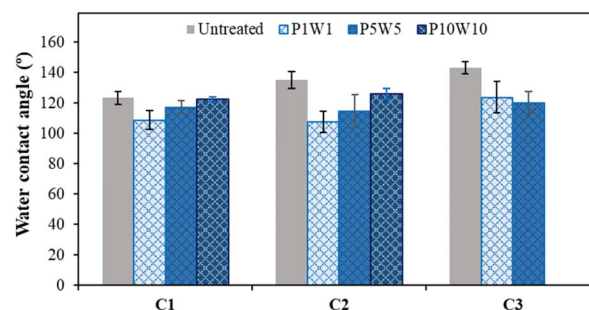
the nano-roughness due to the peeling of the silver layer by increasing the number of washings was not induced. In particular, hydrophobicity was maintained for 5 cycles, at 10 cycles, the contact angle was 0.0°, and the water droplets were completely absorbed from the surface and became hydrophilic.

Based on these results, exposure to perspiration and washing more than 10 times significantly changed the chemical properties and wettability of the surface of the conductive knitted fabric. Therefore, to maintain the original characteristics of the conductive fabric, the cycle frequency need to be reduced to the extent possible, or a manufacturing method that improves the

durability of adhesion between the silver layer and fabric need to be developed.

3.3.3. Conductivity. The changes in the surface resistance of the conductive fabric following repeated exposure to perspiration and washing are shown in Fig. 15. The surface resistance of all the samples increased as the frequency of exposure to perspiration and washing increased. In C1, which was coated with silver on the nylon knitted fabric, surface resistance increased linearly in both the wale and course directions as the frequency of exposure to perspiration and washing increased. Conversely, the surface resistance of C2, where the nylon and spandex knitted fabrics were coated with silver, decreased slightly following exposure to perspiration and washing once but sharply increased as the frequency of this cycle increased to 5 and 10. In the case of C3, knitted by mixing silver-coated nylon yarns with common nylon yarns, the change in surface resistance was insignificant until exposure to perspiration and washing were repeated five times; however, the surface resistance increased rapidly after exposure to perspiration and washing ten times. According to Tajin *et al.*,[9] silver-coated nylon fabrics are vulnerable to perspiration and washing cycles. Exposure to perspiration increased the sheet resistance of the fabric, likely owing to the delamination of the silver coating from the surface of the nylon fibers upon exposure to perspiration and washing. Therefore, as exposure to perspiration and washing are repeated, the silver layer on the fabric surface peels off owing to chemical stress and physical friction, and the surface resistance increases. This was confirmed by the SEM images. However, when the number of the aforementioned iterations was small, such as in C2 or C3, the surface resistance was either temporarily reduced or maintained. If the silver coating is loose and has a large surface area, a large amount of AgCl can form, and the dissolution of the silver coating is accelerated.[7] This can help smoothen the flow of electrons by forming large amounts of Ag^+ ions. However, this effect was temporary, and after repeated exposure to perspiration and washing, Ag changed to AgCl or was destroyed, resulting in increased surface resistance and decreased conductivity. This trend was more pronounced in C1 and C2, which were coated with silver after post-processing in the fabric state, than in C3, which was coated with silver in the yarn state. This is because the coating method in the fabric state attenuated adhesion

between the silver layer and the fabric, and the formation of the silver layer was not uniform. Because the surface of knitted fabric is rough, it easily aggregates in the gaps between the yarns after coating.[18] As a result, the silver layer attached to the surface of the fabric was thin and non-uniform; therefore, it could not completely adhere to the fabric.[18,37] Therefore, an increase in surface resistance was observed despite the small number of iterations (≤5).

Fig. 16 and 17 show the measured linear resistance values of the conductive fabrics in their original and stretched states, respectively, after repeated exposure to perspiration and washing. The linear resistance of each sample increased as with the frequency of exposure to perspiration and washing, but the trend was inconspicuous compared to the surface resistance results. Unlike surface resistance, which calculates the resistance value within a certain area, linear resistance measures the electrical resistance of the linear distance between two probes. Therefore, the damage to the silver layer following exposure to perspiration and washing did not significantly affect the linear resistance per unit cm. These trends were more evident in the wale direction, where the yarns were continuously intertwined, and in the C1 and C2 coated in fabric states. At 10% elongation, the linear resistance decreased compared with the original state, and the electrical conductivity was improved. In addition, the differences due to repeated exposure to perspiration and washing were further reduced. Similar to the results of exposure to perspiration or washing alone, the electron movement path shortened as the loop constituting the knitted fabric was elongated. Consequently, electron movement per unit length became easier, and linear resistance decreased. However, the number of iterations reached ten, damage or chemical changes in the silver layer due to exposure to perspiration and washing affected the linear resistance. Therefore, a clear change in linear resistance is expected as the frequency of exposure to perspiration and washing is increased.

3.3.4. Hand value. The FTT is an integrated instrument that can simultaneously measure four types of physical properties of the fabric, namely compression, bending, surface, and thermal properties, and generates 13 fabric indices.[38] It offers hand and touch sensations of fabrics including smoothness, softness, and warmness, based on these fabric indices.[36,38] Therefore, it is possible to objectively confirm the change in the hand value of the conductive fabric owing to repeated exposure to perspiration and washing.

Table 12 lists the fabric properties of the untreated samples according to the FTT test and the samples that were exposed to perspiration and washed 10 times.

In terms of changes in fabric properties owing to exposure to perspiration and washing, the bending properties tended to decrease slightly after treatment in all samples. Bending rigidity refers to the force required to bend per radian, whereas bending work refers to the work required to bend the specimen.[36] Therefore, the decrease in bending rigidity after treatment is attributed to the increase in the degree of freedom of the yarn as the silver coating on the surface of the conductive fabric was peeled off, or the filament yarn of the common knitted fabric was partially untwisted by chemical and physical treatment.
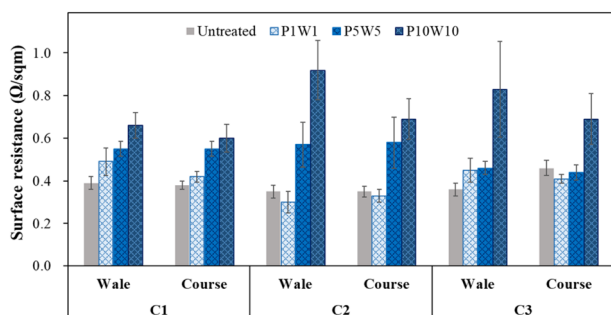

Fig. 15 Surface resistance of the conductive fabrics according to repeating exposure to perspiration and washing.
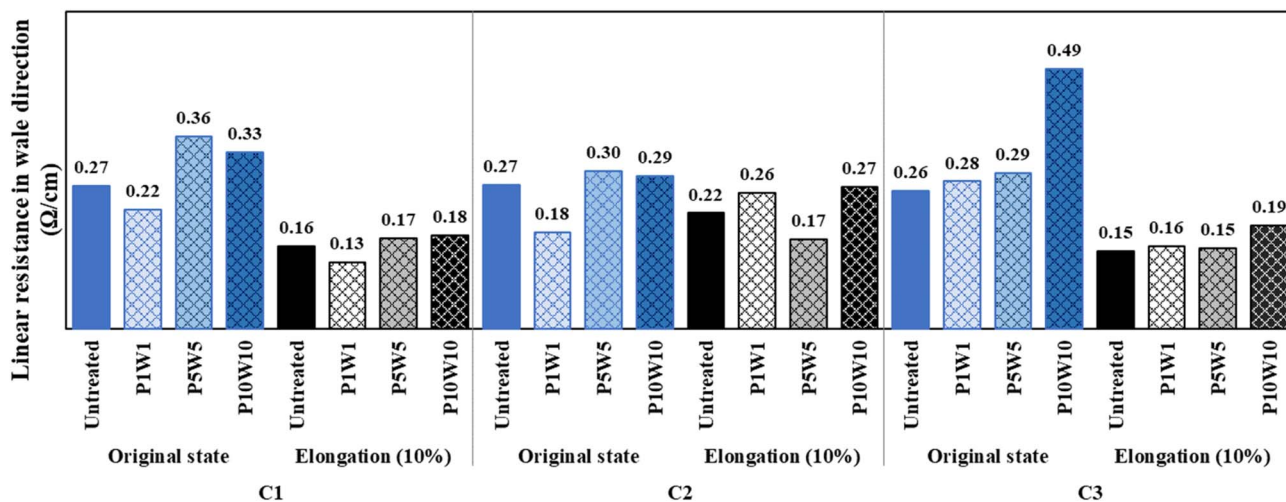
Fig. 16 Linear resistance of the fabric in wale direction according to repeated exposure to perspiration and washing.
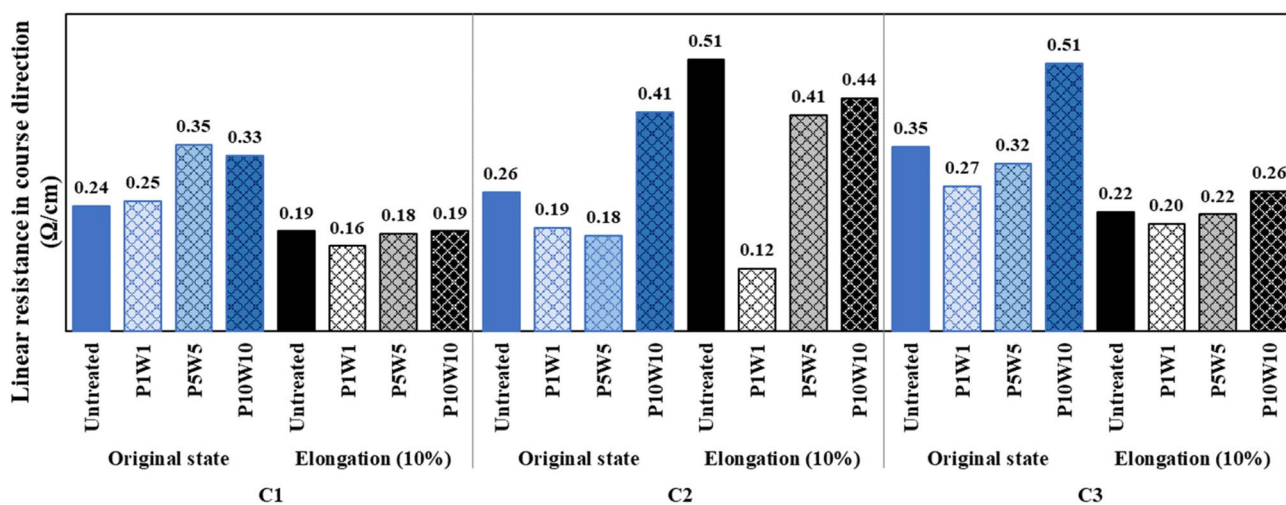
Fig. 17 Linear resistance of the fabric in course direction according to repeated exposure to perspiration and washing.

Ajeli *et al.*[39] studied the bending rigidity of warp-knitted fabrics as a function of the knit structure, density, and yarn bending properties. Their results indicated that the bending rigidity increased for the fabrics with relatively high density.

There was no difference in the thermal conductivity before and after treatment or among the samples. In the case of conductive fabrics, the thermal conductivity was expected to increase as the silver layer on the surface was damaged. However, considering that there was no change in the value of Q_{max}, the silver particles falling off the surface or the chemical changes due to exposure to perspiration or washing were presumed to be insufficient to affect the thermal conductivities.

However, in the case of the compression properties, the compression work of C1 and C2, which were coated with silver in the fabric state, increased after treatment, unlike the other samples that were not coated. High compression implies that the force required to compress the specimen is large.[36] In C1 and C2, the silver layer was oxidized and damaged owing to

exposure to perspiration and washing, and the samples became bulkier than they were before treatment, thus necessitating additional force for compression. In particular, the compression work of C2 was more than twice that of the untreated samples. The resilience of the fabric sharply decreased as the chemical composition of the spandex yarn contained in the sample was changed by perspiration, and the silver layer was peeled off from the fabric surface.

In terms of surface geometry properties, the surface friction and surface roughness of conductive and common knitted fabrics differed before and after the treatment. The coefficient of friction of the common knitted fabric was similar to or slightly increased by the exposure to perspiration and washing, whereas that of the conductive fabrics decreased. Fabrics with low friction coefficients are typically relatively smooth.[40] The coefficient of friction of the fabric is mainly influenced by the nature of the fabric and ambient humidity. The physical characteristics of yarns, such as the yarn count, fiber fineness, and

Table 12 Fabric properties by FTT according to repeating exposure to perspiration and washing

| | | Bending | | | | Thermal conductivity (Q_{max}) | | Compression | | | | Surface Friction coefficient | | Surface roughness | | | |
| | | Bending rigidity (gf mm rad^{-1}) | | Bending work (gf mm rad) | | | | Compression work (gf mm) | | Recovery rate | | | | Amplitude (μm) | | Wavelength (mm) | |
		Face	Back	Face	Back	Face	Back	Face	Back	Face	Back	Face	Back	Face	Back	Face	Back
C1	Untreated	49	52	181	183	0.1	0.1	168	129	0.7	0.8	0.3	0.3	22	23	1.3	1.1
	P10W10	44	41	166	151	0.1	0.1	206	190	0.7	0.7	0.2	0.2	23	22	1.5	1.0
C2	Untreated	95	100	427	409	0.1	0.2	138	148	0.7	0.8	0.3	0.3	23	17	1.1	1.8
	P10W10	103	90	417	372	0.1	0.1	471	331	0.6	0.7	0.2	0.2	15	17	2.0	1.0
C3	Untreated	85	87	314	293	0.1	0.1	330	305	0.6	0.7	0.4	0.4	27	21	1.5	1.9
	P10W10	79	82	342	311	0.1	0.1	294	222	0.7	0.7	0.3	0.3	27	31	1.7	1.8
K1	Untreated	137	189	580	647	0.1	0.1	384	371	0.7	0.7	0.3	0.3	20	23	2.2	2.0
	P10W10	163	175	713	759	0.1	0.1	377	335	0.7	0.7	0.3	0.3	25	27	2.7	2.2
K2	Untreated	108	122	346	364	0.1	0.1	249	250	0.8	0.7	0.2	0.3	17	14	2.2	1.9
	P10W10	89	101	303	323	0.1	0.1	194	185	0.7	0.7	0.5	0.3	33	11	1.5	1.8

yarn twist, together with their alignment and positioning in the fabric structure, are important for the measurement of surface friction properties.[41] In the case of conductive fabrics, silver was oxidized to form AgCl particles owing to exposure to perspiration, and the silver layer was then peeled off during the washing process, exposing the inner nylon filament yarn. Unlike metals, fibers contain a certain amount of moisture because of their chemical functional groups and structural properties. As shown in the contact angle measurement results, the surface of the conductive fabric became hydrophilic following exposure to perspiration and washing. As moisture acts as a lubricant in friction, the coefficient of friction of the conductive fabric was lowered owing to the effect of increasing moisture in the sample after treatment.[42] Upon treatment, the surface roughness, amplitude, and wavelength of common knitted fabrics K1 and K2 increased, but remained the same of decreased for conductive fabrics. Such a change in the surface geometry properties was due to the effect of the mechanical force from repeated washing rather than exposure to perspiration. Washing involves constant abrasion between the drum wall and fabric, which causes a change in the geometric structure of the fabric.[43] The change in the surface structure due to the mechanical force of washing was more pronounced in the uncoated samples, as the fibers were more prone to swelling by water during washing.[44] The common knitted fabric used in this study is a warp-knitted fabric composed of uncoated spun or filament yarns. Therefore, the amplitudes and wavelengths of K1 and K2 were higher than those of the untreated sample because the yarns swelled and dissociated owing to the mechanical and hydraulic forces during washing, resulting in a rough surface.

Table 13 lists the fabric indices of the hand value for the five fabric properties according to repeated exposure to perspiration and washing.

All three fabric indices changed for conductive fabrics C1, C2, and C3. In C1, the softness of the back side of the fabric and the total fabric index decreased. In C3, warmness on the back side of the fabric decreased. The greatest changes were observed in C2; smoothness and softness decreased, warmness increased, and the total fabric index decreased on both sides of the fabric. C2 was considered the most vulnerable to chemical and physical changes caused by exposure to perspiration and washing because it contained spandex yarn and was coated with silver through a post-processing method in a fabric state.

In contrast, the fabric indices of common knitted fabrics, K2 did not change, but K1 showed an increase in smoothness on the face side and a decrease in softness on the back side. This is because K1 is composed of hairy textured yarns rather than filament yarns, and the surface changes due to friction during washing exceed those of K2.[45] Therefore, the general knitted fabric also showed changes in the hand value owing to repeated exposure to perspiration and washing; however, the change was insignificant compared to that of conductive fabrics.

Based on the hand value evaluation, the change in the C2 score was remarkable. Therefore, it is recommended that spandex yarns be avoided in the manufacture of conductive fabrics and that structural elasticity, such as knitted fabrics, be

Table 13 Fabric indices by FTT according to repeating exposure to perspiration and washing

		Smoothness		Softness		Warmness		Total	
		Face	Back	Face	Back	Face	Back	Face	Back
C1	Untreated	3	4	4	4	3	2	3	4
	P10W10	3	4	4	3	3	2	3	3
C2	Untreated	4	5	4	4	2	1	3	4
	P10W10	3.5	4.5	4	3.5	3	1.5	3.5	3.5
C3	Untreated	3	4	4	3	3	2	3	3
	P10W10	3	4	4	3	3	1	3	3
K1	Untreated	2	3	3	3	4	2	3	3
	P10W10	2.5	3	3	2	4	2	3	3
K2	Untreated	3	4	4	3	3	2	3	3
	P10W10	3	4	4	3	3	2	3	3

integrated when stretching is required. In addition, knitting or weaving after pre-coating in the yarn state rather than performing post-processing in the fabric state is advantageous in terms of fabric hand value. However, because these results are based on a limited sample size, additional studies are needed to identify more generalized changes in conductive fabrics.

4. Conclusions

In this study, considering the wearing and management of smart clothing, changes in the appearance, chemical composition, wettability, and electrical properties of conductive knitted fabrics based on exposure to perspiration and washing were investigated.

Overall, the conductive knitted fabric became hydrophilic and significantly changed in appearance and color in accordance with the chemical change in the silver layer caused by perspiration and washing. Additionally, the hand values of all the conductive fabrics varied with decreasing softness and smoothness and increasing warmness after repeated exposure to perspiration and washing.

Here, different changes were observed depending on the manufacturing method used for the conductive fabric. The silver-coated fabric samples were more vulnerable to the durability of the conductivity, and considerable change was observed. Conversely, the conductivity of the sample coated with silver in the yarn state showed slight changes owing to perspiration and washing, but the changes in basic properties such as appearance, color, and hand value were similar to those of common knitted fabrics. Therefore, considering the conductivity and aesthetic characteristics of fabrics such as color and touch, the use of conductive fabric with silver-coated yarn is more optimized for smart clothing to improve the durability of the silver layer. However, because these results are limited to this study, verification using more diverse samples is required.

This study confirmed the extent of change in conductive fabrics that is acceptable by consumers by comparing the changes in the actual wearing environment of conductive fabrics used for smart clothing with those of common fabrics. The changes in the appearance and chemical composition of conductive fabrics following exposure to perspiration and washing allow for the determination of whether harmful substances are generated by the reaction of metals and chemical components in the conductive fibers and present specific manufacturing methods and directions for human-friendly smart fibers. In addition, follow-up research should determine the optimal duration of product quality and functionality through repeated use and washing of smart clothing, and exhaustively identify conditions for washing and management.

Conflicts of interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgements

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