J. Coat. Technol. Res., **20** (6) 1881–1895, 2023
https://doi.org/10.1007/s11998-023-00784-5

Two-dimensional carbon material incorporated and PDMS-coated conductive textile yarns for strain sensing

G. M. Nazmul Islam, Stewart Collie, Maree Gould, M. Azam Ali

Received: 6 October 2022 / Revised: 11 March 2023 / Accepted: 15 March 2023

Abstract In recent years, innovative technology based upon conductive textile yarns has undergone rapid growth. Nanocomposite-based wearable strain sensors hold great promise for a variety of applications, but specifically for human body motion detection. However, improving the sensitivity of these strain sensors while maintaining their durability remains a challenge in this arena. In the present investigation, polydopamine-treated and two-dimensional nanostructured material, e.g., reduced graphene oxide (rGO)-coated conductive cotton and polyester yarns, was encapsulated using polydimethylsiloxane (PDMS) to develop robustly wash durable and mechanically stable conductive textile yarns. Flexibility and extensibility of all textile yarns of every stage were analyzed using texture analysis. The chemical interactions essential for measuring coating performance among all components were confirmed by Fourier transform infrared and scanning electron microscopy. The rGO-coated cotton and polyester yarns exhibited an extensibility of 11.77 and 73.59%, respectively. PDMS-coated conductive cotton and polyester yarns also showed an electrical resistance of 12.22 and 20.33 kΩ, respectively, after 10 washing cycles. The PDMS coating layer acted as a physical barrier against impairment of conductivity during washing. Finally, the mechanically stable and flexible conductive textile yarns were integrated into a knitted cotton glove and armband to create a highly stretchable and flexible textile-based strain sensor for measuring finger and elbow movement. Truly wearable garments able to record proprioceptive maps are critical for further developing this field of application.

Keywords Two-dimensional material, Smart textile, Strain sensor, Coating, Wash durability

G. M. N. Islam, M. Gould, M. A. Ali (✉)
Centre for Bioengineering and Nanomedicine, University of Otago, PO Box 56, Dunedin 9054, New Zealand
e-mail: azam.ali@otago.ac.nz

G. M. N. Islam
Department of Human Ecology, University of Alberta, Edmonton T6G 2N1, Canada

S. Collie
Bioproduct and Fibre Technology, AgResearch, Christchurch 8140, New Zealand

Introduction

Wearable conductive textiles based on conductive fibers, yarns, and fabrics have been applied over a wide range of applications fulfilling different requirements.[1–5] Textile yarns can be made conductive by applying various conductive materials, and the most widely used conductive materials, including grapheme,[6–9] carbon nanotubes (CNTs),[10–14] conducting polymers,[15–19] and carbon black,[20] are suitable for producing textile yarn-based strain sensors.

Graphene, a 2D carbon material formed by sp^2 hybridization of carbon atoms, has achieved great attention as a promising conductive material for fabricating highly conductive yarns due to its remarkable electrical conductivity, flexibility, lower skin effect, and mechanical and thermal stability.[21–23] Two derivatives of graphene exist, such as graphene oxide (GO) and reduced graphene oxide for producing conductive textiles to monitor strain, light, and touch sensing.[24–26] Graphene oxide easily binds with fiber surfaces as it has many polar groups and the reduced graphene oxide has been focused for wearable smart textiles applications due to the interaction with oxygen containing groups in textile fibers.[27–29] Various methods have been applied for the fabrication of graphene-based wearable textiles, including wet spinning,[30] dip coating,[31–33] spray coating,[34] printing,[35, 36] and chemical

vapor deposition.[37] Xu et al.[38] demonstrated GO-coated textile humidity sensors without textile fiber modification for monitoring various human activities but wash durability was not analyzed. Sun et al.[8] produced graphene-coated wearable fabric strain sensor for monitoring human movement and analyzed the mechanical properties without discussing wash durability. In another study, Afroj et al.[39] reported graphene-based wash durable, flexible, and highly conductive e-textiles for skin-mounted strain sensing without modification of the textile substrates.

Though graphene derivatives form chemical bonding with textile substrates to be used as textile based sensors, still it remains a challenge to develop good wash durable conductive textile sensors. Polydimethylsiloxane (PDMS) is a silicon-based biocompatible and chemically inert elastomer with repeating units of $SiO(CH_3)_2$ and is one of the most widely used polymers for fabricating flexible sensors.[40] The degree of flexibility of this polymer is high, and it has demonstrated compatibility to different surfaces such as silicon, glass, and various polymers. Due to its mechanical properties, PDMS can be used as an encapsulation layer.[41]

In the present investigation, the above limitations, including substrate modification, wash durability, and mechanical properties, were considered to develop robustly, wash durable, and mechanically stable conductive cotton and polyester yarns. In this experiment, the textile substrates (100% raw cotton and polyester yarns) were modified by dopamine which consists of catechol, amine, and immine functional groups.[42–45] The textile yarns were modified by polydopamine (PDA). PDA solution was produced by dopamine and Tris-HCl. The key chemical reaction between dopamine and Tris-HCl is illustrated in Fig. 1. PDA-treated and rGO-coated highly flexible conductive yarns which were made stable and robust as the final coated surface was treated with a hydrophobic silicon-based polymer along with a curing agent to increase the wash durability and robustness of coated textile yarns. These robust conductive yarns were integrated into a glove and armband for measuring movements of the human body, i.e., strain sensing.

Materials and methods

Materials

Cotton (100%) plain woven fabric (non-dyed) of mass 169 g/m^2, thickness 0.52 mm, 28 yarns/cm in warp direction, and in weft direction was 22. Polyester (100%) plain woven fabric (nondyed), mass 160 g/m^2, thickness 0.51 mm, 24 yarns/cm in warp direction, and in weft direction was 20, was sourced from Testfabrics, Inc. (USA). Polyvinyl alcohol (PVA) powder (degree of hydrolysis > 99%; MW 8.9–9.8 × 10^4), a hydrophilic polymer obtained from Sigma-Aldrich, New Zealand, was used as the precursor and counterpart layers to form the robust and stable coating. Tris-hydrochloride (Tris-HCl), purchased from Bio-Froxx, GmbH, Germany, was used as buffer solution. Dopamine (98% +) was purchased from Sigma-Aldrich, New Zealand, used as a binding agent for surface modification of yarns. Hydrochloric acid (HCl) (Sigma-Aldrich, New Zealand) was used to maintain pH = 8.5 for producing the solution of dopamine and Tris-HCl. Reduced graphene oxide dispersion (stabilized with polysodium 4-styrenesulfonate, 10 mg/mL, dispersion in H_2O, purity ≥ 98%) was purchased from NANOCHEM-ZONE Inc. (Canada). This rGO was selected as it is commercially available and ready to apply on existing textile yarns/fabrics. Poly(dimethylsiloxane) (PDMS), hydroxy terminated polymer (density: 0.97 g/mL at 25 °C, viscosity: 18k–22k cSt, 432,997-500 mL; CAS 7013-67), was purchased from Sigma-Aldrich, USA. SYLGARD$^{(R)}$ 184 (Silicone Elastomer Kit 761036-5EA, viscosity 2k–20k CP, volume resistivity 2.9e+014 Ω cm) was purchased from Dow Chemical, Midland, USA, imported by Sigma-Aldrich used as a curing agent.

Methods

Polyester and cotton yarns extraction

Woven fabrics were washed according to ISO 6330:2012 for 2.5 h (a total of 6 wash cycles) in an Electrolux Wascator washing machine FOM71MP-Lab using a nonphosphate powder detergent 3 (ECE

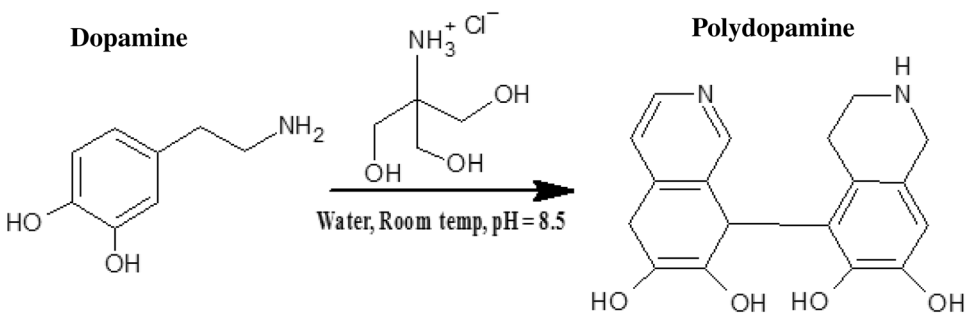

Fig. 1: Synthesis of polydopamine (PDA)

reference detergent 98), and then, the washed fabrics were flat dried. The yarns were separated from both fabrics by a needle and collected for ensuring the 100% purity of textile yarns.

Polydopamine treatment of textile yarns

The cotton and polyester yarns were modified by PDA as shown in Fig. 2. Tris-HCl solution was prepared and modified according to our previous work.[18] Bundles of cotton and polyester yarns were immersed in this Tris-HCl aqueous solution. Shaking and stirring times were 24 h and 70 rpm, respectively. The surface-modified yarns were washed thoroughly with distilled water for 1 min and dried at 100 °C for 20 min.

Preparation of PVA Solution

To prepare 100 mL of 10% PVA solution, 10 g of PVA was dissolved in 90-mL distilled water at 80 °C followed by magnetic stirring for 3 h, before making up to 100 mL with distilled water.

Fabrication of conductive textile yarns

A bundle of PDA-treated yarns were dip-coated in the PVA solution for 5 min and dried at 100 °C for 30 min. PVA was used as the precursor and counterpart layers to form the stable and robust conductive coating. The PVA-coated yarns were submerged in the rGO dispersion for 5 min and dried at 100 °C for 30 min. These coating and drying steps were repeated in order to control the thickness of the rGO layer deposited onto the yarns.

PDMS coating

The PDMS formulation was prepared by first degassing the mixture of the PDMS and the curing agent (SYLGARD® 184) (10:1 weight ratio) in a vacuum desiccator for 30 min to remove the bubbles from the mixture. The rGO-coated yarns were dipped in the degassed PDMS and SYLGARD® 184 mixture. The rGO-coated yarns were removed from the PDMS mixture and cured at 120 °C for 45 min. The whole fabrication process is illustrated as shown in Fig. 3.

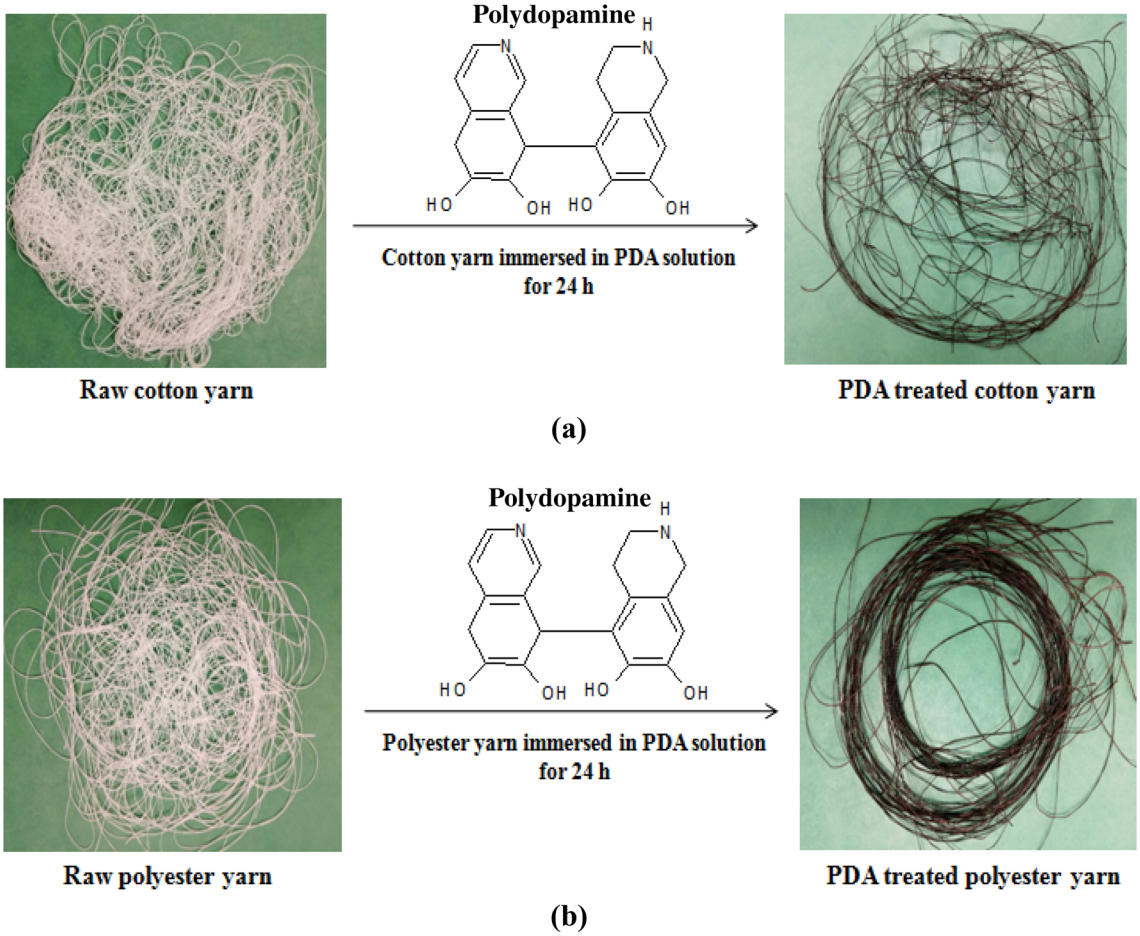

Fig. 2: Polydopamine-modified (a) cotton and (b) polyester yarns

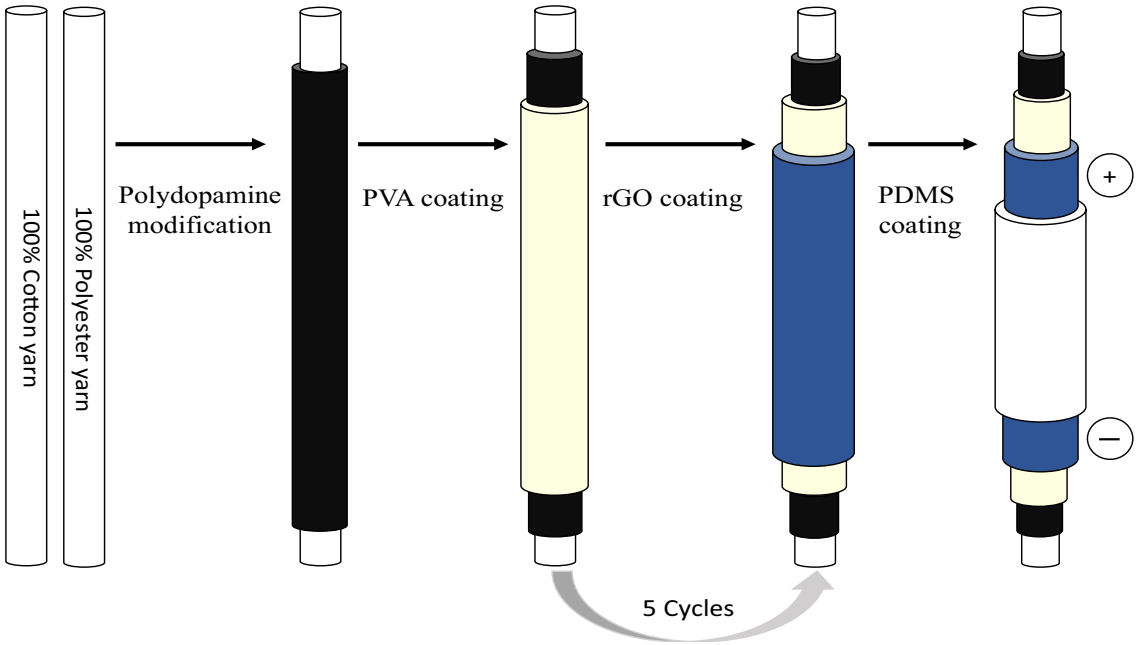

Fig. 3: A schematic illustrating the fabrication of conductive textile yarns

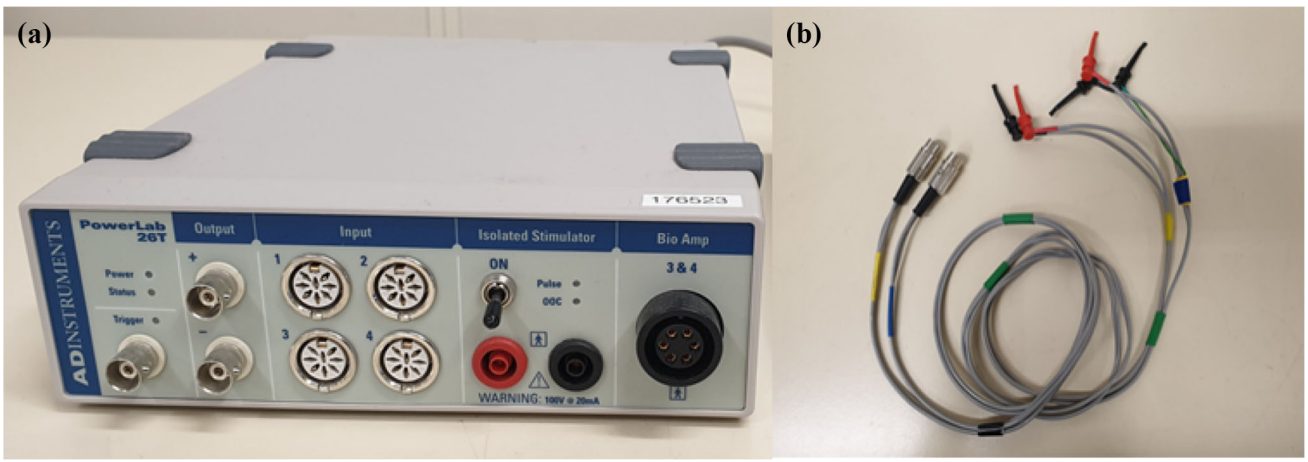

Fig. 4: Power Lab setting of (a) A-D converter and (b) connecting wires for physiological signal analysis

Characterization and measurement of electrical resistance of conductive yarns

The chemical interactions among the functional groups of different components such as cotton, polyester, PDA, PVA, and rGO were assessed using Fourier transform infrared (FTIR) with a total of 24 scans/sample over the range of 4000–400 cm^{-1} at resolution of 4 cm^{-1} using a PerkinElmer # 100 spectrometer (PerkinElmer Inc., MA, USA).

The direct current (DC) electrical resistance for each conductive yarn was measured 3 times using a multimeter (FLUKE 114 TRUE RMS, USA) before and after wash and averaged.

The diameter of each yarn was measured by digital caliper (Trade Tools, Auckland, New Zealand). It is also noted that the term 'yarn' means a product of substantial length and relatively small cross section consisting of fibers and/or filament(s) with or without twist.[46]

The surface morphological analysis of conductive yarns was performed using a Tabletop Scanning Electron Microscope (SEM Microscope TM3030, Hitachi, Japan) with a voltage of 15 kV at different magnifications.

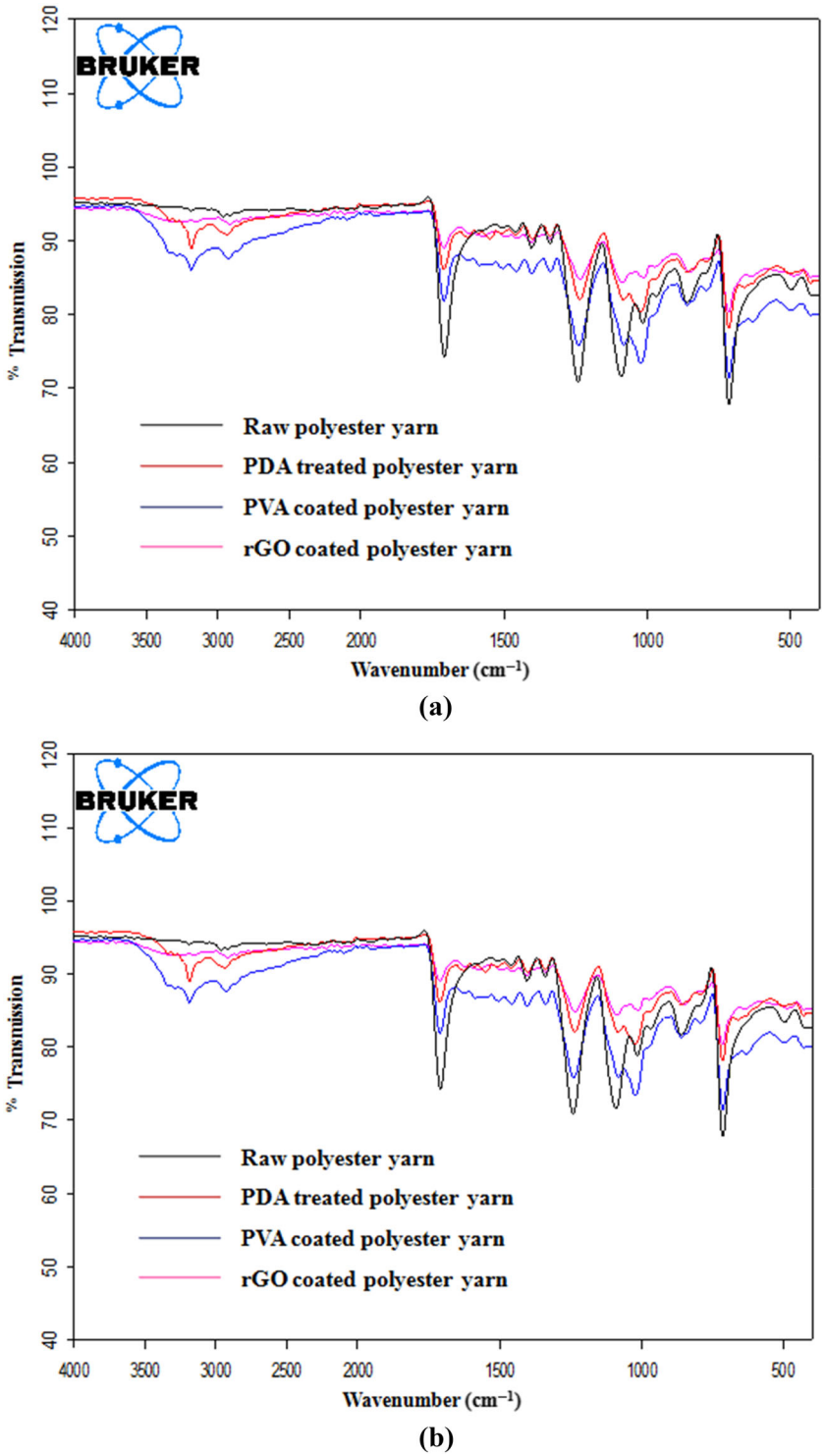

Fig. 5: FTIR spectra of (a) cotton and (b) polyester yarns

The mechanical properties of all yarns were analyzed by a TA.HD plusC Texture Analyzer (UK) applying 5-kg load cell, gauge length of 25 mm, and tensile speed 20 mm/min at room temperature.

The wash durability of rGO- and PDMS-coated conductive cotton and polyester yarns was washed according to the standard ISO 6330:2012. The coated yarns were washed in water containing ECE detergent

Table 1: FTIR absorption bands of textile yarns

IR absorption bands (cm^{-1})	Description
3431	O–H bonded to C=O groups
3331	Hydroxyl group (O–H) stretching
3282	Stretching vibration of the –OH groups
3182	Stretching vibrations of N–H
3178	Stretching vibrations of O–H
2970	C–H stretching
2889	Asymmetric C–H stretching
1718	Stretching vibration of aromatic C=O
1709	Stretching of C=O
1648	Carbonyl (C–O) of carboxylic group
1638	Stretching vibration of C=C
1385	Stretching vibration of C–OH
1300	C–O–C stretching
1050	Stretching vibration of C–O
1045	C–O stretching
1029–838	Stretching vibration of –C–C–
1015	C–C stretching
1013	C–H bending
715	C–C bending

Table 2: Electric resistance of rGO-coated textile yarns before PDMS coating

Conductive yarns	Coating cycles	Mean electrical resistance (kΩ)
Cotton	1	–
	2	–
	3	8.82
	4	8.02
	5	7.06
Polyester	1	–
	2	–
	3	14.16
	4	13.17
	5	11.50

(2 g/L) at room temperature for 30 min with continuous stirring. The washed conductive yarns were dried at 80 °C for 20 min. This washing process was repeated 10 times to evaluate the robustness of conductive yarns.

The highly stretchable and flexible conductive thermoplastic fibers and textile yarns were integrated into a knitted glove and an armband to measure the movement of finger and elbow. These physiological signals were measured using a generic analog-to-digital (A-D) converter as shown in Fig. 4.

Table 3: Electric resistance of rGO-coated conductive yarns after PDMS coating

Conductive yarn types	Electric resistance (kΩ)	Mean (kΩ)	SD
Cotton	8.25	9.09	0.75
	9.67		
	9.35		
Polyester	14.85	14.85	0.90
	15.75		
	13.95		

SD, standard deviation

The connecting wires were connected to the A-D converter, and this converter was also connected to an Apple Mac computer (USA). The other ends of these wires were related to the glove and the armband using a crocodile clip to get the physiological signal. These signals were displayed on the Mac computer screen and were analyzed by LabChart (AD Instruments Inc.) (www.adinstruments.com/products/labchart) for assessing the strain sensing performance.

Results and discussion

Fourier transform infrared (FTIR) analysis

FTIR study and analysis were conducted to compare 100% cotton and polyester yarns, PDA treatment, PVA, and rGO coatings performance. FTIR spectra are presented in Fig. 5. For clarity, all important absorption bands are reported in Table 1. From Fig. 5a, it is seen that 100% cotton showed three important peaks at 1648, 2889, and 3331 cm^{-1} corresponding to the carbonyl (C–O) of carboxylic group, the asymmetric (C–H) stretching, and hydroxyl group (O–H) stretching of cellulosic fiber, respectively.[47] The absorption bands placed among 1015, 1045, and 1300 cm^{-1} correspond to the C–C, C–O, and C–O–C stretching on the cellulosic fiber.[48] From Fig. 5b, it is also seen that the absorption bands are assigned at 3431, 2970, 1709, 1013, 715, and 860 cm^{-1} corresponding to the O–H bonded to C=O groups, weak C–H stretching, strong C=O symmetric stretching of the carbonyl groups, C–H bending, and C–C bending vibrations of the benzene rings in the polyester chains.[49] After surface modification by PDA, the absorption bands at 3178 cm^{-1} of cotton and 3182 cm^{-1} of polyester, respectively, are assigned to stretching vibrations of O–H and N–H groups of polydopamine.[50] The PVA-treated cotton yarn showed the absorption bands at 3282 cm^{-1}, 1414 cm^{-1}, and 1029–838 cm^{-1} corresponding to the stretching vibration of the –OH groups in the PVA and cotton, carbonyl stretching vibration, the stretching vibration of carbon–carbon bonds (–C–C–) which indicated the

Table 4: Electric resistance of rGO-coated conductive yarns after washing

No. of washing cycles	Type of conductive yarns			
	Cotton		Polyester	
	Mean electrical resistance (kΩ)	SD (kΩ)	Mean electrical resistance (kΩ)	SD (kΩ)
0	9.09	0.75	14.85	0.90
1	9.89	0.07	16.32	0.09
2	10.15	0.05	16.75	0.14
3	10.33	0.08	17.21	0.23
4	10.60	0.13	17.58	0.11
5	10.88	0.08	17.95	0.10
6	11.14	0.10	18.36	0.10
7	11.42	0.11	18.94	0.14
8	11.80	0.09	19.26	0.06
9	12.11	0.04	19.51	0.08
10	12.22	0.03	20.33	0.59

SD, standard deviation

physical bonding of cotton fabric and PVA as no new characteristics peaks were visible.[51] Similarly, the PVA-treated polyester yarn depicts an absorption band at 3282 cm^{-1} that corresponded to hydroxyl groups, and the band at 2349 cm^{-1} was absent in this yarn which confirmed the attachment of PVA onto the polyester yarn surface.[52] However, there are significant changes in the intensity of absorption peaks of rGO-coated yarns which were observed compared to raw cotton yarn. The peaks associated with asymmetrical C–H stretching and O–H stretching became relatively weak, and the C=O stretching was absent in rGO-coated conductive cotton yarn.[53] All these peak changes indicated the attachment of rGO on the cotton yarn. Moreover, the main significant absorption peaks at 1718, 1638, 1385, and 1050 cm^{-1} corresponded to the stretching vibration of aromatic C=O, C=C, C–OH, and C–O in rGO-coated polyester yarn, respectively.[54]

Electrical resistance before washing

The optimal electrical conductivity of conductive yarns is a primary requirement for producing a new generation of smart and intelligent textiles. The electrical resistance of conductive textile yarns was measured before and after PDMS coating. After the 1st and 2nd coating cycles of rGO, there was no detectable conductivity, presumably because of insufficient rGO deposition into the textile yarns which could be due to the relatively low concentration of rGO (10 mg/mL). But after the 3rd coating, conductivity was achieved as expected. This coating process was repeated to give 5 coating cycles in total for controlling the flexibility and stiffness of conductive yarns, and the mean electric resistance of conductive yarns is reported in Table 2.

From Table 2, it is seen that the electrical resistance of cotton and polyester yarns without PDMS coating provided readings between 7.06 and 11.50 kΩ, respectively. It is also worthwhile mentioning that the rGO-coated conductive cotton yarn showed lower electric resistance or higher conductivity compared to conductive polyester yarn due to the hydrophilic and adhesive properties of cotton cellulosic structure.[55]

The yarns with coated PDMS under 5 coating cycles illustrated a much smoother coating surface that was considered optimal for analyzing the wash durability as these yarns showed lower electrical resistance (high electric conductivity) compared to 4 coating cycles coated yarns with PDMS reported as shown in Table 3.

After PDMS coating and curing, it was observed that PDMS created an insulating surface layer on the rGO-coated yarns. We anticipated that this PDMS coating onto the rGO-coated yarns would potentially create a robust coating layer which could enhance wash durability. In Table 3, it was seen that the increase in electric resistance for cotton and polyester yarns was 28.75% and 29.13%, respectively. The PDMS surface coating layer increased electrical resistance of the conductive yarns as this layer created a physical insulative barrier between the yarn and connectors of the resistance measurement multimeter.[56]

Wash durability

Wash durability is a critical aspect in developing wearable smart textiles for real-life applications. The material selection and the fabrication method are key factors for producing wash durable conductive textiles.[57] Although graphene derivatives form chemical bonds with textile substrates to be used as textile-based substrates, it is still a challenge to develop a good wash

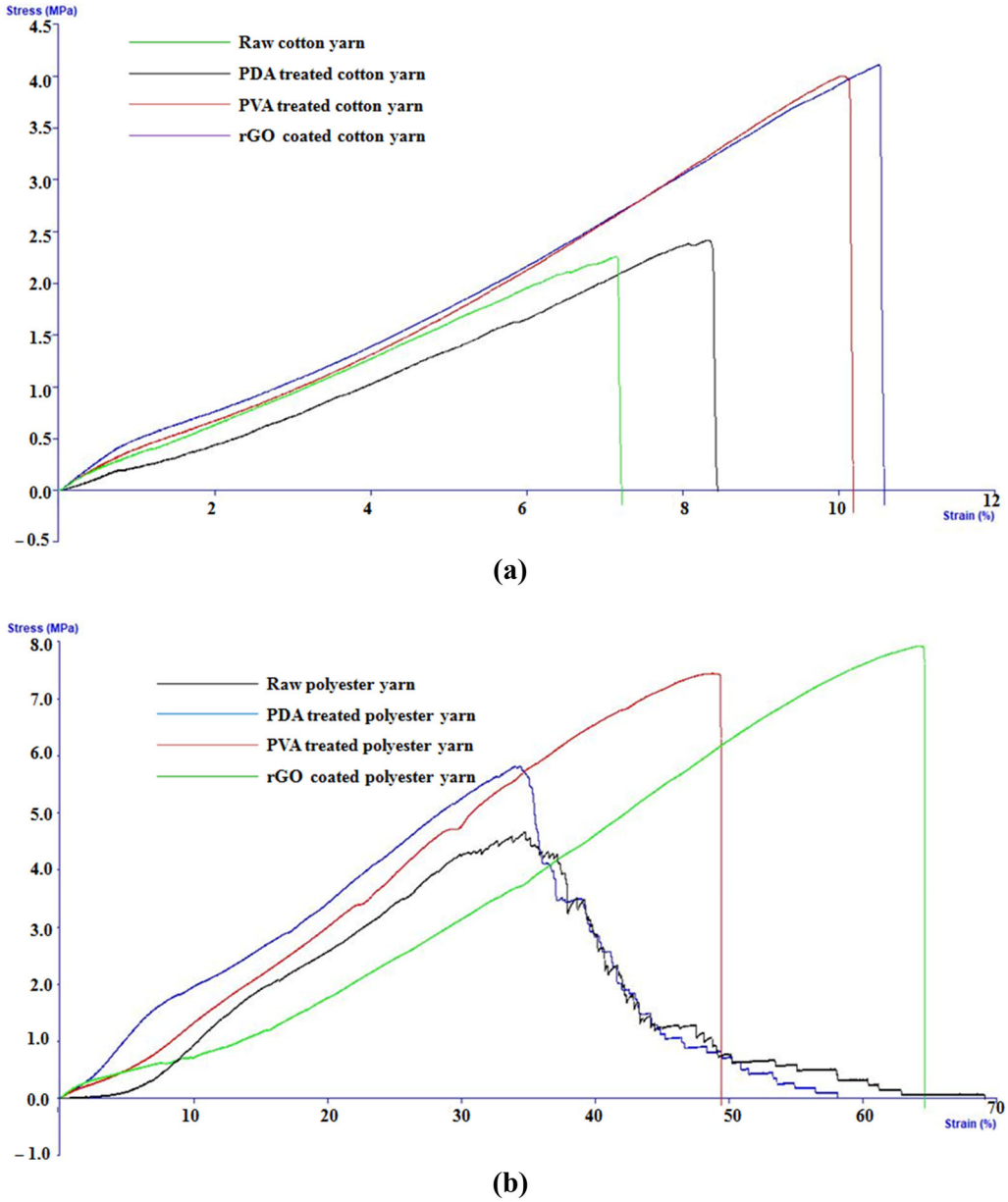

Fig. 6: Mechanical properties of (a) cotton and (b) polyester yarns (representative stress vs strain curves are shown)

Table 5: Mechanical properties of conductive textile yarns

Type of yarn	Tensile strength (MPa)	SD (MPa)	Young's modulus (MPa)	SD (MPa)	Elongation at break (%)	SD
Raw cotton	2.26	1.08	1.81	0.63	8.61	4.65
PDA-treated cotton	3.55	1.76	2.40	1.29	10.49	2.72
PVA-coated cotton	4.25	3.73	2.67	1.79	11.38	2.82
rGO-coated cotton	4.38	2.18	2.82	1.66	11.77	1.97
Raw polyester	4.68	3.09	2.01	0.48	41.69	3.27
PDA-treated polyester	5.10	2.59	2.20	1.74	46.79	2.54
PVA-coated polyester	5.23	1.96	3.03	1.04	54.28	1.38
rGO-coated polyester	7.97	3.21	3.23	1.64	73.59	2.23

SD, standard deviation

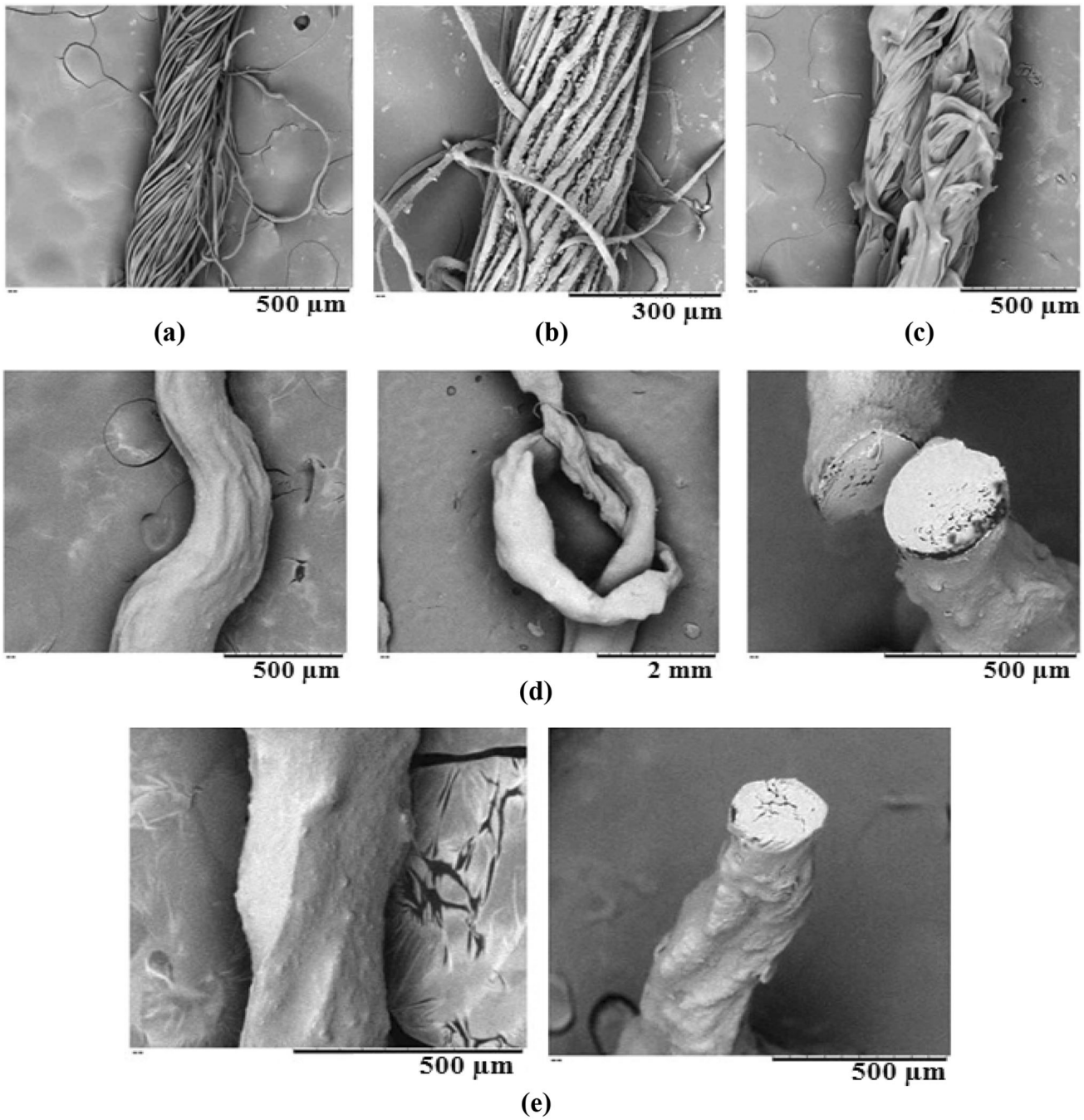

Fig. 7: Surface morphology of (a) raw cotton, (b) PDA-treated, (c) PVA-coated, (d) rGO-coated, and (e) PDMS-coated conductive cotton yarn at different magnifications

durable conductive textile sensor with the ability to withstand against washing. Therefore, PDMS-coated conductive cotton and polyester yarns were washed 10 times to evaluate the wash durability of conductive textiles. The increased electrical resistance of conductive yarns of each washing cycle is reported in Table 4. It is also mentioned that cotton yarns absorbed more conductive rGO solution due to porous cellulosic structure and strong absorption capability of cotton compared to ester polyester yarn.[58] Before washing, the electrical resistance of conductive cotton and polyester yarns was observed at 9.09 and 14.85 kΩ, respectively. After the 5th washing cycle, the electrical resistance of conductive cotton and polyester yarns was measured at 10.88 and 17.95 kΩ, respectively. After the 10th washing cycle, the electrical resistance of conduc-

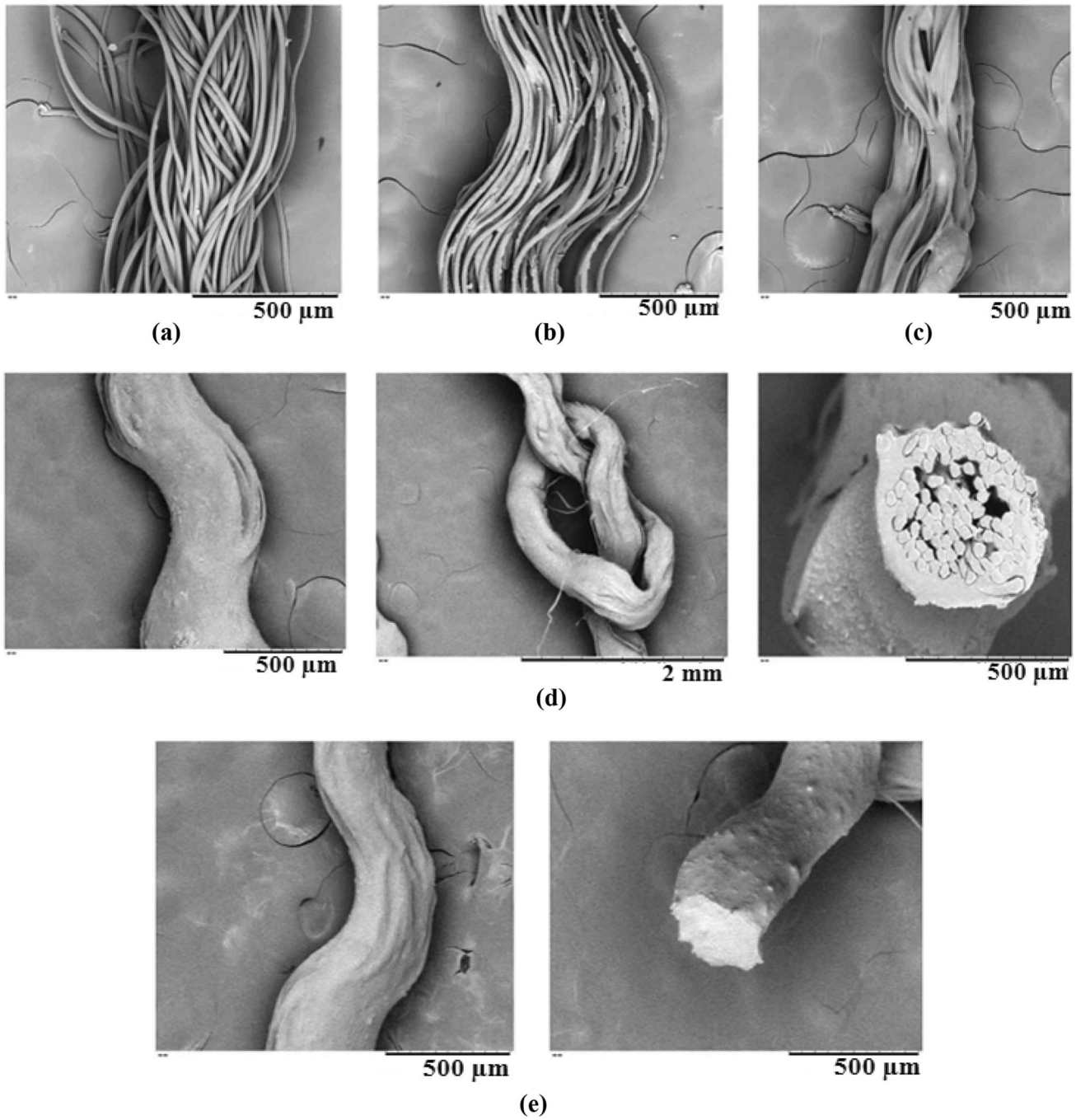

Fig. 8: Surface morphology of (a) raw polyester, (b) PDA-treated, (c) PVA-coated, (d) rGO-coated, and (e) PDMS-coated conductive polyester yarn at different magnifications

tive cotton and polyester yarns showed 12.22 and 20.33 kΩ, respectively. The increased electrical resistance for conductive cotton and polyester yarns from the 5th washing cycle to the 10th washing cycle was 12.32 and 13.26%, respectively.

Mechanical properties

In order to investigate the effect of PDA, PVA, and conductive material on the mechanical properties of cotton and polyester yarns, tensile testing was performed. The stress vs strain (%) curves of cotton and polyester yarns at various steps are depicted in Fig. 6a and 6b, respectively. All test characteristics of mechan-

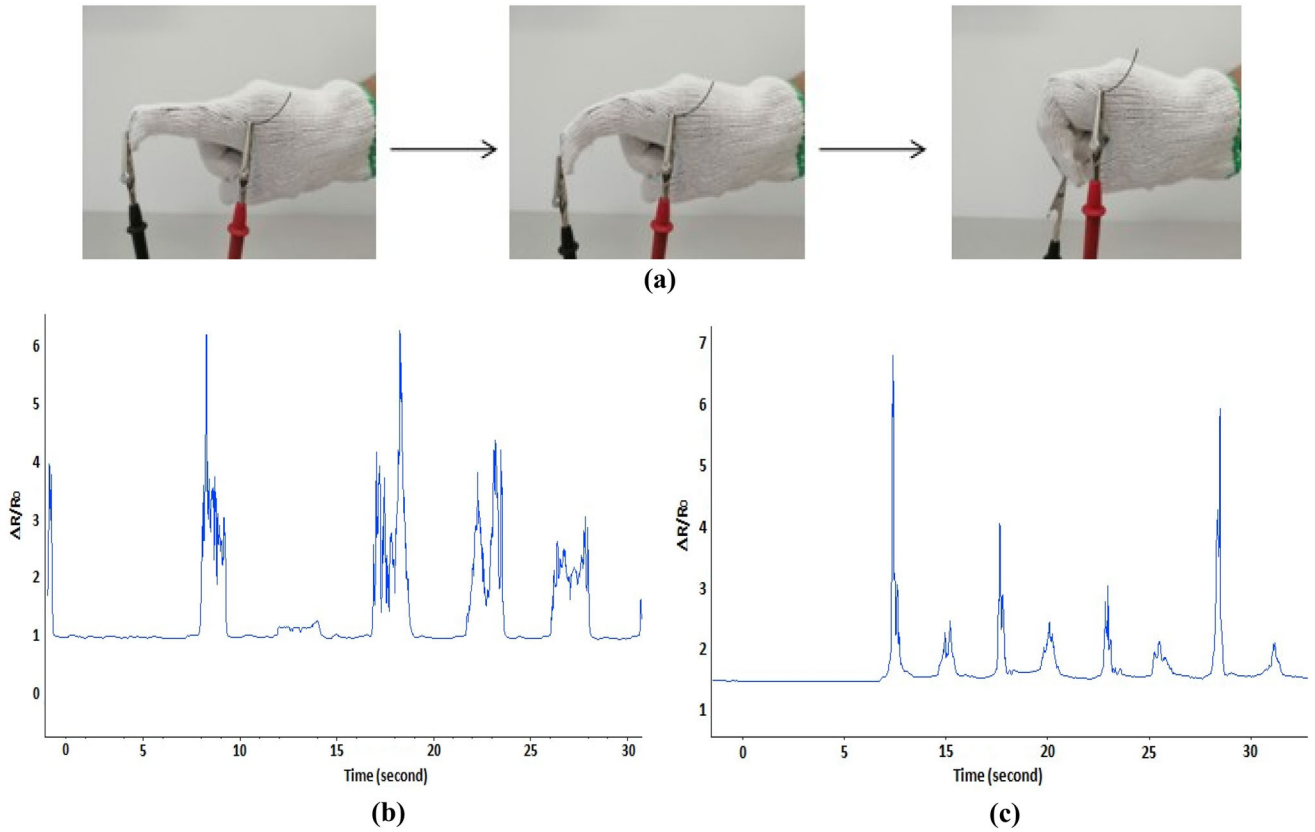

Fig. 9: Detection of human motion with the strain sensor attached to the human finger joint. Photographic image of (a) bending finger and the relative electrical resistance change of conductive (b) cotton and (c) polyester yarns due to finger bending

ical properties such as tensile strength, Young's modulus, and elongation at break (% EAB) are reported. The tensile strength of 100% cotton and polyester yarns (control), PDA-treated, PVA-coated, and rGO-coated cotton and polyester yarns showed 2.26, 3.55, 4.25, 4.38 and 4.68, 5.10, 5.23, 7.97 MPa, respectively. In Table 5, it was seen that 100% polyester yarn illustrated stronger than 100% cotton yarn due to the basic properties of polyester structure. Similarly, the Young's modulus of 100% cotton and polyester yarns, PDA-treated, PVA-coated, and rGO-coated cotton and polyester yarns observed 1.81, 2.67, 3.03, 2.82 and 2.01, 2.20, 3.03, 3.23 MPa, respectively. Moreover, the elongation at break of 100% cotton and polyester yarns, PDA-treated, PVA-coated, and rGO-coated cotton and polyester yarns exhibited 8.61, 10.49, 11.38, 11.77% and 41.69, 46.79, 54.28, 73.59%, respectively.

From these mechanical properties analyses, it is confirmed that PDA and PVA modifications increased the extensibility of conductive yarns due to the chemical bonding between -NH_3 group of dopamine and -OH group of cotton yarn which has been confirmed by FTIR analysis.

Morphological analysis

Changes in surface morphology and cross-sectional appearance of the cotton and polyester yarns at different steps of the fabrication of the conductive yarns were seen throughout the process. These images are shown in Figs. 7 and 8, respectively. The surface of original cotton and polyester yarns was entirely flat, smooth, and clean which was evidenced by the SEM images in Figs. 7a and 8a, respectively. The untreated raw cotton and polyester yarns appear to be free of particles or coatings and separated from each other. Figures 7b and 8b displayed the rough surfaces of PDA-modified cotton and polyester yarns brought about by deposition of dopamine. The granular of dopamine is responsible for significant changes which were properly distributed on the surface of cotton and polyester yarns. The deposition of PDA appears to be uniformly present on the innermost and outermost layer of all textile yarns. PVA is a film-forming polymer, which performed as a coating that bridged the gaps between the cotton and polyester yarns shown in Figs. 7c and 8c, respectively. The PDA-treated rough surface of cotton and polyester yarns has become smooth with the increased number of PVA

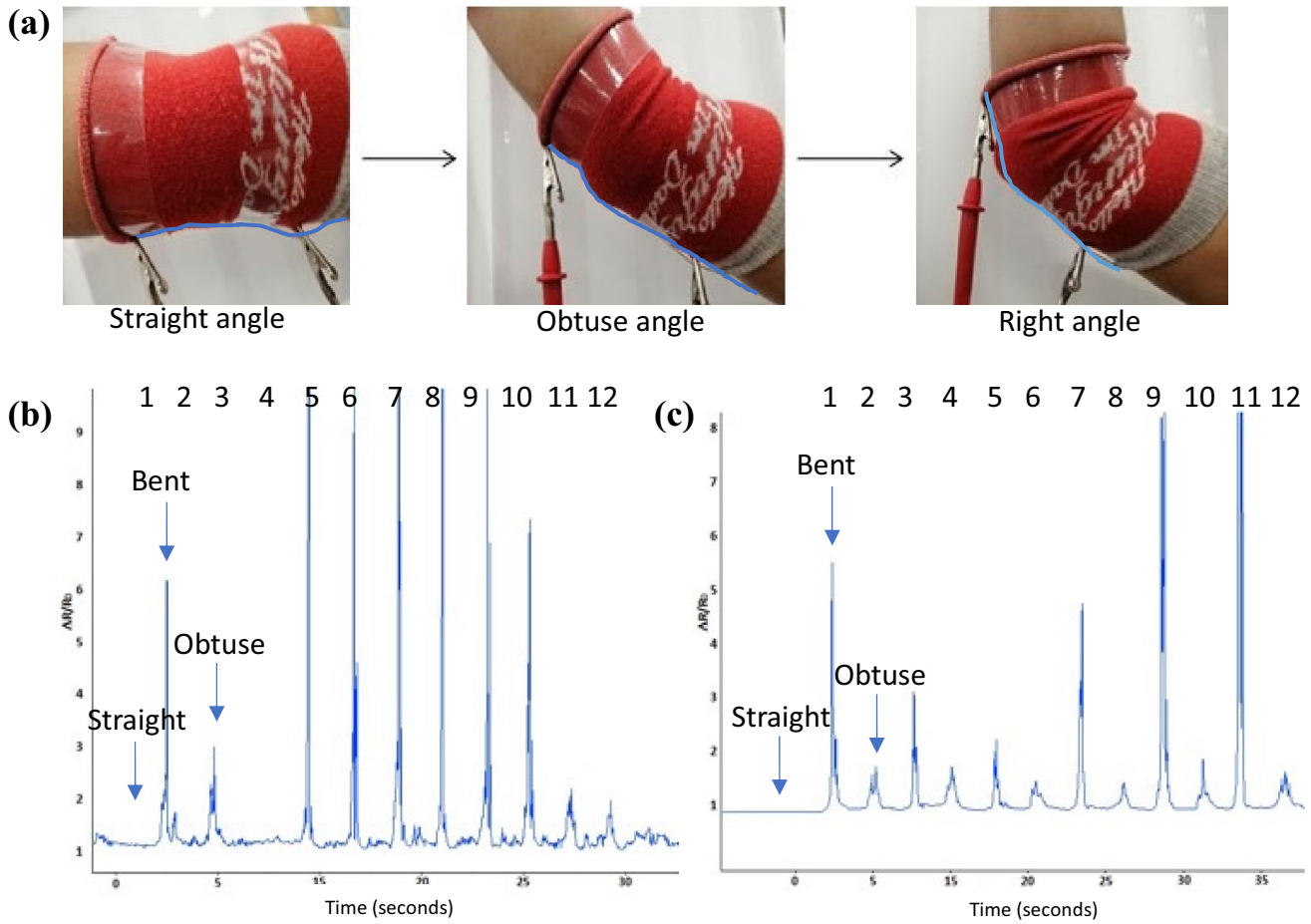

Fig. 10: Detection of human motion with the strain sensor attached to the human elbow joint. Photographic image of the conductive sensor (highlighted in blue) (a) bending elbow and the relative electrical resistance change of conductive (b) cotton and (c) polyester yarns due to elbow movement

coating cycles. It is seen that the cotton and polyester yarns are closely stuck together due to the PVA film.

Figures 7d and 8d show that cotton and polyester yarns were clad with rGO, and it was distributed on the surface successfully. The cotton and polyester yarns (knotted and cross-sectional) clearly revealed that the yarns were uniformly wrapped by rGO coatings due to the hydrogen bonding between rGO and yarn surfaces.[59] From the knotted images, the rGO coatings did not affect the flexibility of all yarns. After PDMS coating, the rGO-coated yarns had a hydrophobic layer, which resisted water penetration due to the presence of silicon (Si) incorporation of PDMS onto the yarn surface.[60] This resultant PDMS wrapped conductive yarns became water resistant, which probably played a vital role in increasing the wash durability.[41] A reduction in the active material density, fragmentation, or the generation of micro/nano-cracks on the active material would decrease the electron conduction pathway.

Strain sensing performance analysis

The rGO-coated and PDMS-encapsulated conductive textile yarns were integrated into a glove or armband by stitching to detect the movement of a finger or an elbow. A variation in electrical resistivity due to the motion frequency and different movements of the finger was observed. Figure 9b and 9c exhibited a real-time proportional increase in relative electrical resistance with the finger repeatedly bending and straightening. In Fig. 9b and 9c, it was established that the higher the bending angle corresponding to the higher value of relative electrical resistance appears that the conductive yarns almost recovered their original lengths due to the improved mechanical properties of PDMS wrapped layer when released.

Figure 10a, 10b, and 10c illustrates the large and small extension and bending of the elbow and the relative electrical resistance changes. The resistivity $\Delta R/R_0$ value of each of the conductive yarn exhibited changes which could be due to the higher deformation

and back and forth movement of the elbow from its original state to a bent position. When the rGO-coated fibers were stretched, the active materials led to a decrease in the overlapped area between active materials and thus the decrease in the electron conduction pathway. The changes in the relative resistance of the strain sensor reflected the finger bending angles. With the increase in the bending angle of the finger, the relative resistance increases. Hence, it is confirmed that the relatively stable and high electrical physiological sensitivity under various bending states can also be applied in sportswear applications for tracking the body movement and respiration monitoring such as heartbeat and pulse.

Conclusions

Highly conductive, responsive, and flexible conductive textile yarns have achieved attention for their applications in wearable smart textiles. In this study, an efficient engineering method was developed to fabricate robust and wash durable conductive textile yarns based on a rGO fiber composite, which were directly integrated into textiles for monitoring the body movements associated with strain sensing. The 2D nanomaterial, in particular, rGO-coated conductive cotton and polyester yarns achieved high wash durability due to the PDA treatment and the hydrophobic PDMS layer. The enhancement of the sensitivity of the strain sensor is ascribed to the incorporation of an electron conduction pathway by utilization of rGO. The highly sensitive strain sensor showed successful detection of body movements demonstrating its potential applications as a wearable human body motion monitor and in soft robotics. This conductive textile yarn has the potential for several applications, including sports clothing, protective clothing, medical textiles, and wearable garments associated with humidity, motion, and pressure sensing.

Acknowledgments The authors would like to acknowledge the financial support from Home Science Alumnae/Todhunter/Carpenter Scholarship, University of Otago, Dunedin, New Zealand.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Conflict of interest The authors declare that they do not have any conflict of interest.

References

1. Tian, X, Chan, K, Hua, T, Niu, B, Chen, S, ''Wearable Strain Sensors Enabled by Integrating One-Dimensional Polydopamine-Enhanced Graphene/Polyurethane Sensing Fibers into Textile Structures.'' *J. Mater. Sci.*, **55** (36) 17266–17283 (2020)
2. Islam, GMN, Ali, A, Collie, S, ''Textile Sensors for Wearable Applications: A Comprehensive Review.'' *Cellulose*, **27** (11) 6103–6131 (2020)
3. Makhlouf, G, Abdelkhalik, A, Ameen, H, ''Preparation of Highly Efficient Chitosan-Based Flame Retardant Coatings with Good Antibacterial Properties for Cotton Fabrics.'' *Prog. Org. Coat.*, **163** 106627–106639 (2022)
4. Xu, Q, Wang, L, Fu, F, Liu, X, ''Fabrication of Fluorine-Free Superhydrophobic Cotton Fabric Using Fumed Silica and Diblock Copolymer via Mist Modification.'' *Prog. Org. Coat.*, **148** 105884–105895 (2020)
5. Gao, Q, Zhang, J, Xie, Z, Omisore, O, Zhang, J, Wang, L, Li, H, ''Highly Stretchable Sensors for Wearable Biomedical Applications.'' *J. Mater. Sci.*, **54** (7) 5187–5223 (2018)
6. Zhao, Y, Wang, J, Li, Z, Zhang, X, Tian, M, Zhang, X, Liu, X, Qu, L, Zhu, S, ''Washable, Durable and Flame Retardant Conductive Textiles Based on Reduced Graphene Oxide Modification.'' *Cellulose*, **27** (3) 1763–1771 (2020)
7. Xu, T, Zhang, Z, Qu, L, ''Graphene Based Fibers: Recent Advances in Preparation and Application.'' *Adv. Mater.*, **32** (5) 1901979–1901994 (2020)
8. Sun, L, Wang, F, Jiang, J, Liu, H, Du, B, Li, M, Liu, Y, Li, M, ''A Wearable Fabric Strain Sensor Assemblied by Graphene with Dual Sensing Performance Approach to Practice Application Assisted by Wireless Bluetooth.'' *Cellulose*, **27** (13) 1–13 (2020)
9. Junrong, Z, Weihua, S, Jun, P, Yunjie, Y, Bo, X, Chaoxia, W, ''Microwave Thermally Expanded Graphene/Polyaniline Conductive Paste for Elaborate Conductive Pattern and Conductive Polyester Fabric Fabrication via Screen Printing.'' *J. Coat. Technol. Res.*, **19** (2) 477–485 (2022)
10. LepakKuc, S, Taborowska, P, Tran, TQ, Duong, HM, Gizewski, T, Jakubowska, M, Patmore, J, Lekawa-Raus, A, ''Washable, Colored and Textured, Carbon Nanotube Textile Yarns.'' *Carbon*, **172** 334–344 (2021)
11. Zhuang, Z, Cheng, N, Zhang, L, Liu, L, Zhao, J, Yu, H, ''Wearable Strain Sensor Based on Highly Conductive Carbon Nanotube/Polyurethane Composite Fibers.'' *Nanotechnology*, **31** (20) 205701–205710 (2020)
12. Yang, HJ, Lee, JY, Yu, WR, ''Carbon Nanotube Fiber Assemblies with Braided Insulation Layers for Washable Capacitive Textile Touch Sensors.'' *Funct. Compos. Struct.*, **2** (1) 015007–015016 (2020)
13. Khair, N, Islam, R, Shahariar, H, ''Carbon-Based Electronic Textiles: Materials, Fabrication Processes and Applications.'' *J. Mater. Sci.*, **54** (14) 10079–10101 (2019)

14. Farbod, A, Mazeyar, PG, Ali, S, ''Functional Cellulose Fibers via Polycarboxylic Acid/Carbon Nanotube Composite Coating.'' *J. Coat. Technol. Res.*, **10** (1) 123–132 (2013)
15. Tseghai, GB, Mengistie, DA, Malengier, B, Fante, KA, Van Langenhove, L, ''PEDOT:PSS Based Conductive Textiles and Their Applications.'' *Sensors (Basel)*, **20** (7) 1–18 (2020)
16. Luo, R, Li, H, Du, B, Zhou, S, Zhu, Y, ''A Simple Strategy for High Stretchable, Flexible and Conductive Polymer Films Based on PEDOT:PSS-PDMS Blends.'' *Org. Electron.*, **76** 105451–105458 (2020)
17. Kayser, LV, Lipomi, DJ, ''Stretchable Conductive Polymers and Composites Based on PEDOT and PEDOT:PSS.'' *Adv. Mater.*, **31** (10) 1806133–1806145 (2019)
18. Islam, GMN, Collie, S, Qasim, M, Ali, MA, ''Highly Stretchable and Flexible Melt Spun Thermoplastic Conductive Yarns for Smart Textiles.'' *Nanomaterials*, **10** (12) 1–23 (2020)
19. Islam, GMN, Ali, MA, Collie, S, ''Polydopamine Treated and PEDOT:PSS Coated Wash Durable Conductive Textiles for Wearable Applications.'' *Fibers Polym.*, **23** (4) 914–924 (2022)
20. Krause, B, Rzeczkowski, P, Potschke, P, ''Thermal Conductivity and Electrical Resistivity of Melt-Mixed Polypropylene Composites Containing Mixtures of Carbon-Based Fillers.'' *Polymers (Basel)*, **11** (6) 1–15 (2019)
21. Yu, R, Zhu, C, Wan, J, Li, Y, Hong, X, ''Review of Graphene Based Textile Strain Sensors, with Emphasis on Structure Activity Relationship.'' *Polymers*, **13** (1) 151–172 (2021)
22. Zahid, M, Papadopoulou, EL, Athanassiou, A, Bayer, IS, ''Strain-Responsive Mercerized Conductive Cotton Fabrics Based on PEDOT:PSS/Graphene.'' *Mater. Des.*, **135** 213–222 (2017)
23. Lee, H, Glasper, MJ, Li, X, Nychka, JA, Batcheller, J, Chung, HJ, Chen, Y, ''Preparation of Fabric Strain Sensor Based on Graphene for Human Motion Monitoring.'' *J. Mater. Sci.*, **53** (12) 9026–9033 (2018)
24. Meng, Q, Liu, Z, Han, S, Xu, L, Araby, S, Cai, R, Zhao, Y, Lu, S, Liu, T, ''A Facile Approach to Fabricate Highly Sensitive, Flexible Strain Sensor Based on Elastomeric/Graphene Platelet Composite Film.'' *J. Mater. Sci.*, **54** (15) 10856–10870 (2019)
25. Niu, B, Hua, T, Hu, H, Xu, B, Tian, X, Chan, K, Chen, S, ''A Highly Durable Textile-Based Sensor as a Human-Worn Material Interface for Long-Term Multiple Mechanical Deformation Sensing.'' *J. Mater. Chem. C*, **7** (46) 14651–14663 (2019)
26. Chen, S, Liu, S, Wang, P, Liu, H, Liu, L, ''Highly Stretchable Fiber-Shaped e-Textiles for Strain/Pressure Sensing, Full-Range Human Motions Detection, Health Monitoring, and 2D Force Mapping.'' *J. Mater. Sci.*, **53** (4) 2995–3005 (2017)
27. Afroj, S, Karim, N, Wang, Z, Tan, S, He, P, Holwill, M, Ghazaryan, D, Fernando, A, Novoselov, KS, ''Engineering Graphene Flakes for Wearable Textile Sensors via Highly Scalable and Ultrafast Yarn Dyeing Technique.'' *ACS Nano*, **13** (4) 3847–3857 (2019)
28. Qu, J, He, N, Patil, SV, Wang, Y, Banerjee, D, Gao, W, ''Screen Printing of Graphene Oxide Patterns onto Viscose Nonwovens with Tunable Penetration Depth and Electrical Conductivity.'' *ACS Appl. Mater. Interfaces*, **11** (16) 14944–14951 (2019)
29. Hong, X, Yu, R, Hou, M, Jin, Z, Dong, Y, Zhu, C, Wan, J, Li, Y, ''Smart Fabric Strain Sensor Comprising Reduced Graphene Oxide with Structure-Based Negative Piezoresistivity.'' *J. Mater. Sci.*, **56** (30) 16946–16962 (2021)
30. Gabryś, T, Fryczkowska, B, Biniaś, D, Ślusarczyk, C, Fabia, J, ''Preparation and Properties of Composite Cellulose Fibres with the Addition of Graphene Oxide.'' *Carbohydr. Polym.*, **254** 117436–117446 (2021)
31. Gao, S, Li, H, Zheng, L, Huang, W, Chen, B, Lai, X, Zeng, X, ''Superhydrophobic and Conductive Polydimethylsiloxane/Titanium Dioxide@Reduced Graphene Oxide Coated Cotton Fabric for Human Motion Detection.'' *Cellulose*, **28** (11) 7373–7388 (2021)
32. Schäl, P, Juhász Junger, I, Grimmelsmann, N, Ehrmann, A, ''Development of Graphite Based Conductive Textile Coatings.'' *J. Coat. Technol. Res.*, **15** (4) 875–883 (2018)
33. Madheswaran, B, Shanmugam, S, Tetsuo, S, ''Coating of Green-Synthesized Silver Nanoparticles on Cotton Fabric.'' *J. Coat. Technol. Res.*, **14** (3) 735–745 (2017)
34. Zeng, F, Qin, Z, Li, T, Chen, Y, Yang, L, ''Boosting Phosphorus–Nitrogen–Silicon Synergism Through Introducing Graphene Nanobrick Wall Structure for Fabricating Multifunctional Cotton Fabric by Spray Assisted Layer-by-Layer Assembly.'' *Cellulose*, **27** (11) 6691–6705 (2020)
35. Liu, L, Shen, Z, Zhang, X, Ma, H, ''Highly Conductive Graphene/Carbon Black Screen Printing Inks for Flexible Electronics.'' *J. Colloid Interface Sci.*, **582** 12–21 (2021)
36. Aminayi, P, Young, B, Young, T, Sprowl, L, Joyce, M, ''Inkjet Printing and Surface Treatment of an Optimized Polyurethane Based Ink Formulation as a Suitable Insulator Over Silver for Contact with Aqueous Based Fluids in Low Voltage Applications.'' *J. Coat. Technol. Res.*, **14** (3) 641–649 (2017)
37. Kim, Y, Kim, S, Lee, WH, Kim, H, ''Direct Transfer of CVD-Grown Graphene onto Eco-friendly Cellulose Film for Highly Sensitive Gas Sensor.'' *Cellulose*, **27** (3) 1685–1693 (2019)
38. Xu, L, Zhai, H, Chen, X, Liu, Y, Wang, M, Liu, Z, Umar, M, Ji, C, Chen, Z, Jin, L, Liu, Z, Song, Q, Yue, P, Li, Y, Ye, TT, ''Coolmax/Graphene-Oxide Functionalized Textile Humidity Sensor with Ultrafast Response for Human Activities Monitoring.'' *Chem. Eng. J.*, **412** 128639–128647 (2021)
39. Afroj, S, Tan, S, Abdelkader, AM, Novoselov, KS, Karim, N, ''Highly Conductive, Scalable and Machine Washable Graphene-Based E-Textiles for Multifunctional Wearable Electronic Applications.'' *Adv. Funct. Mater.*, **30** (23) 2000293–2000302 (2020)
40. Li, Y, Samad, YA, Liao, K, ''From Cotton to Wearable Pressure Sensor.'' *J. Mater. Chem. A*, **3** (5) 2181–2187 (2015)
41. Li, X, Koh, KH, Farhan, M, Lai, KWC, ''An Ultraflexible Polyurethane Yarn-Based Wearable Strain Sensor with a Polydimethylsiloxane Infiltrated Multilayer Sheath for Smart Textiles.'' *Nanoscale*, **12** (6) 4110–4118 (2020)
42. Feng, J, Yu, T, Sun, M, Sen, H, Ji, X, Li, C, Wang, X, ''Polydopamine-Coated Cotton Fibers as the Adsorbent for In-Tube Solid-Phase Microextraction.'' *J. Sep. Sci.*, **42** (12) 2163–2170 (2019)
43. Ou, J, Ma, J, Wang, F, Li, W, Fang, X, Lei, S, Amirfazli, A, ''Unexpected Superhydrophobic Polydopamine on Cotton Fabric.'' *Prog. Org. Coat.*, **147** 105777–105784 (2020)
44. Li, P, Lu, Z, Ma, K, Zou, G, Chang, L, Guo, W, Tian, K, Li, X, Wang, H, ''UV-Triggered Self-Healing SiO_2/PDA Hybrid Microcapsules with Both Enhanced UV-Shielding Ability and Improved Compatibility for Epoxy Resin Coating.'' *Prog. Org. Coat.*, **163** 106636–106644 (2022)
45. Oroujeni, M, Kaboudin, B, Xia, W, Jönsson, P, Ossipov, DA, ''Conjugation of Cyclodextrin to Magnetic Fe_3O_4 Nanoparticles via Polydopamine Coating for Drug Delivery.'' *Prog. Org. Coa.*, **114** 154–161 (2018)

46. Denton, MJ, Daniels, PN, *Textile Terms and Definitions*. The Textile Institute, Manchester (2018)
47. Emam, HE, Bechtold, T, ''Cotton Fabrics with UV Blocking Properties Through Metal Salts Deposition.'' *Appl. Surf. Sci.*, **357** 1878–1889 (2015)
48. Barkhordari, S, Yadollahi, M, Namazi, H, ''pH Sensitive Nanocomposite Hydrogel Beads Based on Carboxymethyl Cellulose/Layered Double Hydroxide as Drug Delivery Systems.'' *J. Polym. Res.*, **21** (6) 454–453 (2014)
49. Parvinzadeh, M, Ebrahimi, I, ''Influence of Atmospheric-Air Plasma on the Coating of a Nonionic Lubricating Agent on Polyester Fiber.'' *Radiat. Effects Defects Solids*, **166** (6) 408–416 (2011)
50. Boroumand, Y, Razmjou, A, Moazzam, P, Mohagheghian, F, Eshaghi, G, Etemadifar, Z, Asadnia, M, Shafiei, R, ''Mussel Inspired Bacterial Denitrification of Water Using Fractal Patterns of Polydopamine.'' *J. Water Process Eng.*, **33** 101105–101115 (2020)
51. Xu, J, Jiang, SX, Peng, L, Wang, Y, Shang, S, Miao, D, Guo, R, ''AgNps-PVA–Coated Woven Cotton Fabric: Preparation, Water Repellency, Shielding Properties and Antibacterial Activity.'' *J. Ind. Text.*, **48** (10) 1545–1565 (2018)
52. Swarna, N, Jeyakodi, JM, ''Surface Modification of Polyester Fabric Using Polyvinyl Alcohol in Alkaline Medium.'' *Indian J. Fibre Text. Res.*, **37** 287–291 (2012)
53. OlakKucharczyk, M, Szczepańska, G, Kudzin, MH, Pisarek, M, ''The Photocatalytical Properties of rGO/TiO_2 Coated Fabrics.'' *Coatings*, **10** (11) 1041–1055 (2020)
54. Wang, F, Mu, P, Zhang, Z, Chen, T, Li, Y, Sun, H, Zhu, Z, Liang, W, Li, A, ''Reduced Graphene Oxide Coated Hollow Polyester Fibers for Efficient Solar Steam Generation.'' *Energy Technol.*, **7** (7) 1900265–1900274 (2019)
55. Deogaonkar, SC, ''Dielectric Barrier Discharge Plasma Induced Surface Modification of Polyester/Cotton Blend Fabrics to Improve Polypyrrole Coating Adhesion and Conductivity.'' *J. Text. Inst.*, **111** (10) 1530–1537 (2020)
56. Wilson, S, Laing, R, Tan, EW, Wilson, C, ''Encapsulation of Electrically Conductive Apparel Fabrics: Effects on Performance.'' *Sensors*, **20** (15) 1–30 (2020)
57. Jose, M, Oudebrouckx, G, Bormans, S, Veske, P, Thoelen, R, Deferme, W, ''Monitoring Body Fluids in Textiles: Combining Impedance and Thermal Principles in a Printed, Wearable and Washable Sensor.'' *ACS Sensors*, **6** (3) 896–907 (2021)
58. Rana, M, Hao, B, Mu, L, Chen, L, Ma, PC, ''Development of Multi-Functional Cotton Fabrics with Ag/AgBr–TiO_2 Nanocomposite Coating.'' *Compos. Sci. Technol.*, **122** 104–112 (2016)
59. Nazmul, K, Afroj, S, Tan, S, He, P, Fernando, A, Carr, C, Novoselov, KS, ''Scalable Production of Graphene Based Wearable e-Textiles.'' *ACS Nano*, **11** (12) 12266–12275 (2017)
60. Jin, Y, Jiang, P, Ke, Q, Cheng, F, Zhu, Y, Zhang, Y, ''Superhydrophobic and Superoleophilic Polydimethylsiloxane-Coated Cotton for Oil–water Separation Process: An Evidence of the Relationship Between Its Loading Capacity and Oil Absorption Ability.'' *J. Hazard. Mater.*, **300** 175–181 (2015)