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RESEARCH

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Washability and abrasion resistance of illuminative knitted e-textiles with POFs and silver-coated conductive yarns

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Abstract

For the integration of conductive yarns in e-textiles, knitting offers structural versatility and malleability for wider product applications in the contexts of wearables and interiors. To enable mass adoption of conductive materials, it is imperative for users to be able to launder these materials as part of product maintenance. Interactive textiles knitted from polymeric optical fibres (POFs) and silver-coated conductive yarns are able to illuminate and change colours via integrated touch sensor systems. Current research only focuses on the washability and abrasion resistance of conductive yarns solely and not both POF and conductive yarn within the same fabric structure. This study is novel as it investigates the washability and abrasion resistance of POF and silver-coated conductive yarn integrated knitted textiles with different loop structures and the impact to their illuminative function. POFs were knitted within the same fabric structure by the inlay method using a 7-gauge industrial hand-operated flatbed knitting machine. This study examined how washing and abrasion affect POFs and silver-coated conductive yarn in five different knit structures, and the illuminative function of the knitted textiles. Washing and abrasion affected the resistance of conductive yarns. Scratches and bent POFs were observed after 20 gentle washing cycles. However, washing had minimal impact on the illuminative function of the knitted e-textiles examined in this study. The experiments provide evidence that e-textiles knitted with POFs and conductive yarns in the same fabric structure withstand washing and abrasion and thus have the potential for mass market adoption in fashion and interior applications.

Keywords: Washability, Conductive yarns, Polymeric optical fibres (POFs), Flatbed knitting machine, POF integrated knitted textile, Illuminative knitted textile

Introduction

The area of electronic textiles (e-textiles) is an emerging sector of the textile industry. Market research forecasts that the wearable technology market will grow from $116.2 billion in 2021 to $265.4 million by 2026. Surging demand for smart devices will drive the growth of the market in the coming years (MarketsandMarkets, 2021). Interdisciplinary research that has applied technology to fabrication techniques has brought technological advances in the development of smaller and more powerful electronic components that can be integrated into a variety of wearables (Kumar & Vigneswaran, 2015). Applications made possible by integrating electronic components into textiles to achieve functions such as heating, light emitting, sensing, and communication are not limited to the fields of health monitoring, rehabilitation, gaming, sports, and the military (Ashour & Rashdan, 2021; Shi et al., 2020; Zahid et al., 2021).

In the fabrication of e-textiles, conductive yarn is both the key element and the backbone of the textile in achieving good conductivity for wearable applications (Ismar et al.,2018). Silver-coated conductive yarns have been widely used in wearable e-textiles, as silver is the most conductive of all metals and is cost effective and hypoallergenic (Atwa et al., 2015; Chui et al., 2016). These yarns have potential in the use of e-textiles in wearables and interior applications. Regarding the integration of conductive material into textiles to achieve different functions, knitting offers versatility and malleability for fabrication. Knitting techniques give the stretchability and flexibility needed for the development of a shaped panel and body-conscious garment (Chen et al., 2020).

For the mass adoption of e-textiles, it is essential to provide solutions for daily maintenance. It is therefore crucial to investigate how typical laundry conditions affect their functionality. Conductive materials are sensitive to washing and wear (Hwang et al., 2020). The impact of washing and abrasion on the electrical resistance of e-textiles with conductive material cannot be overlooked because the daily care of e-textiles affects conductivity and functionality. Hence, research into conductive knitted e-textiles has become a focus of attention, as this is one of the major problems to overcome in product development (Hossain & Bradford, 2021; Van der Velden et al., 2015). Understanding of concerns about launderability will benefit the potential development of an interactive knitted e-textile with integrated conductive material in terms of the mass market adoption, reliability and applicability of the product (Ismar et al.,2019).

E-textiles with an illumination function aim to increase interactivity by emitting light and changing colour. The application of polymethyl methacrylate (PMMA) polymeric optical fibre (POF) achieves illumination through knitting and coupling to a light source. By integrating conductive yarn into POF textiles, a touch or proximity sensitive function is enabled, allowing control of the illumination and colour-changing effects of the end product (Tan et al., 2019). The illuminative property of POF has the potential to achieve personalised aesthetic features because of the colour changing effect. It could be used in a variety of applications and scenarios that are not limited to fashion, interiors and wearables (Gong et al., 2019; Tan et al., 2021).

This study examines the washability and abrasion resistance of illuminative e-textiles knitted with POF and silver-coated conductive yarns. POFs were integrated into five knitted structures by the inlay method in a 7-gauge industrial hand-operated flatbed knitting machine. Cotton-blend yarns were used as the base yarn in our knitted e-textile, and silver-coated conductive yarn was knitted with the base yarn to form the e-textile. Both POF and silver-coated conductive yarn are knitted within the same fabric structure.

POF is brittle and fragile, and the core of the fibre tends to break when abruptly bent. The broken core disrupts light transmission and affects the illumination of the textiles. Challenges in knitting POFs, such as slippery yarn, lack of elasticity, breakage on yarn unwinding and tension, were discussed in previous research, and viable knitting structures were developed to overcome the integral characteristics of POF. Research by Chen et al. (2020) focused on developing POF knit textiles by using a hand-operated flatbed knitting machine, which offers the flexibility for the yarn to unwind from the cone with the proper tension and without a specialised yarn feeding machine, as well as a simpler system for instant tension adjustment. Computerised knitting machines are built with protective cases around the knit beds, whereas hand-operated flatbed knitting machines have exposed knitting beds, enabling researchers to observe the textile close-up during the manufacturing process, allowing the immediate adjustment of tension to prevent breakage.

Many studies have assessed the resistance of the conductive yarn or thread stitched onto textiles after washing or abrasion (Briedis et al., 2019; Dourado et al. (2016); Eskandarian et al., 2020; Linz, 2011; Parkova & Vi, 2014; Sofronova & Angelova, 2020; Tao et al., 2017; Zaman et al.,2020). However, knitted e-textiles with integrated POF and silver-coated conductive yarn are currently under-explored. This study investigates the washability and abrasion resistance of knitted textiles made with POF and silver conductive yarn to achieve illuminative functions by connecting to a light source. We now conduct a review of the literature on the washability and abrasion resistance of general conductive yarn and textiles to understand the changes in electrical resistance after mechanical stresses.

There are many challenges to the successful commercialisation of an e-textile prototype in terms of reliability and durability (Hossain & Bradford, 2021). The ability of a textile to retain its electrical properties after washing is critical to the development of a wearable e-textile. Many researchers and scholars have explored the washability of e-textiles with silver-coated conductive yarn.

Linz (2011) examined the embroidered conductive yarn on a thin flexible substrate after 20 washes, its resistance rose from 1Ω to 8.5Ω. Tao et al. (2017) investigated the resistance changes of twenty fabric specimens with conductive threads sewn after washing. The resistances of sewn conductive threads increase gradually after 10 wash cycles and even reached 2773 Ω/m after 50 wash cycles. Briedis et al. (2019) measured the changes of electrical resistance of silver-coated conductive yarn sewn onto fabric substrate after multiple washing. Resistance increased to nearly 10 times of initial resistance after 17 washes. Sofronova and Angelova (2020) measured the resistance of single silver-coated conductive yarn and yarn sewn onto knitted textile after washing for five times. Increase of resistance of both samples was found after washed for one, three and five cycles. Results from both studies showed that the resistances of most of the conductive yarns increased with the increasing the number of washing cycles. It is summarised that washing has affected to the electrical properties of conductive yarn stitched into textile layer. Gaubert et al. (2020) reported the increase of resistance of silver-coated conductive yarn after washing for 30 times (ratio of 19.3 compared to unwashed value). And, the removal of silver layer from the core nylon yarn was observed, and damage to the yarn was obvious. Eskandarian et al. (2020) explained the increase in the resistance of a fabric sample with silver yarn after washing was in the range of 100% to 300%.

Parkova and Vi (2014) investigated the resistance changes on silver-coated conductive yarn sewn onto fabric substrate and integrated woven fabric. In the washing test, silver-coated conductive yarn in both sewn and woven samples reached at around 39.3–40.3Ω after 5 wash cycles. Rotzler et al. (2020) analysed the electrical resistance of and damage to three conductive textiles after 10 wash cycles. The impact found on the conductive yarn after 10 delicate washes was relatively low. The result was showed by the evaluation of breakages observed on X-ray microscopy images on yarn after 10 wash cycles. The breakages found on higher setting of washing time, temperature and mechanical action were significantly higher than the sample in delicate mode (nearly six to eight times more). It is suggested to have delicate washing to minimise the friction in washing to the silver-coated conductive yarn. Repon et al. (2021) examined a series of knitted fabrics with silver-coated polyamide yarn after washing, while some of the fabrics reached around 4.5Ω from 1.8Ω after 5 wash cycles.

Dourado et al. (2016) evaluated the resistance changes of silver-coated conductive yarn embroidered on fabric substrates after 20 washes and 80,000 rubs. The resistance increased rapidly after nine washes (from around 20 Ω to 90 Ω). Authors suspected that part of the silver-coated layer is lost with the washing process. After 40,000 abrasion cycles, pronounced increase in the resistance was found on samples (2.5 to 3 times more). Zaman et al. (2020) investigated in detail the wash damage to conductive fabric made of silver-coated conductive yarn embroidered on fabric substrate after 50 washes and the damage caused by Martindale abrasion. The surface resistance increased to 1.2 ratio after 50 washes. While the resistance change of samples after abrasion testing after 10,000 rubs was increased to 2 in ratio.

Ahmmed et al., (2021) examined the resistance of silver coated Vectran (SCV) conductive yarns after 25 washes, it increased from 0.84Ω to 1.9Ω per 0.3 m gauge length. Besides, Simegnaw et al. (2021)studied the resistance changes of a Vectran e-yarn was fabricated by integrating SCV with surface mounted electronic device after washing and abrasion. After 25 wash cycles, the resistance of SCV-conductive yarn and e-yarn reached 72.16Ω per 0.13 m length. After 800 times of mechanical abrasion cycle, the resistance of SCV conductive yarn and e-yarn increased by 114.6% and 240.9% respectively.

When it comes to the application of silver conductive yarn in textiles, both chemical and mechanical impacts to the material is crucial for the development of e-textile. uz Zaman et al. (2019) studied the impact of washing and abrasion to the silver-coated conductive yarn stitched into textile layer. It is showed the linear trend for the changes of resistance after washing for 10 times and abrasion for 3000 cycles. The increase of the resistance with the increasing number of wash cycles and abrasion cycles.

Numerous studies into the washability of conductive yarn have shown that washing impacts the resistivity. Electrical resistance increases with the number of washing cycles and abrasion. Current research only focuses on the washability and abrasion resistance of conductive yarns or thread stitched onto the textile. Limited research studied on the damage from washing and abrasion to the resistance and illuminative function of e-textiles with silver conductive yarn and POF knitted fabric structure. This study is different in that it considers textiles with conductive yarn and POF that are integrated into the same knitted structure. There is a lack of research focused on the issues of washing and abrasion of POF knitted textiles with integrated conductive yarns, and their illuminative effects. Knitted textiles made with POFs and silver conductive yarn using a 7-gauge industrial hand-operated flatbed knitting machine. This study examined how washing and abrasion affect POFs and silver-coated conductive yarn in five different knit structures, and the illuminative effects of the knitted textile after washing.

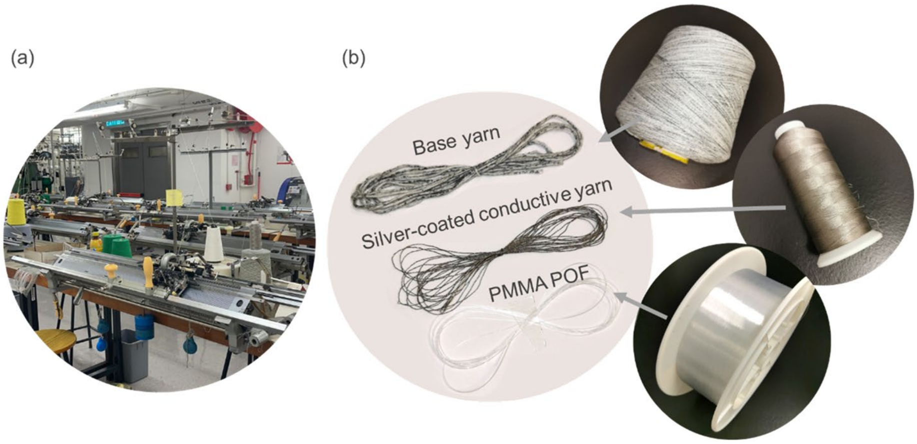

Fig. 1 shows photos of **a** a 7-gauge hand-operated flatbed knitting machine; **b** Yarns and POF used in the knitted e-textile: base yarn; silver-coated conductive yarn; and polymethyl methacrylate (PMMA) polymeric optical fibre (POF)

Table 1 Specification of materials used for the knitted e-textile

Material	Yarn count	Composition	Resistance
Silver-coated conductive yarn	200 D	18% Silver 82% Nylon	< 5 Ω/cm
Base yarn (Di.Vè S.p.A. SUPERBO ETNICO)	5.2 Nm	95% Cotton 5% Polyester	–
POF (Eska™)	0.25 mm	PMMA	–

Notes: *POF* polymeric optical fibre, *PMMA* polymethyl methacrylate

Methods

Materials

Five knitted structures were developed on a 7-gauge hand-operated flatbed knitting machine (Wealmart, Hong Kong, China) (Fig. 1a) for the experiments. The specifications of the materials used in the knitted e-textile are listed in Table 1 and photos are shown in Fig. 1b. In this study, a 5.2Nm 95% cotton, 5% polyester yarn was used as the base yarn and knitted together with a 200D silver-coated conductive yarn (18% Silver, 82% Nylon). The resistance of untreated silver-coated conductive yarn is < 5 Ω/cm. 0.25 mm Eska™ PMMA POF was selected for all of the knitted textiles to achieve the illuminative effect.

Double-knitted structure designs

Five double-knitted textiles with knit, tuck and miss stitches were developed in this study, including double knit, half cardigan, full cardigan, half Milano and full Milano. Four pieces of 0.25 mm Eska™ POFs were inlaid manually in every two courses during knitting.

Figure 2 illustrates the knitting notation of five double-knitted structures indicating where the POFs were inlaid. Four different symbols indicate five different types of stitches: a cross means a technical front knit stitch, a white circle with black outline means a technical back knit stitch, a black circle means a tuck stitch, an empty box means a miss stitch and a left-pointing arrow means the inlay of POFs. The corresponding loop

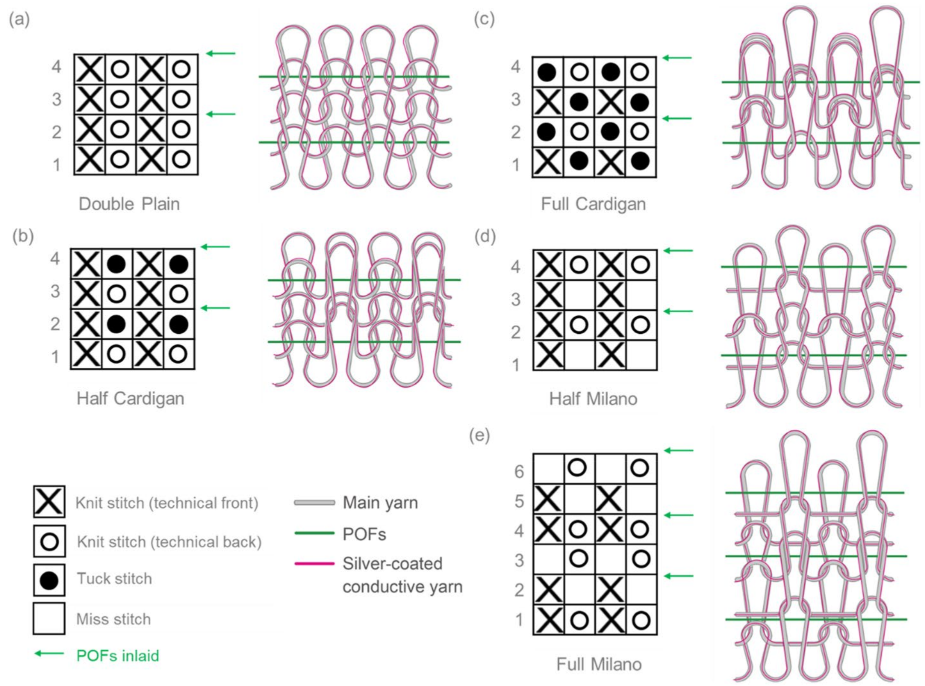

Fig. 2 Diagram showing the stitch notations and illustrations of five double-knitted structures with the indication of polymeric optical fibre (POF) inlaid: **a** double plain; **b** half cardigan; **c** full cardigan; **d** half Milano; and **e** full Milano

formation and POFs inlaid are illustrated, in which grey indicates the base yarn, red indicates the silver-coated conductive yarn and green indicates the POFs.

Figure 3 shows a 'waste section' that was added to the edge of the main body of the knitting structure to attach a light source to the textile for the illuminative effect (Chen et al., 2020). In Fig. 3a, the waste section included a part of the POF floats and was added to the right side of the structure for POF bundling and light-emitting diode (LED) coupling (Fig. 3b). The additional 6-stitch waste section was added to the 35-stitch main body of the POF long floats. When the textile was cast off, the waste section was cut and prepared for POF bundling.

Table 2 shows the specification of the five double-knitted textiles developed for this study, which include double plain (DP), half cardigan (HC), full cardigan (FC), half Milano (HM) and full Milano (FM). The wales per inch (WPI) / course (CPI) of the five knitted textiles were 7.77/11.33, 5.74/8.38, 6.5/9.55, 8.74/8.59 and 8.89/15.29, respectively. The densities of the five knitted textiles were 88.05, 48.12, 62.1, 75.01 and 135.94, respectively.

Washing and drying

For further product development of the proposed knitted e-textile, the goal was that the product should retain functionality and performance after being subjected to customers' normal home laundering washing methods. The washing and drying test was performed in accordance with AATCC TM135-2018. A Whirlpool 3LWTW4815FW top-loading machine was used in this washing test. The delicate cycle in cold wash (27 ± 3 °C) was chosen to give a gentle movement of washing and spinning during the whole washing procedure. The agitation speed was 27 strokes/min and the

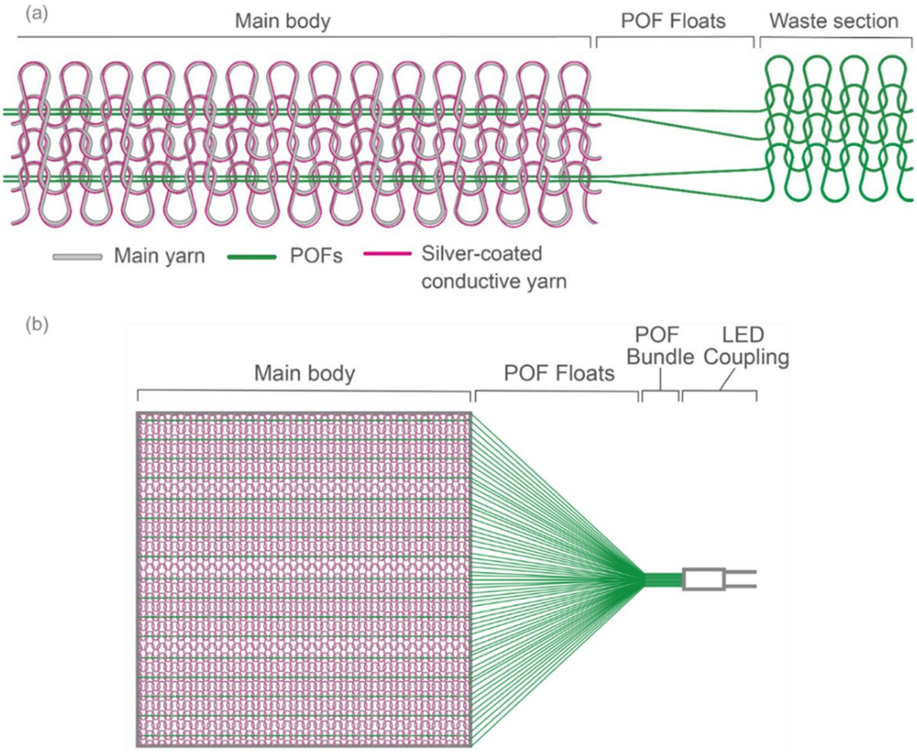

Fig. 3 Diagram showing **a** the 'waste section', part of the polymeric optical fibre (POF) floats knitted into the main body of knitted textiles, and **b** the POF bundle attached to a light source (LED coupling)

Table 2 Specification of double-knitted samples

Knitted textile code	DP	HC	FC	HM	FM
Knitting structure	Double Plain	Half cardigan	Full cardigan	Half milano	Full milano
Weight (g/cm^2)	7.2	7.4	9.1	8.2	10.5
Thickness (mm)	3.0	4.5	5.1	3.2	3.6
WPI	7.8	5.7	6.5	8.7	8.9
CPI	11.3	8.4	9.6	8.6	15.3
Density	88.1	48.1	62.1	75.0	135.9

DP, double plain (DP); HC, half cardigan; FC, full cardigan; HM, half Milano; FM, full Milano; WPI, Wales per inch; CPI, Courses per inch; Density, Wales per inch x Courses per inch

final spin speed was 500 rpm. Three specimens of each type of knitted textile were prepared. Washing specimens were placed in separate laundry bags to offer greater protection to the bodies of the textile and POF bundle and to reduce friction from contact between each specimen and the laundering ballast. The total load weight was 1.8 ± 0.1 kg, including the e-textile specimens, laundry bags and laundering ballast type 3. 66 ± 1 g of AATCC 1993 Standard Reference Detergent was added as per the washing machine's instructions. The whole washing procedure was completed in approximately 40 min. All of the washed specimens were dried flat on a horizontal screen for at least 24 h in a controlled temperature and relative humidity environment (20 ± 2 °C and 65 ± 5%) after each washing cycle.

Measurements

Initial electrical resistance prior to washing was measured after 24 h of conditioning for all of specimens. Resistance per inch in the direction of the weft was also measured on all knitted textiles after each wash from 1 to 10, 15 and 20 washes using a UNI-T digital multimeter UT890C+.

Optical microscopic (Leica DFC290HD) and scanning electron microscopic (SEM) observations (Hitachi Tabletop Microscope TM3000) on washed specimens were carried out to investigate the condition of the silver-coated conductive yarn and the POFs.

Comparison of the illuminating effect was conducted via observation of the photos of unwashed specimens and of those washed for 20 cycles. Specimens were connected with an LED light source for the whole capturing process. The camera setting was adjusted according to the level of visible illuminative effects that appeared on the camera screen. The images were taken with the camera setting at 1/10 s., f/ 1.8, ISO 200.

The Martindale abrasion test was performed using a Martindale abrasion tester in accordance with ASTM standard D4966-12. Three 38-mm-diameter circular specimens from each knitted textile were cut for this test. A separate set of standard abradant fabrics (a plain weave worsted wool fabric) was prepared for each specimen. A top weight of 9 kPa was added to put pressure on each specimen as indicated in the standards.

Resistance was measured after abrasion of 0, 1000, 5000, 10,000, 15,000, 20,000 and 30,000 cycles on the specimens using a UNI-T digital multimeter UT890C+.

Digital microscopic (Leica DFC290HD) and SEM (Hitachi Tabletop Microscope TM3000) observations were conducted on the washed specimens to investigate the condition of the silver-coated conductive yarn and the POFs.

Statistics

One-way analysis of variance (ANOVA) at a 95% confidence limit (level of significance $\alpha = 0.05$) was carried out for different knitted textiles and resistance after washing; and different knitted textiles and resistance after abrasion by using SPSS Statistics 26.

Results and discussion

Impact to knitted e-textile after washing

Changes in resistance

The resistance values of different knitted textiles measured in the direction of the weft before and after 1 to 10, 15 and 20 wash cycles are recorded in Table 3. The ANOVA results listed in Table 4.

In Fig. 4a, after 20 wash cycles, double plain had the highest resistance value (19.75 Ω/inch) in the weft direction of all knitted textiles. Half cardigan had the second-highest resistance value (11.62 Ω/inch). The resistance value of the half Milano increased from the initial value (2.99 Ω/inch) to 10.02 Ω/inch. Of the five different knitted textiles, full Milano had the lowest resistance value (7.11 Ω/inch) after 20 washes.

Figure 4b shows the ratio of relative change in resistance (percentage of change in resistance from the initial (unwashed) value) in the direction of the weft after 5, 10, 15 and 20 wash cycles of the five knitted textiles. All five knitted textiles showed a linear trend in the evolution of resistance. Half Milano had the highest ratio for change in resistance value after 20 washes, reaching more than 235% from its initial value. Full

Table 3 The resistance values (unit: Ω) in the weft direction of the five knitted textiles with their before and after values for 1 to 10, 15 and 20 wash cycles

	Resistance (Ω/inch)									
Knitted textile	**Double plain**		**Half cardigan**		**Full cardigan**		**Half milano**		**Full milano**	
Wash cycle	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
0	8.93	0.27	5.70	0.37	4.22	0.32	2.99	0.07	2.75	0.08
1	7.99	0.31	6.28	0.27	4.97	0.13	3.76	0.10	3.07	0.07
2	9.05	0.11	6.46	0.13	4.74	0.39	4.48	0.10	3.22	0.14
3	10.12	0.20	7.32	0.20	5.85	0.27	4.27	0.22	3.38	0.11
4	11.59	0.57	7.25	0.38	5.51	0.23	4.92	0.19	3.93	0.27
5	12.96	0.34	7.10	0.30	5.29	0.26	4.99	0.18	3.92	0.20
6	12.89	0.09	6.82	0.25	5.72	0.14	4.91	0.16	4.06	0.22
7	13.51	0.26	7.32	0.26	6.10	0.24	4.96	0.16	3.86	0.10
8	13.30	1.37	7.70	0.33	5.89	0.20	5.32	0.12	4.74	0.21
9	14.48	1.18	7.73	0.43	6.02	0.23	5.99	0.17	5.62	0.33
10	14.84	0.97	7.92	0.37	6.04	0.29	6.53	0.42	5.43	0.29
15	15.79	1.56	10.28	0.39	7.64	0.25	7.38	0.50	8.15	0.20
20	19.75	3.62	11.62	0.44	9.26	0.22	10.02	0.43	7.11	0.32

Table 4 One-way ANOVA carried out for different knitted textiles and washing

Source of variance	Sum of squares	df	Mean square	F	p-value
Different knitted textiles—resistance after washing	2673.419	12	222.785	11.716	< 0.0001
Double plain—resistance after washing	1257.340	12	104.778	66.977	< 0.0001
Half cardigan—resistance after washing	312.241	12	26.020	240.812	< 0.0001
Full cardigan—resistance after washing	199.600	12	16.633	261.678	< 0.0001
Half Milano—resistance after washing	383.415	12	31.951	487.647	< 0.0001
Full Milano—resistance after washing	315.341	12	26.278	571.694	< 0.0001

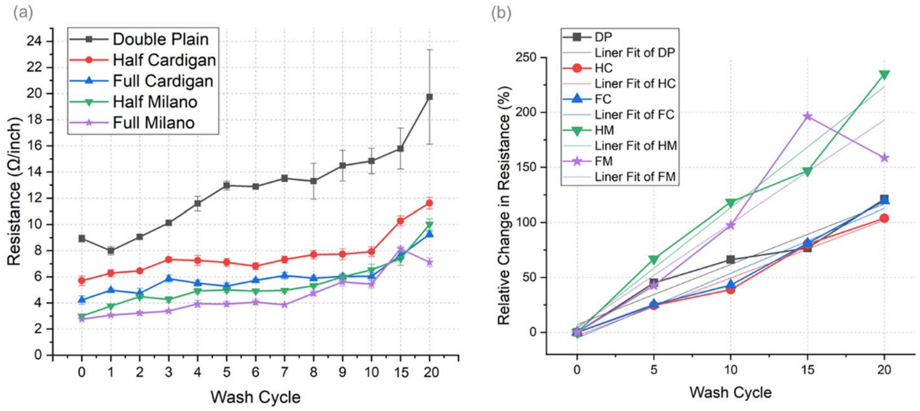

Fig. 4 **a** Resistance value (unit: Ω) of the weft direction of different knitted textiles before and after 1 to 10, 15 and 20 wash cycles and **b** relative change in resistance (%) and linear regression of weft direction in different knitted textiles after 5, 10, 15 and 20 wash cycles. Note: DP, double plain; HC, half cardigan; FC, full cardigan; HM, half Milano; FM, full Milano

Milano textile showed a similar trend in change ratio, rising almost 100% after wash cycle 10. Its resistance value rose to approximately 196% before decreasing to 158.55% after wash cycle 20.

Half cardigan showed a steadily increasing trend from wash cycles 1 to 10 and doubled (103.86%) its initial resistance value after 20 washes. Its resistance value rose to 38.95% after wash cycle 10 and 80.35% after wash cycle 15. Full cardigan textile showed a similar ratio of changes compared with half cardigan. It increased from 43.13% after wash cycle 10 to 81.04% after wash cycle 15. The change ratio after 20 washes was 119.43%.

Although double plain had the highest resistance value after washing, its ratio of change after 20 washes was comparable to the half and full cardigan textile. The change ratio rose to 66.18% at wash cycle 10 and 121.16% at wash cycle 20.

The comparatively high ratio of change in the resistance value before and after washing of the half and full Milano samples is explained by the decrease in the weft dimension. We suspect that there was greater shrinkage of textile in the half (−4.76%) and full Milano (−5.41%) compared with the double plain (−3.79%), half (2.52%) and full cardigan textiles (−1.8%).

Based on the existing research, it is perceived that the tendency of resistance value increased with the number of wash cycles for conductive yarn (Briedis et al., 2019; Eskandarian et al., 2020; Sofronova & Angelova, 2020; uz Zaman et al., 2019). Despite that there was a linear trend that the resistance value increased with the number of wash cycles of most of the knitted textiles in this study. The change ratios of resistance for five knitted e-textile after 20 washes is around 100% to 235%. These results can be explained by the WPI of knitted textile and the relative change in resistance increase with the number of loops in a wale. Knitted textile with Milano structures had a greater increase in relative change in resistance after 20 wash cycles. In both Fig. 4a, b, it is noticed that a drop of the resistance value of full Milano after 20 washes. It could be suspected the results with two main reasons: The measurement of resistance on full Milano was comparatively difficult as the structure of it is tighten than the others. The shrinkage of full Milano increased the density of stitch in fabric. It increased the difficulty of accurate measurement by the digital multimeter of the silver-coated conductive yarn in the compact structure.

Figure 5 shows the images of knitted textiles and the damage to conductive yarn before and after washing as seen by optical microscopy and SEM. Figures 5a–e are the images captured before washing. Images were captured after 20 washes to identify the damage caused by delicate washing cycles (Fig. 5f–j). The light grey areas are the silver coating and the dark grey areas are the scratches (after abrasion). Looking at the images, we can see that there were some scraped areas on the silver coating of conductive yarns after 20 wash cycles. Coating peeling off appeared on all knitted textiles, which is clearer on the double plain, half and full Milano textile (Fig. 5f–j). It is suspected that the higher ratio of changes in resistance (Fig. 4b) due to the coating peeling off observed in Fig. 5i, j.

Compared to the unwashed half cardigan, there was not much damage to the surface of the conductive yarn (Fig. 5g). In Fig. 5h, massive scratches of the coating on one ply of conductive yarn were observed in the full cardigan sample. Observation of the unwashed silver yarn under a microscope showed a small amount of abrasion on the surface caused by mechanical abrasion during the knitting process. Further degradation of the silver

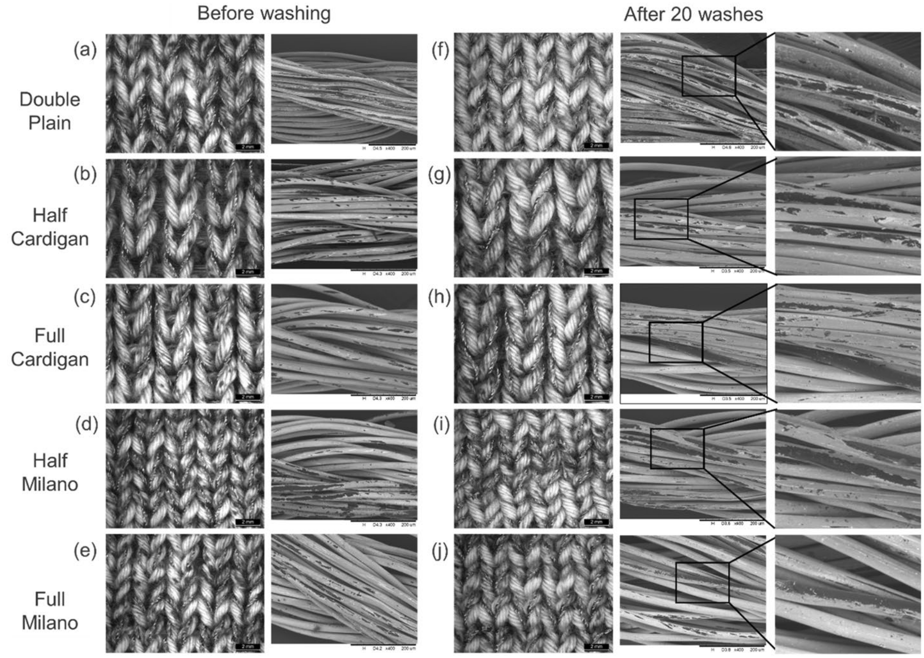

Fig. 5 Optical microscopic and SEM images of knitted textiles: **a** double plain before washing; **b** half cardigan before washing; **c** full cardigan before washing; **d** half milano before washing; **e** full milano before washing; **f** double plain after 20 washes; **g** half cardigan after 20 washes; **h** full cardigan after 20 washes; **i** half milano after 20 washes; and **j** full milano after 20 washes

yarn was observed after washing. The areas of silver coating that were detached from the surface increased as the number of washing cycles increased because of mechanical movement during the washing process.

Observation of POF strands and the illuminative effect after washing

Figure 6 shows the damage to the POF before and after washing as seen under an optical microscope. POF was observed with the sample body under the optical microscope. The images were captured after every five washes to observe the damage caused by the delicate washing cycles. It can be seen that there was little change in the appearance of the POF after five washes (Fig. 6a, b). In some of the knitted textiles, bent POFs were found, as shown in Fig. 6c. After the completion of wash cycle 10, there were a few cracks in the POF strands found in every textile (Fig. 6d). Figure 6e shows that there is a bent POF strand with two cracks around the bent area. To show the effect of a crack on the passage of light, the optical microscopic image was captured by connecting a green LED light. The light's passage ended at the first crack, which could cause light leakage on the surface. After 20 washes, there was a broken POF strand found in one of the knitted textiles (Fig. 6f).

Figure 7 shows the damage to the POF before and after washing as observed with a SEM with the unwashed POF shown in Fig. 8a. The POF was cut out of the fabric sample for SEM observation. The images were captured after every five washes to observe the damage to the POF caused by the delicate washing cycles. There were some shallow scratches on the surface of the POF after 5 and 10 washes (Fig. 7b, c).

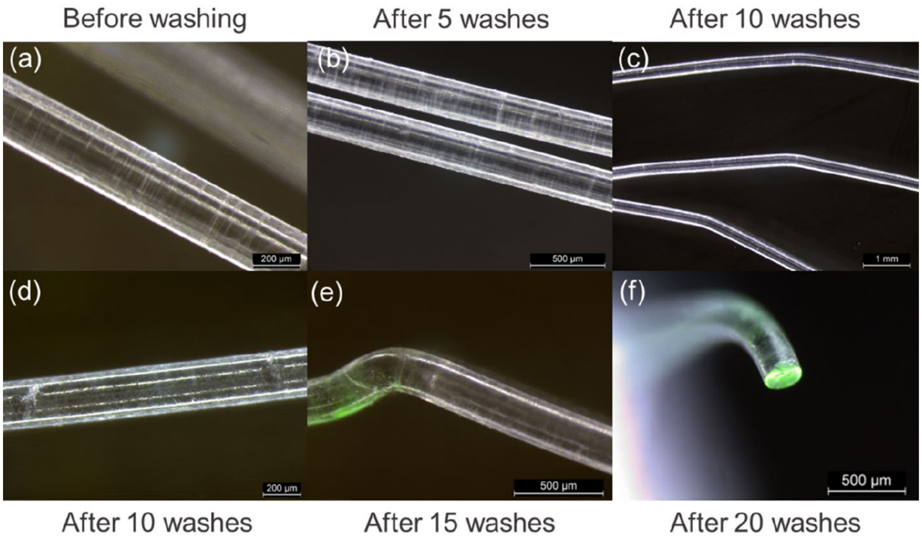

Fig. 6 Optical microscopic images of POF before and after washing: **a** original; **b** after 5 washes; **c** and **d** after 10 washes; **e** after 15 washes; and **f** after 20 washes

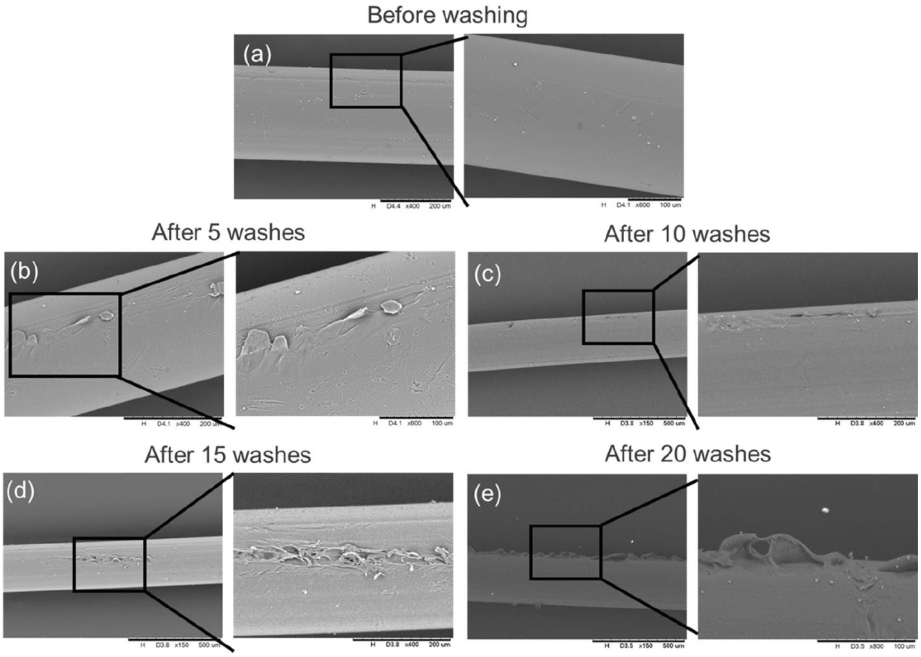

Fig. 7 SEM images of POF before and after washing: **a** before washing; **b** after 5 washes; **c** after 10 washes; **d** after 15 washes; and **e** after 20 washes

An area with deeper scratching was found on the POF strand after 15 wash cycles, as seen in Fig. 7d. After 20 washing cycles, an abundance of deep scratches was found on the surface of the POF strand.

The results of washing on the illuminative effects of the five types of textiles were captured on camera. A comparison of the illumination of all five types of textiles before and after washing is shown in Fig. 8. Figures 8a–e are the images of knitted

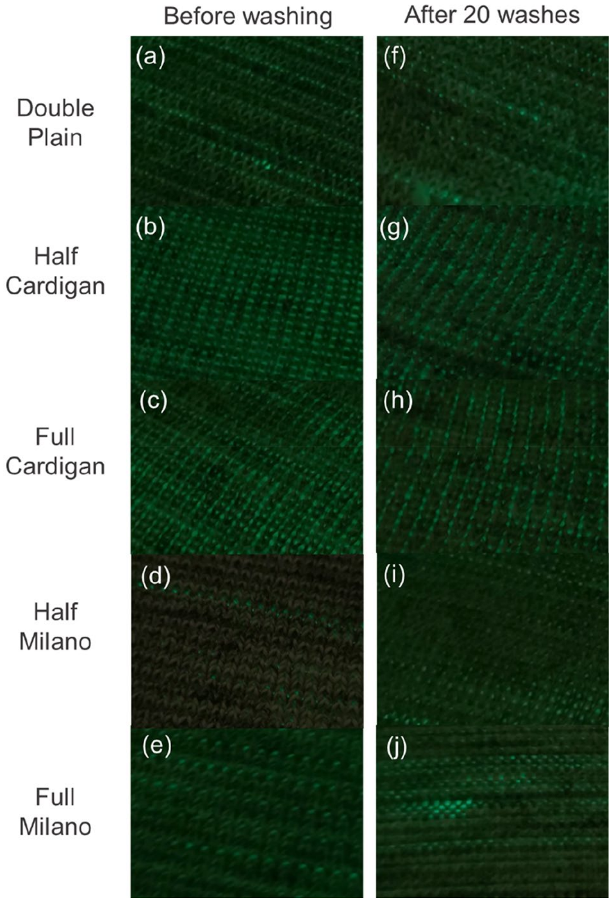

Fig. 8 Illuminative effect of textiles before washing: **a** double plain; **b** half cardigan; **c** full cardigan; **d** half milano; **e** full milano; and after 20 washes: **f** double plain; **g** half cardigan; **h** full cardigan; **i** half milano; and **j** full milano

textiles taken before washing; Figs. 8f–j are the images captured after 20 wash cycles. The images were captured by connecting a light source to observe the illumination effect after washing. Some bright spots of light were visible on the textiles, indicating that the POFs were broken in certain areas. Streaks of light were observed on the sample surfaces. Thus, the results showed that the effect of washing on illumination visibility was minimal. The double plain, half and full cardigan structures demonstrated a better illuminative effect than the half and full Milano structures. More open stitching reveals larger areas of the POFs, meaning better illumination of the knitted e-textiles.

The images captured by both optical microscopy and the camera provided evidence that washing can damage the POF strands. Bent points and cracks on the fibres caused by 20 wash cycles are visible in the optical microscopic images of the POFs. When the sample was connected to a light source, those damaged points could cause light leakage, causing bright spots or streaks of light. As observed using a SEM, scratches on the surface of the knitted textiles were found every five wash cycles and were more severe when the wash cycle was increased. However, the effect of laundering on the illuminative function and visibility of the textiles was minimal. Although the ratios of changes in

Table 5 The resistance values (unit: Ω) of the five knitted textiles before and after abrasions from 1000, 5000, 10,000, 15,000, 20,000 and 30,000 rubs

Knitted textile code	Resistance (Ω/inch)									
	Double plain		**Half cardigan**		**Full cardigan**		**Half milano**		**Full milano**	
Rubs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
0	8.06	0.86	5.22	0.73	5.10	1.07	3.82	0.63	3.57	0.93
1000	7.02	0.84	5.60	1.13	5.80	0.24	4.98	0.87	3.75	0.63
5000	8.72	0.96	6.31	1.74	5.94	0.94	4.90	0.99	3.61	0.52
10,000	11.85	1.63	6.55	1.70	6.42	1.88	5.40	0.77	4.28	0.75
15,000	14.92	2.06	8.36	1.81	6.71	2.15	5.31	1.23	3.95	0.64
20,000	15.37	2.52	5.82	1.60	5.17	0.91	4.71	0.75	4.13	0.55
30,000	16.28	2.90	6.02	1.13	5.91	1.18	5.66	1.05	4.94	0.84

Table 6 One-way ANOVA carried out between different knitted textiles and abrasion

Source of variance	Sum of squares	df	Mean square	F	p-value
Different knitted textiles—resistance after abrasions	515.595	6	85.933	7.803	< 0.001
Double plain—resistance after abrasions	1198.762	6	199.794	60.722	< 0.001
Half cardigan—resistance after abrasions	76.868	6	12.811	6.354	< 0.001
Full cardigan—resistance after abrasions	30.853	6	5.142	2.914	0.012
Half Milano—resistance after abrasions	32.655	6	5.442	6.459	< 0.001
Full Milano—resistance after abrasions	3.133	6	0.522	6.784	< 0.001

resistance for all five knitted textiles increased with the washing cycles, the illuminative effects of knitted e-textile were not compromised by washing.

Impact to knitted e-textile after abrasion

Changes in resistance

Electrical resistance was measured and analysed to evaluate the effect of abrasion on the knitted textiles examined in this study. The resistance values of different samples in the direction of the weft before and after the abrasions resulting from 1,000, 5,000, 10,000, 15,000, 20,000 and 30,000 rubs are recorded in Table 5. The ANOVA results are listed in Table 6.

As shown in Fig. 9a, after abrasion with 30,000 rubs, double plain textile showed the highest resistance value (16.28 Ω/inch) in the direction of the weft of all of the knitted textiles (Table 5). The resistance value in the direction of the weft of half cardigan after abrasion with 30,000 rubs was 6.02 Ω/inch. For the full cardigan sample, resistance after abrasion with 30,000 rubs was 5.91 Ω/inch. The resistance value of the half Milano textile was 5.66 Ω/inch. Of the five different knitted textiles, full Milano had the lowest resistance value (4.94 Ω/inch) after abrasion with 30,000 rubs.

Figure 9b shows the ratio of relative change in resistance (percentage of change in resistance from the initial unabraded value) in the direction of the weft after abrasion by 1,000, 5,000, 10,000, 15,000, 20,000 and 30,000 rubs of the five knitted textiles. All five showed a linear trend in the evolution of resistance. The change ratios of resistance for

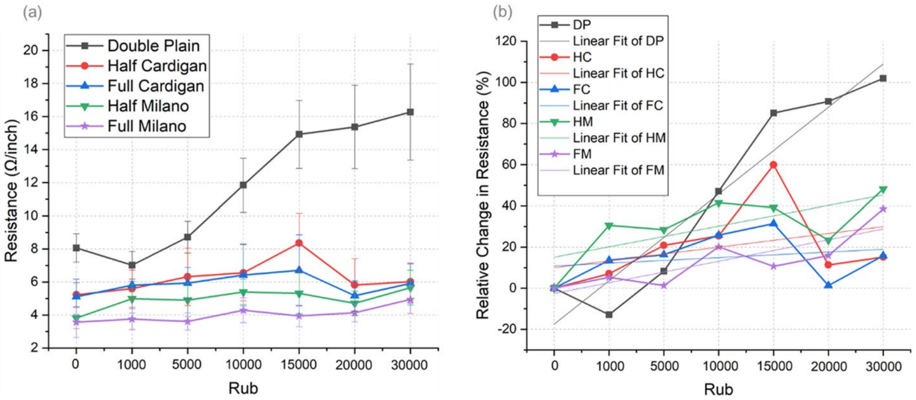

Fig. 9 **a** Resistance value (unit: Ω) in the direction of the weft in different knitted textiles before and after abrasion from 1000, 5000, 10,000, 15,000, 20,000 and 30,000 rubs and **b** relative change in resistance (%) and linear regression in the direction of the weft in different textiles after abrasion from 1000, 5000, 10,000, 15,000, 20,000 and 30,000 rubs. Note: DP, double plain; HC, half cardigan; FC, full cardigan; HM, half Milano; and FM, full Milano

five knitted e-textile after abrasion was varied. The ratio of relative change in the resistance value of half cardigan and full cardigan after abrasion with 30,000 rubs was 15.18% and 15.83% respectively. Half Milano was the second highest of the knitted textiles, the relative change in resistance increased to 48.23% after abrasion with 30,000 rubs. Full Milano had a similar fluctuation in changes to relative resistance after abrasion, rising to 38.53% after abrasion with 30,000 rubs. Double plain showed the highest ratio for the change in resistance value after abrasion by 30,000 rubs, reaching more than 100% when compared with its initial value. It changed rapidly after abrasion with 10,000 rubs, with the resistance value increasing to 47.08%.

The increase of resistance after abrasion may due to the reason that the breakage of conductive yarn and the coating was rubbed away. The removal of the silver coating on the conductive yarn due to abrasion is visible and caused the increase in the electrical resistance of all knitted textiles. After abrasion with 20,000 rubs, it is notice that there were dropping points for knitted textiles in half Milano (-11.37%) and two cardigans (Half Cardigan: -30.41% and Full Cardigan: -22.96%) (Fig. 9b). It was suspected that decrease of resistance for few reasons. The structure of conductive yarn after abrasion was loosen, and it lead to the increase of contacting point within structure. Based on the microscopic observation of conductive yarn in textiles, the impact of silver coating detached from the surface after abrasion was severe (Fig. 10). The second reason for the decrease was that the measurement difficulties after abrasion test. As the conductive yarn was loosen and it was relatively difficult to observe and pick the right point for measurement. These findings explained that the electrical resistance and the functionality of e-textiles could be affected by abrasion, we conclude that cardigan textiles are more viable and have the potential to develop interactive textiles that can withstand surface abrasion.

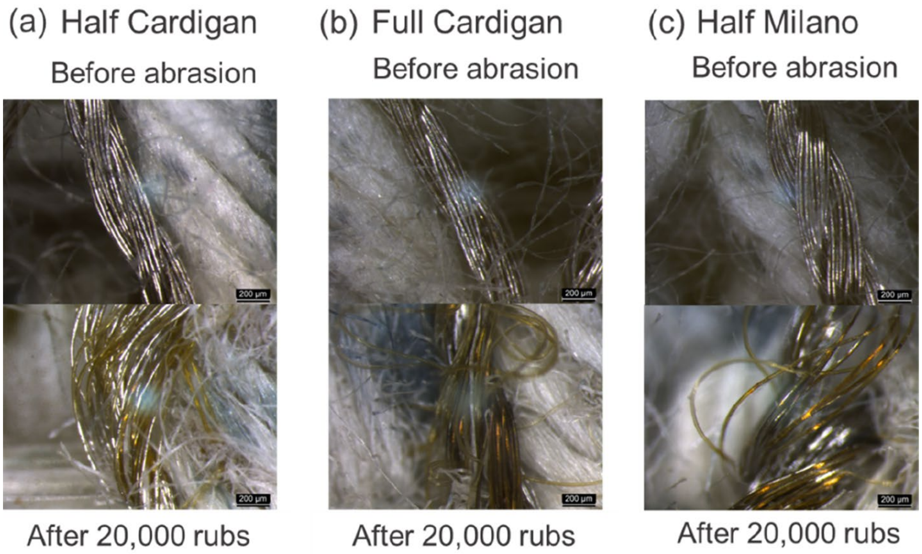

Fig. 10 Optical microscopic images of knitted textile before and after abrasion of 20,000 rubs: **a** Half Cardigan; **b** Full Cardigan; and **c** Half Milano

Conclusions

Five illuminative interactive POF knitted textiles—double plain, half and full cardigan, and half and full Milano—were developed using an industrial hand-operated flatbed knitting machine. This study investigated how washing and abrasion affect the illumination and conductivity of interactive POF knitted textiles. The resistance values of all five samples increased when the wash cycle increased. Half and full milano textiles had comparatively high ratios of change in their resistance values after washing because of the increase in loop density in the direction of the weft (decrease of the weft dimension). Microscopic observations showed the damage to POFs caused by washing, influenced the illuminative effect of POF knitted textiles. Scratches were found on the surface of the POF after five washes, a phenomenon that became more severe when the washing cycle increased. Bent points and cracks on the fibres appeared on the surface of the POF after 20 wash cycles. However, the consequences were minimal in terms of the visibility of the illuminative effect on the textiles after washing. We found that abrasion had a different impact on the changes in resistance in all the knitted textiles. As abrasion cycles increased, the resistance of the double plain textile rose significantly. Under the microscope, the removal of the silver coating of the conductive yarn due to abrasion was visible, which caused the increase in the resistance value of all of the knitted textiles.

This study concludes that out of all of the knitted e-textiles with POF and silver-coated conductive yarn, there was the least impact to the cardigan (half and full) structures in terms of changes to resistance values after washing and abrasion, and the visibility of the illuminative effects was sustained. The openness of the stitching also offered better visibility for the illumination of the POF. The electrical resistance of knitted e-textile is one of the main performance to determine its application. However, in the e-textile with the integration of POF in the same fabric, the illuminative effects after washing and abrasion is also crucial to the further development. The authors recommend that future studies investigate whether it is feasible to knit POFs and conductive yarn on computerised knitting machines. This study has shown that knitted textiles are viable for use in everyday life and offer the potential for mass adoption with ease of maintenance for fashion and interior applications. The functionality of the illuminative effect of the POF is sustainable after laundering. Future studies using computerised knitting machines will contribute to the mass production of POF integrated knitted e-textiles, making wider applications feasible.

Abbreviations

E-textiles	Electronic textiles
LED	Light-emitting diode
PMMA	Polymethyl methacrylate
POF	Polymeric optical fibre

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Author contributions

NYKL has prepared draft of work, experiments, ideation and design of the analysis, interpretation of data, and major contributions to writing. JT led the research inclusive of conception, methodologies, and major contributions to writing. AT has contributed to the conception and methodologies. KCJC contributed to textiles knitting and preliminary part of experiments. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in this published article.

Declarations

Competing interests

The authors declare that they have no competing interests.

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