Enhancing the wearability and accessibility of illuminated POF garment

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Abstract
Purpose – The purpose of this paper is to develop an illuminated polymeric optical fibre (POF) garment – the LUMI jacket – with accessibility and wearability improvements. This paper demonstrates how wearable technology can be seamlessly integrated into daily life.
Design/methodology/approach – An interdisciplinary approach involving design and technological techniques was adopted. Both garment design approaches and textile technologies were used to optimise the performance of a POF jacket. A group of tactile sensors was developed to create an easy-to-access interactive function. A POF fabric sample and garment were washed and examined to prove that a POF garment could be made part of a domestic laundry routine.
Findings – As a result, an illuminated POF garment – the LUMI jacket with textile-based switches – was created. Compared with current POF garments, the LUMI jacket's wearability and accessibility were highly improved.
Originality/value – This project explored an unobstructive POF-illuminated garment to address the functional and wearable barriers to adoption. The interaction between wearer and garment is accessible. Electronics and textile touch sensors were seamlessly integrated into garment. Washability of POF garment was proved. This research explores how e-textiles can fit into everyday life.

Keywords POF fabric, Tactile sensor, Accessbility, E-textile, Wearability, Wearable garment
Paper type Research paper

1. Introduction

Researchers introduced the polymeric optical fibre (POF) into a textile structure to provide all-over illumination (Bai *et al.*, 2012; Schrank *et al.*, 2017). Instead of integrating LEDs directly into fabric (CuteCircuit, 2013; Layne, 2007; Michel and Fraunhofer, 2008), a POF textile system can be used to create a large illumination area. Fashion designers such as Zac Posen (Chang, 2016) and Richard Nichol (Blanks, 2014) have used POF fabrics. POFs have also been used in fashion statement pieces (Tan, 2015) and to add decorative illumination to a garment (Figure 1(a) and (b)). A "MoodWear" was introduced with interactive woven POF fabric in 2013 (Stylios and Yang, 2013). In most cases, POF fabrics are developed into high fashion or conceptual works.

Same as most of the existing wearables, POF fabrics have not been widely adopted in mainstream. How to enhance the wearability and accessibility are still main challenges to most of the wearable technology. Take Urban Glow for example, the LEDs, printed circuit board (PCB), battery and wires were placed beneath the fabric. The wearable systems are obtrusive and uncomfortable. The style is close-fitted, which is complicated to put on (Figure 2).

Sheth and Ram (1989) stated that there are two types of barriers to customers' adoption of innovation: functional and psychological. These barriers can create a resistance to adopting new technologies. Dvorak stated that only one technology cannot bring the wearables to mainstream. Aesthetics, lifestyles and nature of fashion should be considered. He suggested an Operational Inertia, a fundamental principle for developing wearables that are transparent to use (Dvorak, 2008). Tan *et al.* (2018) suggested an interdisciplinary design method for interactive POF textile development.

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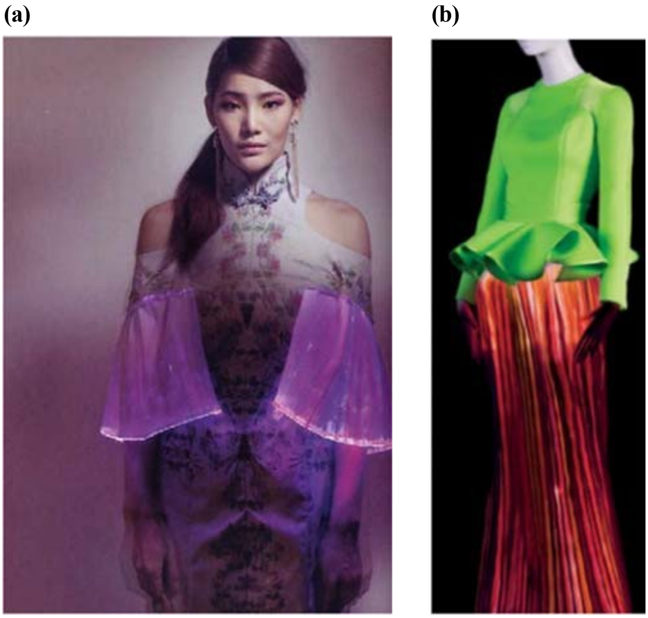

Figure 1.
POF fabrics in fashion pieces

Notes: (a) Urban Glow (Jeanne Tan, Legacies & Innovations: Cheongsam Fashion Show, 2013); (b) Neo-Neon, collected as part of The China National Museum of Silk's permanent collection, 2013

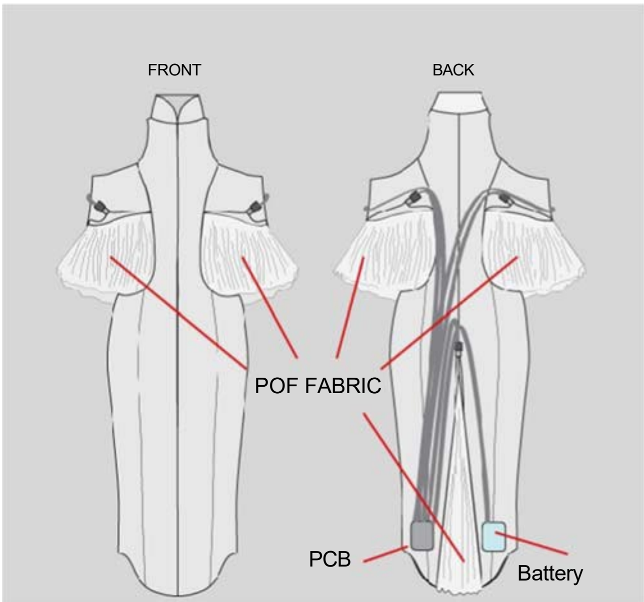

Figure 2.
Placement of electronic components of urban glow

Therefore, there are two aspects which should be addressed in order to design a POF-illuminated garment for daily wear. The first is illumination function of the garment. The second is the use of the garment within the context of the wearer's lifestyle, such as how well it fits into the wearer's daily life or laundry routine.

This design project explored the design of an illuminated POF garment, with a focus on decreasing the resistance to adoption through considerations made during the design process. The outcome of this project was a prototype garment that illustrated the potential use of POFs in interactive garments while still retaining the appearance of a conventional jacket.

2. Concept of POF garment

This project adopted a similar approach that considered both functionality and aesthetics. The project aimed to seamlessly integrate technology with daily wear. The potential market for the garment comprised young people with a preference for novel designs. The garment allowed the wearer to control changes in colour on a POF fabric panel through a set of tactile sensors. Each tactile sensor controlled a different coloured light, produced by an RGB LED. There were no exposed hard electronic devices or components on the garment. A multifunctional POF garment was designed to suit the wearer's daily activities: in the daytime, the jacket functioned as an ordinary denim jacket; at night, the jacket's colour-changing capability could make a personal statement.

In keeping with the aim of the research project, a set of design objectives for the garment was devised. Table I presents the objectives for both considerations of functionality and aesthetics.

Figure 3 illustrates the initial design. The PCB and battery were located under the back yoke, where they were connected to the POF bundle. Three embroidered tactile touch sensors with conductive yarn were provided on the front yoke to realise the touch control of the RGB lights. Embroidered conductive threads were used to form the circuitry to connect

Table I.
Objectives for consideration of functionality and aesthetics

Functionality	Aesthetics
The POF garment should function as normal clothing The interface that allows the user to control illumination should be easy to access and use	The POF garment has a casual style for daily life The tactile sensors should be inconspicuous
Comfortable and lightweight	The illuminative panel should be conspicuous when illuminated and inconspicuous when not illuminated
Removable electronic parts; no exposed electronics; washing ability	Fit into daily routine

Figure 3.
Initial design illustration

the electronics and touch sensors. However, upon evaluation, it was found that the placement of the electronics on the back of the garment would affect the comfort, appearance and practical usage of the garment.

The design was revised to improve the usability of the POF garment (Figure 4). The revised design was based on a denim jacket, with a POF panel integrated onto the back of the garment. The denim jacket design was selected in part to suit the integration of the POF textile system. As an outerwear garment, it was more conspicuous. The weight and feel of denim were an appropriate match for the POF fabric, reducing the potential impact of the POF integration on the appearance of the garment. The pockets of the jacket provided a suitable place to hold the rigid electronics (the battery and microcontroller). Due to the LED attachment process, the large rectangular panel on the back of the standard denim jacket made it the optimum place to integrate the POF fabric. As illustrated in Figure 4, the textile sensors were moved to the pocket to improve accessibility and reduce the distance from the PCB to the sensors. The pocket was designed with three layers, where the PCB and battery could be hidden. The LED coupler, which was attached to the POF bundle, could be sewn into the waistband. How the garment could be used in daily life was also considered. The PCB and battery were designed to be detachable for washing. The POF panel of the garment was designed to match the denim fabric as closely as possible to make it less conspicuous when not illuminated. Therefore, a blue POF fabric was used to match the denim fabric.

3. Experimental work

The garment development consisted of a number of experimental processes. This section details the processes used in the production of the POF garment, including the POF fabric production, textile sensor production, washing ability test, textile surface design and garment assembly.

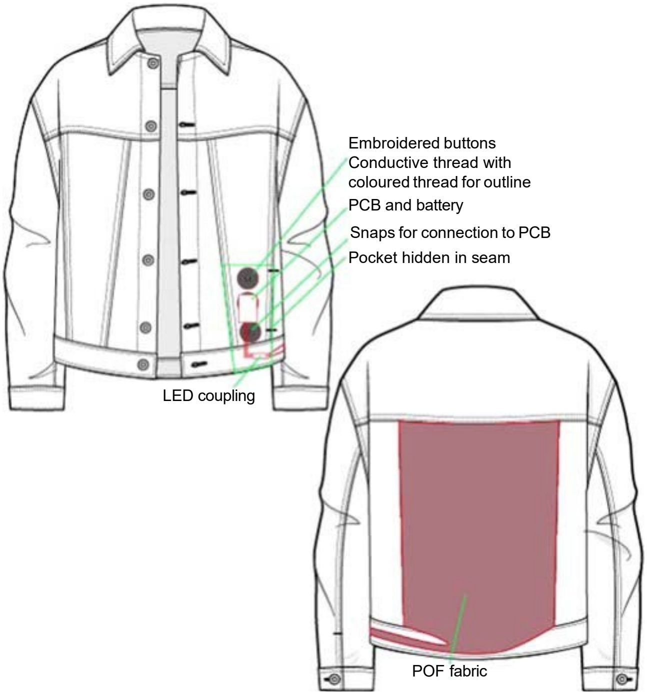

Figure 4. Revised POF jacket design

3.1 POF fabric production

The POF textiles came from a mini-collection called “Current”, with textiles inspired by the movement of water. The new textile was pliable and possessed a handle similar to that of washed denim. The POF textile design process started with sketch drawings of motifs. A CAD design of the POF textile was first rendered in Photoshop software as shown in Figure 5. The CAD design was then transferred into ArahWeave® software, and weave patterns and structures were inserted.

In this project, a jacquard loom was used to weave 0.25-mm MITSUBISH PMMA optical fibre with other yarns. The jacquard weaving machine was a STAUBLI Jacquard Head JC6, Dornier Weaving Loom PTV 8/J with 8,192 hooks. The warp system was made of 100-D white polyester. The filling yarns were designed with two systems. The first filling system used a 0.25-mm POF filament. The second filling system used 150-D navy blue polyester to build the background colour. The POF fabric was woven with a warp density of 47 ends/cm and a filling density of 20 picks/cm, which ensured stable construction of the fabric. The proportions of two filling systems were placed at a ratio of 1:1. Table II shows the POF fabric specification. The POF textiles were “fluid” and soft and had a good drape, as shown in Figure 6.

3.2 Tactile sensors

To enable the seamless integration of electronics and textiles in the jacket, tactile sensors were explored for the lighting controls. Different types of textile-based buttons and sensors use different underlying principles, such as contact sensing (Perner-Wilson *et al.*, 2011) or resistive sensing (Roh, 2013). In this case, the jacket used capacitive sensing as the principle underlying the textile sensors. Capacitive sensing works by measuring how long it takes to

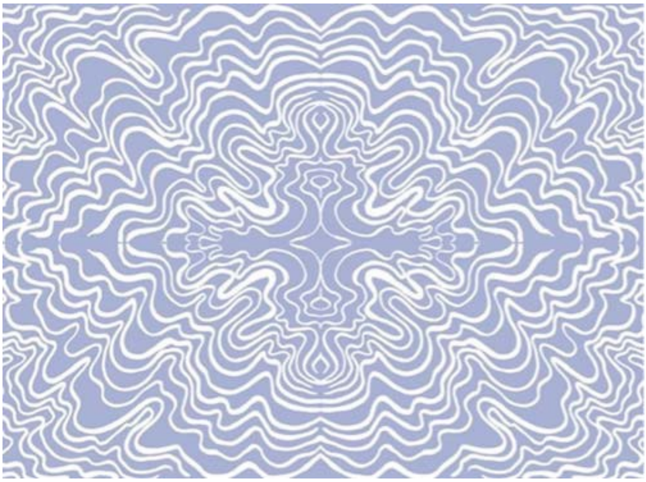

Figure 5.
CAD design of weave pattern

Table II.
Material parameters of POF textile

	Composition	Yarn Count	Colour	Density
Warp system	Polyester	100 D	White	47 ends/cm
Filling system 1	Polymeric optical fibre (POF)	0.25-mm diameter	Transparent	20 picks/cm
Filling system 2	Polyester	150 D	Navy blue	20 picks/cm

Figure 6. Weave pattern of POF fabric

charge the capacitance between the switch and the user (Karvinen *et al.*, 2014). It is beneficial in that the contact area can be made with a variety of conductive materials, including metal foil (Bai *et al.*, 2015) and conductive fabric, and does not require electrical components to be placed directly behind the fabric. The sensing function is produced by the PCB, which can be placed away from the sensors. Here, conductive yarn was used, as it could be embroidered precisely into different shapes on the garment (Agcayazi *et al.*, 2016). In this experiment, the 210-D silver-coated conductive yarn (18 per cent silver and 82 per cent nylon) was used for the textile buttons.

Two embroidered samples were finished using a TAJIMA embroidery machine (Figure 7). Sample 1 was located on the front piece of the garment, while Sample 2 was located on the pocket. The electronics and wires were connected with the tactile sensors through a metal snap button.

The tactile sensors in the second sample consisted of three embroidered circles 4 cm in diameter, embroidered using the pre-set stitch pattern complex fill pattern 1. The fill density was 5.0 pt. Each sensor corresponded to a different lighting option: red, green or blue. The circle shape was chosen to complement the circular metal snaps, which were attached to the embroidered areas to connect them to the electronics. The satin stitch produced a solid

Sample 1

Sample 2

Figure 7. Embroidered conductive textile sensors

embroidery area that contrasted with the fabric of the garment both visually and tactilely. Texture was further used to subtly distinguish the sensors from one another, as each circle had a slight variation in its embroidery design.

3.3 Textile surface design

Denim fabric was chosen as the shell fabric. A laser engraving and washing method was adopted to enrich the surface design of the outer fabric. The pattern on the denim was designed to match the pattern on the POF fabric to create a cohesive look. Laser engraving was used on the denim fabric to engrave the pattern, which matched the pattern of the POF fabric (Figure 8). Laser engraving technology uses a high-power laser to cut materials, and a computer can precisely control the engraving. This technique has been adopted to amend the colour fading of denim fabric and for textile surface embellishment (Ondogan *et al.*, 2005; Ortiz-Morales *et al.*, 2003; Ozguney, 2007). The engraving is performed using a carbon dioxide (CO_2) laser, a type of gas laser that emits light at a wavelength of 10.6 μm in the far infrared region of the electromagnetic spectrum.

After the laser engraving, some of the engraved parts had a yellow colour caused by the high temperature of the laser. A bleach wash was used to remove the yellow stains and soften the denim. Strong oxidising agents usually carry out this bleaching. As shown in Figure 9, the yellow stains were removed, and the stiffness of the fabric was reduced.

3.4 Garment construction

The garment assembly of a POF garment is not dissimilar to that of a conventional garment, which should aid in the mass adoption of the technology. Here, an industrial sewing machine was used in the assembly of the garment pieces. Following the wash test conducted as detailed in Section 3.2, flat felled seams on the edges of the POF panel were used to prevent fraying. The main differences were the inclusion of the POF panel and the alterations performed to conceal the electronic devices. The jacket had a 487 cm×24 cm POF panel on the back (Figure 10).

Figure 8. Laser-engraving pattern design on denim

Figure 9.
Fabric after
bleach washing

Figure 10.
POF garment
during construction

All POFs can be bundled together and connected to a customised LED coupler, in which a tri-colour LED was integrated (Tan *et al.*, 2019). As illustrated in Figure 6 in Section 2, the electronic components could be sewn into the waistband. After assembly, the electronic devices can be connected to the touch sensors via three metal snaps. Since only one LED was used as the light source, only one PCB in small size was used. The PCB was enclosed in a 67 cm×47 cm×1.7 cm 3D-printed control box (Figure 11), which is lightweight and wearable.

4. Results and discussion

4.1 LUMI jacket

As shown in Figure 12, a touch-sensing jacket with flexible illuminated fabric – the LUMI jacket – was developed. As such, POF fabric and electronics were seamlessly integrated into

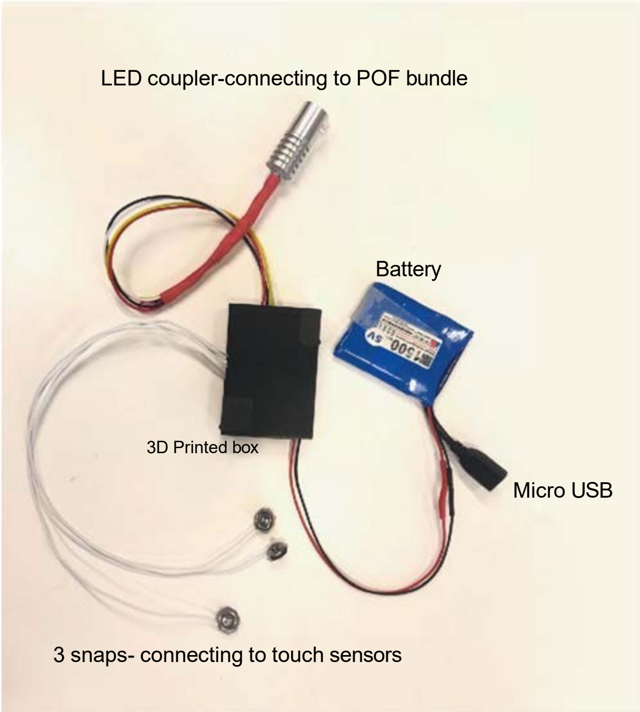

Figure 11.
Electronic devices

Outside view Inside view

Figure 12.
LUMI jacket

daily wear. No external device was needed as a controller. By touching the textile sensors on the pocket, the POF panel could change up to six different colours of light. Wearers could easily interact with the POF garment and change their personal style.

4.2 Wash test

The point of highest concern was the washability of the POF fabric, as POFs are rigid. Quandt *et al.* (2017) conducted a wash test of POF sensors in and embroidered structure over ten laundry cycles. However, large pieces of POF fabric woven for illumination have not been machine-wash tested. By washing the whole garment, as opposed to a fabric sample, the impact on the entire garment construction can be observed.

To determine whether the LUMI jacket could fit into daily laundry routines, a wash test was conducted. The electronics and LED could be easily taken apart before washing. A kind of laundry bag commonly seen in domestic laundry routines was used. The washing protocol followed ISO 6330 (The International Organization for Standardization, 2012), and the wash cycle included a machine wash at 30°C on the delicate cycle with a line dry. The whole garment was washed for ten cycles. Table III details the washing conditions.

Figure 13 shows the appearance of the POF panel. The surface of the POF fabric exhibited no obvious change before and after washing. Changes were visible on the seam

Table III. Washing conditions

Programme step	Main wash	Rinse 1	Rinse 2	Rinse 3
Time	360 s	120 s	120 s	120 s

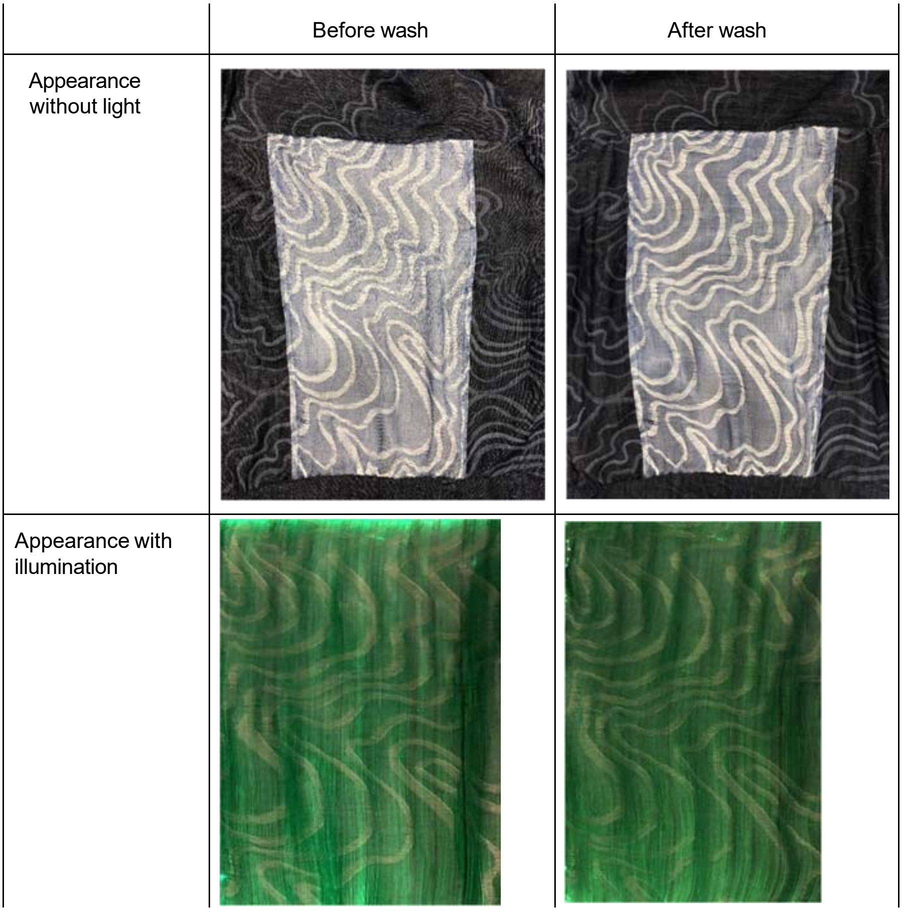

Figure 13. Appearance evaluation

due to the different degrees of washing shrinkage of denim fabric and POF fabric. Little change in illumination was seen after laundering. Damages of POF fibre and normal fibre at the seam can be seen after ten cycles. The results indicate that a LUMI jacket can be washed for up to ten laundry cycles.

4.3 Improvement of LUMI jacket

Table IV illustrates the improvements made in the LUMI jacket compared with previous works Urban Glow and Neo-Neon. The amount of rigid electronics was reduced, with fewer LEDs and a smaller size microcontroller unit. The complexity of the electronics system was also decreased, as the control system was integrated into the garment itself rather than used as a separate device.

The LUMI jacket fulfilled the objectives set at the start of the project. It was easy to access, control and wear as an everyday garment. The inside structure of the LUMI jacket was not visibly different from that of a conventional denim jacket. There were no exposed electronics on the garment, thereby improving comfort and safety. The wash test demonstrated that POF fabric is able to withstand machine washing without severely impacting on the illumination of the fabric. The wash test has also shown that pre-shrinking of POF fabric and denim fabric is necessary, due to the effect of different fabric shrinking rates on the appearance of the garment seams.

5. Conclusion

This research developed a wearable interactive POF garment that considered functional, aesthetic and practical aspects. It illustrated the necessity of tacit garment design and manufacturing knowledge, in conjunction with technical knowledge, when constructing a wearable illuminated POF garment. Issues of concern such as comfort, washability and usability were addressed through careful consideration. The LUMI jacket demonstrated how current garment and textile construction techniques could be used to produce an illuminated garment with integrated controls, and how wearable system could be seamlessly integrated into the fashion design process. Future research may consider the design of illuminated garments, particularly in terms of ergonomics, interaction and the use of new technologies, in the fashion and electronics fields.

Table IV.
Comparison of LUMI jacket, Urban Glow and Neo-Neon

	LUMI Jacket	Urban Glow	Neo-Neon
Design			
Style	Jacket	Dress	Dress
Occasion	All day	Fashion show	Fashion show
Silhouette	Loose fitting	Close fitting	Close fitting
Main colour	Blue, tone-on-tone	Digital print floral pattern	Neon green
Shell fabric	Denim	Polyester	Polyester
POF fabric	Weave pattern	Plain grey	Pleated
Technology			
No. of LEDs	1	3	4
Controller	Textile touch sensor	Mobile phone	Mobile phone
MCU	STM32	Arduino	Arduino
Size of PCB	6 cm×4 cm×1.7 cm	8 cm×5 cm×2 cm	10 cm×7 cm×3 cm
Placement of wires	Embedded	Exposed	Exposed
Laundry	Yes	No	No

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