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Illuminative Knitted Textiles: Machine Knitting with Polymeric Optical Fibres (POFs)

Abstract

Purpose: Unlike woven textiles, knitted textiles are versatile and malleable, offering greater stretchability and comfort. This paper investigated how different knitted structures affect the illuminative effect of polymeric optical fibres (POFs).

Design/methodology/approach: Knit prototypes were constructed using a 7-gauge industrial hand flat knitting machine. The textile prototype swatches developed in this study tested POF illumination in three types of knitting structures: (1) intervallic knit and float stitch structures; (2) POF inlaid into double plain and full cardigan structures; and (3) double plain and partial knitting structures. The illuminative effects of the POFs in seven prototype swatches were analysed and compared.

Findings: It is possible to use an industrial hand flat knitting machine to knit POFs. Longer floats expose more POFs, which boosts illumination but limits the textile's horizontal stretchability. The openness of the full cardigan structure maximises POF exposure and contributes to even illumination. The partial knitting in different sections achieves the most complete physical integration of POFs into the knitted textiles but constrains the horizontal stretchability of the textiles.

Originality: This study is novel as it investigates new POF knitted textiles with different loop structures. This study examined how knit stitches affect POFs in intervallic knit and float stitch, inlaid POF double knit, double plain and partial knit and the illuminative effects of the knitted textile.

Practical implications: The integration of POFs into knitted textiles provides a functional illuminative effect. Applications include but are not limited to fashion, architecture and interior design.

Keywords

Polymeric optical fibres (POFs); hand flat knitting machine; knit structure; POF integrated textile; illuminative knitted textile.

Introduction

Polymethyl methacrylate (PMMA) polymeric optical fibres (POFs) can add an illuminative function to textiles by weaving or knitting that has applications in fashion, architecture and interior design (Militky *et al.*, 2018, Schrank *et al.*, 2017, Tan *et al.*, 2021, Mohr *et al.*, 2016). The technology for producing POF woven textiles is relatively mature (Mohr *et al.*, 2016, Quandt *et al.*, 2017, Yang *et al.*, 2013), and POFs can be woven and knitted to create interactive textiles. The application of POF integrated textiles with coupled light sources, sensors and electronic components enable designers and users to create interactive features that can offer different illuminative effects for soft furnishings, wearables and multisensory environments for rehabilitation (Harlin *et al.*, 2003, Bai *et al.*, 2019, Bai *et al.*, 2012, Bai *et al.*, 2015, Ge and Tan, 2021, Tan, 2015, Tan *et al.*, 2019, Kim *et al.*, 2018, Kim *et al.*, 2019).

The authors' research team has developed woven POF textiles using a Jacquard loom (Bai *et al.*, 2019, Bai *et al.*, 2012, Bai *et al.*, 2015, Ge and Tan, 2021, Kim *et al.*, 2019, Tan, 2015, Tan *et al.*, 2019, Tan, 2013, Tan *et al.*, 2021). Previous studies have examined different weaving technologies for producing POF integrated textiles. Researchers have developed POF textiles and soft furnishings that create user-friendly and interactive cushions with illuminative effects (Bai *et al.*, 2012, Bai *et al.*, 2015). The fabrics were produced by applying plain and jacquard weaving techniques to POFs and polyester yarns; the POFs were woven in through the weft and the polyester yarns were the warp. The surface of the POF textile was treated with laser engraving, which damaged the surface of the POFs, allowing them to achieve lateral light emission.

Tan *et al.* (2019) developed double-layer weave patterns with POFs and conductive yarns on a Jacquard loom (Dornier Weaving Loom PTV 8/J with the STAUBLI Jacquard Head JC6). The textile was used to create 'CAPI', an interactive cushion, and 'LUMI' (Bai *et al.*, 2019), an interactive POF jacket. The double layer structure created embossed textures that were distinct from previous flat POF designs.

Wang *et al.* (2012) created an innovative jacquard fabric with POFs. POFs, as the weft yarns, were interwoven with warp yarns on a Jacquard loom. The textile comprised of a two-layered pattern that was superimposed onto the same pattern grid to create a dynamic illuminative effect when connected to a light source . To enhance the illuminative effect in woven structures, Quandt *et al.* (2017) investigated the illumination intensity achieved through light in-coupling in a series of woven textiles with different structures produced on a semi-automatic loom (Patronic B60, ARM AG, Biglen, Switzerland). They found that the illuminative effect was strongly enhanced by a long float in a sateen weave.

There have been a number of commercial applications of POF textiles. Samsara srl. (2020), an Italian company, created the DreamLux fabric and used it in a variety of products, such as POF woven fabrics, clothing and accessories, and furnishings. A Chinese company, Jiangxi Daishing POF Co., Ltd., has integrated POFs into illuminative textiles, fashion and furnishings (Daishing POF Co. Ltd., n.d.). In general, the integration of POF into woven fabrics has reached a relatively mature stage in both the commercial and research arenas. There is comparatively more potential for the growth in the development of knitted POF textiles.

However, POFs are challenging to knit because of their susceptibility to breakage when they are bent (Schrank *et al.*, 2017). A breakthrough in knitted POF materials was made by SHINDO (2015), which used warp knitting technology to produce a mesh knit trim with a retractable structure. This technique produced fabrics that were flexible in the horizontal direction with an extendable effect but had limited vertical stretch. Tan and Chen (2019) successfully knitted POFs using weft knitting, creating fabrics with vertical stretch and a small amount of stretch in the horizontal direction. The weft knitting technology is more suitable for the integration of POFs, as it offers soft handle and can be used in a variety of wearables and furnishings. Schrank *et al.* (2017) noted that POFs can be integrated into knit structures via the inlay method, which enables the POFs to lie flat, minimising the disruption to the illumination. However, such materials offer very little horizontal stretch, as POF is more rigid than conventional knitting yarn. POFs are brittle, fragile and prone to breaking when abruptly bent thus making it challenging to knit into a looped structure (Mohr *et al.*, 2016).

The POF in the knitted jumper prototype developed by Chen *et al.* (2020) was directly incorporated into a knitting structure with acrylic yarn consisting of 5 back stitches x 1 double stitch. The resulting POF knitted textile demonstrated stretchability in both the vertical and horizontal directions, with better stretch performance in the horizontal direction. The knitted structure was malleable and had versatile applications in wearables and furnishings. The main advantage of knitting in the production of POF textiles is that the knitting process allows the POFs to be selectively integrated into panel pieces, whereas woven fabrics must be split into sections, some of which include POFs (Ge and Tan, 2021). However, it is difficult to maintain the appropriate tension when knitting POFs. Chen *et al.* (2020) suggested that tensions of eleven for the main body yarn and thirteen for the POF were necessary for a successful knit structure. Furthermore, fibre breakage is a challenge, as the transmission of light through the core of the POF is disrupted by broken fibres or damage to the central core of the fibre.

This study is novel as it investigates new POF knitted textiles with different loop structures. It explored how knit stitches affect POFs in different knitted structures and the illuminative effects of the POFs in the different structures. The study examined three groups of knitted structures: (1) intervallic knit and float stitch structures, where 'intervallic' refers to the manipulation of a set of knit and float stitches as a single unit; (2) inlaying POF in double plain and full cardigan structures; and (3) double plain and partial knitting structures. This explained the possibility of POF knitting which without compromising the illumination in its looped formation by different knitted structures. All the textile swatches were knitted on a 7-gauge industrial hand flat knitting machine. Cotton-blend yarns were used as the main knit yarn in the textile swatches. A pure cotton yarn served as a supporting yarn to create a smoother yarn feed and to prevent tangling during yarn feeding. As the study was exploratory, an industrial hand flat knitting machine was more suitable than a computerised knitting machine, as it enabled the researchers to closely observe the knitting process and adapt the tensions without the need for detailed system programming. The illuminative effects of the POFs in seven prototype swatches were analysed and compared by photographing the textile swatches. The specific knit parameters needed to achieve positive illumination were identified. The findings contribute to the refinement of the production of knitted POF textiles, which have many potential applications in fashion and furnishings.

Materials and the development of prototype swatches

All of the experimental prototype swatches were knitted on a 7-gauge industrial hand flat knitting machine (Wealmart, Hong Kong, China). Three types of prototype swatches were used to examine the characteristics and knittability of POF and its use in illuminative textiles. We used 0.25 mm Eska™ PMMA POF in all of the experimental prototype swatches. The specifications of the materials used in the illuminative knitted prototype swatches are listed in Table I. The main yarn formed the body of the textile and the POF provided the illumination. The main yarn in Groups 1 and 2 was 2/24 Nm 95% Cotton 5% Polyester, and the main yarn in Group 3 was 2/30 Nm 92% Cotton 8% Cashmere. In the knitting procedures, the POF became easily tangled with itself during yarn feeding and frequently clogged the yarn feeder. Therefore, a supporting yarn (1/34 Nm 100% Cotton) had to be knitted with the POF to create a smoother yarn feed. The supporting yarn allowed the knitter to control the tension and the yarn feed.

Table I Materials used in the prototype swatches

	Group 1			Group 2		Group 3	
Prototype Swatch Code	**K1-1**	**K1-2**	**K1-3**	**K2-1**	**K2-2**	**K3-1**	**K3-2**
POF (Eska™)	0.25 mm						
Main Yarn	2/24 Nm 95% Cotton 5% Polyester			2/24 Nm 95% Cotton 5% Polyester		2/30 Nm 92% Cotton 8% Cashmere	
Supporting Yarn	1/34 Nm100% Cotton						

Knitted structure designs

Seven knitted prototype swatches were developed and categorised into three groups based on the knitting structures. Figure 1 shows the workflow of knitted POF illuminative textile development. Three groups of knitted structures were designed for the investigation of how knit stitches affect POFs in different knitted structures and the illuminative effects of the POFs in the different structures. The prototype swatches in Group 1 used an intervallic knit and float stitch structure that enabled the use of longer floats, thus allowing more POF exposure. In this study, 'intervallic' refers to the manipulation of a set of knit and float stitches as a single unit. The prototype swatches in Group 2 used the inlay method to integrate POFs into double plain and full cardigan structures; the inlay method allows the POFs to lie flat, thus increasing the illuminative surface. The prototype swatches in Group 3 tested the knittability of POFs in full needle and partial knitting structures. All knitted prototype swatches were completed with POF bundling and LED coupling for the measurement and analysis of illumination effects. The specifications of three groups of knitted prototype swatches were list in Table II.

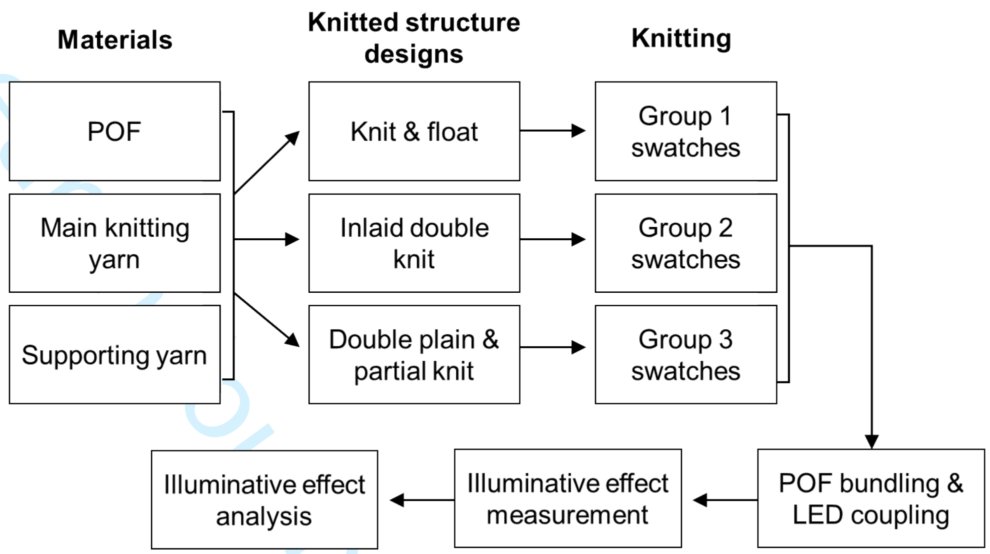

Figure 1 Workflow of knitted POF illuminative textile development

Table II Specifications of knitted prototype swatches

	Group 1			Group 2		Group 3	
Prototype Swatch Code	**K1-1**	**K1-2**	**K1-3**	**K2-1**	**K2-2**	**K3-1**	**K3-2**
Knit structure	Knit & float	Knit & float	Knit & float	Double plain	Full cardigan	Double plain	Partial knit tubular
Stitch type	1 knit x 5 float	1 knit x 7 float	1 knit x 11 float	Full needle knit	Knit and tuck	Full needle knit	Tubular
WPI	14	8	7	9	7	8	7
CPI	20	17	17	12	9	18	14
Density (WPI x CPI)	280	136	119	108	63	144	98
Placement of POF		1 strand / course; Fixed by knit stitch in structure		2 strands / course; Inlaid, flexible	2 strands / course; Inlaid, flexible	1 strand / course; Knitted with main yarn	2 (1 front and 1 back) strands / course; Knitted

			with main yarn
Supportin g yarn	Unremovable	Removable	Unremovable

Notes: WPI: wale per inch; CPI: course per inch

Figure 2 shows the images of the intervallic knit and float swatches, schematic image and their knitting notations. The prototype swatches in Group 1 were labelled K1-1 (1 knit x 5 floats) (Figure 2a), K1-2 (1 knit x 7 floats) (Figure 2b) and K1-3 (1 knit x 11 floats) (Figure 2c). Float stitch sequences of three different lengths (5, 7 and 11 floats) were used to investigate how the manipulation of a set of knit and float stitches as a single unit affected the illuminative effect. Each prototype swatch was knitted with the specified number of float stitches in a single unit, and this unit was repeated over the sample. The WPI (wale per inch) / CPI (course per inch) of the three prototype swatches in Group 1 were 14 / 20, 8 / 17 and 7 / 17. In the Group 1 swatches, 1 strand of POF and a strand of supporting yarn were knitted in every course. The supporting yarn was needed to create a smooth yarn feed and prevent the POF from tangling during yarn feeding. It is part of the integral structure of the knitted fabric and could not be removed.

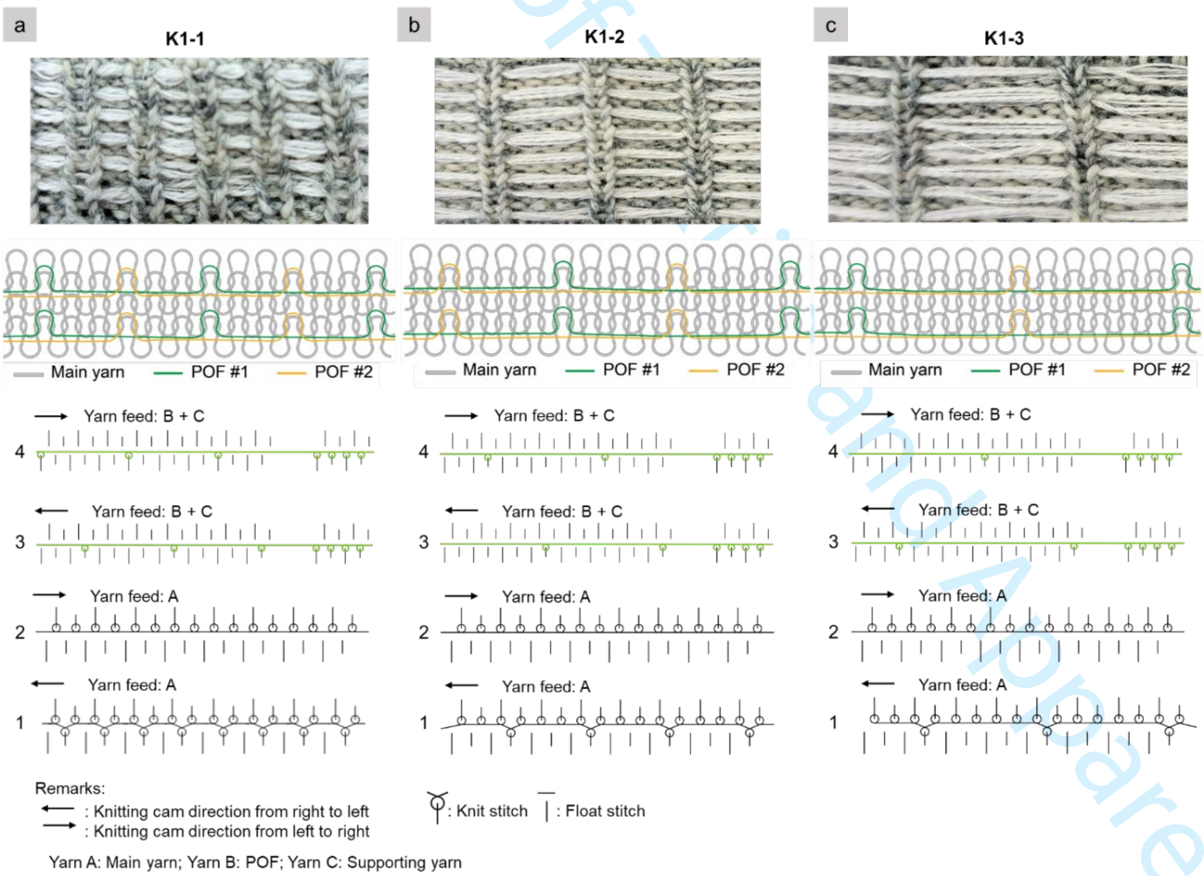

Figure 2 Images of the swatches with intervallic knit and float structures, schematic image, and their knitting notations: (a) K1-1, (b) K1-2 and (c) K1-3.

The float stitch structure increased the exposure of the POFs, which could contribute to a brighter illumination effect. In these Group 1 prototype swatches, the main yarn was knitted as a single unit in the first two courses. In every third and fourth course, a waste section with a long float was added at one end using the supporting yarn. The supporting yarn was integral to the structure of the swatch.

In K1-1 (Figure 2a), the first course had the structure of 1 double x 1 back stitch, and the second course was knitted as pure back needle. In the third course, the POF was knitted on the first needle right after the waste section and had a 5-stitch long float as part of the first unit; this 1 knit x 5 float stitch pattern was repeated until the required length was reached. The fourth course started with a knit and float stitch in the middle of the 5-stitch sequence in the previous course – that is, the fourth needle after the waste section and long float.

In K1-2 (Figure 2b), the first course consisted of 1 double x 3 back stitches, and the second course was knitted as pure back needle. In the third course, the POF was knitted on the first needle right after the waste section and had a 7-stitch long float as part of the first unit; this pattern was repeated until the required length was reached. The fourth course started with a knit and float stitch in the middle of the 7-stitch sequence in the previous course – that is, the fifth needle after the waste section and the long float.

In K1-3 (Figure 2c), the first course consisted of 1 double x 6 back stitches, and the second course was knitted as pure back needle. In the third course, the POF was knitted on the first needle right after the waste section and had an 11-stitch long float as part of the main unit; this unit was repeated until the required length was reached. The fourth course started with the knit and float stitch in the middle of the 11-stitch sequence in the previous course – that is, the seventh needle after the waste section and long float.

The prototype swatches in Group 2 used the inlay technique to insert POFs into double plain and full cardigan structures. The inlay method allowed the POFs to be flat, whereas the main yarn creates knit structures around the POFs. The two prototype swatches in this group were named K2-1 (POF inlaid double plain) (Figure 3a) and K2-2 (POF inlaid full cardigan) (Figure 3b). The WPI / CPI of the swatches were 9 / 12 and 7 / 9. In both prototype swatches, two strands of POF were knitted in every course together with the supporting yarn to create a smoother yarn feed. The waste section and long float were created on the right side of the swatches. As the supporting yarn was the inlaid component forming the weft, the POFs were fixed to the textile via the main yarn. The POFs in this structure could be easily extracted from the textile, and the fabrics were flexible.

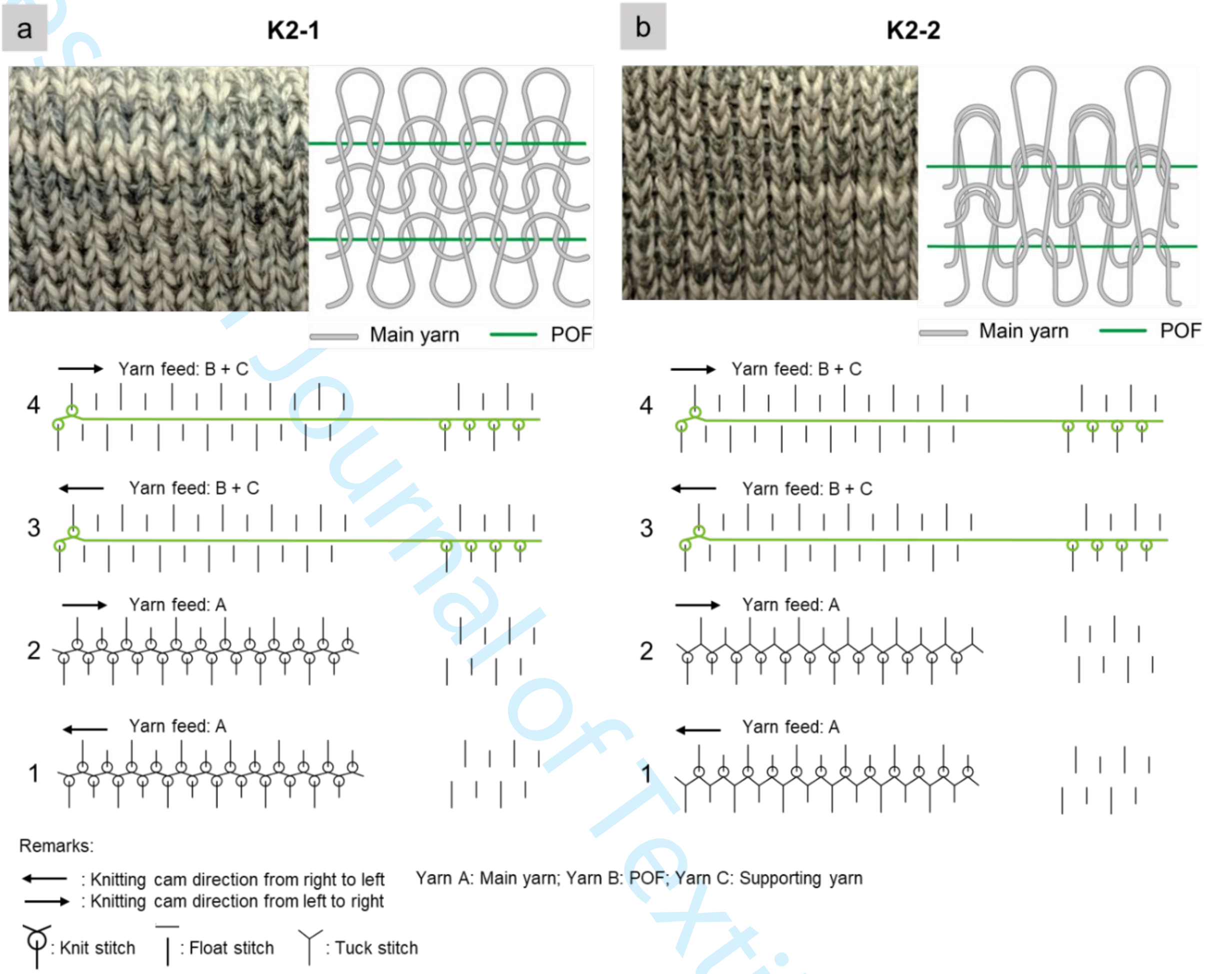

Figure 3 Images of the swatches with double plain and full cardigan structures, schematic image, and their knitting notations: (a) K2-1 and (b) K2-2.

In the Group 2 prototype swatches, the main yarn was knitted as a single unit on the first and second courses. In K2-1 (Figure 3a), the first and second courses used the double plain knit structure, and in the third and fourth courses, the POF was inserted in the structure using the inlay technique. Every third and fourth course required additional knit stitches at one end to create a waste section and a long float for the POF fringe. In K2-2 (Figure 3b), the first and second courses used the knit and tuck structure for a full cardigan structure. The third and fourth courses were the same as in K2-1 – that is, the POF was inserted in the structure using the inlay method.

Figure 4 shows the images of the fabrics created with the double plain and partial knitted structures, schematic image and their knitting notation. The prototype swatches in Group 3 used the basic double plain knit stitch and partial knit structures. K3-1 (Figure 4a) used the basic double plain knitted structure and K3-2 was created using partial knitting of a double plain structure in different sections (Figure 4b). The WPI / CPI of the two swatches were 8 / 18 and 7 / 14. The waste section was added to the right side to allow POF bundling. In the Group 3 swatches, 1 strand of POF was knitted in every course with the supporting yarn. As the supporting yarn formed part of the knit structure, it could not be removed.

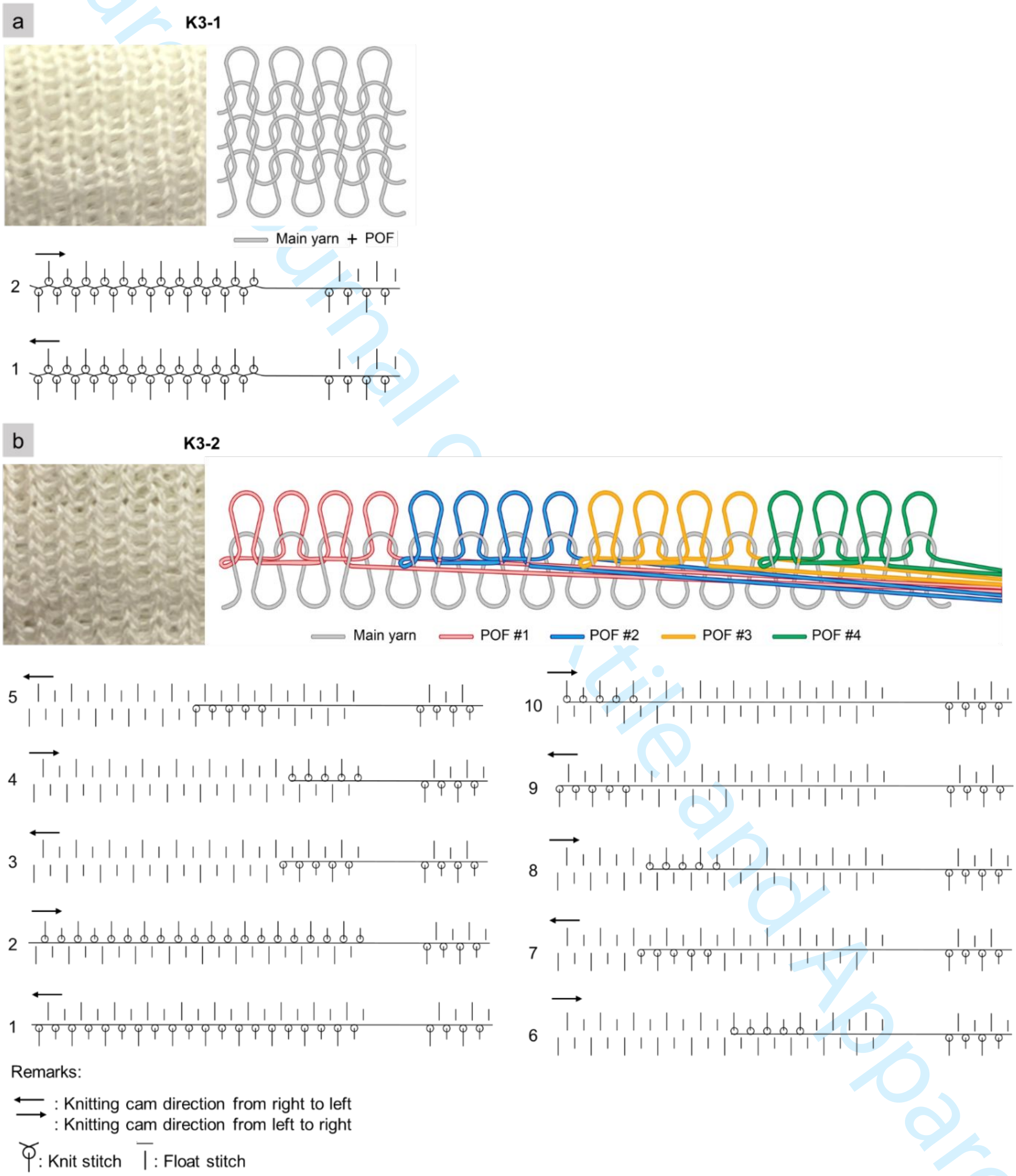

Figure 4 Images of swatches with double plain and partial knitted structures, schematic image, and their knitting notations: (a) K3-1 and (b) K3-2.

The prototype swatches in the third group tested the knittability of POFs in full needle and partial knitting structures. Those structures were designed for the investigation on minimising POFs breakage and resulting illumination disruption. In the swatches, the main yarn was knit together with the POF right after the waste section and long float. In K3-1 (Figure 4a), the first and second courses used the double plain structure, and this pattern was repeated for the entire swatch. In K3-2 (Figure 4b), the first and second courses formed a tubular structure. From the third to tenth course, there was a partial knit tubular: i.e., in the third and fourth courses, it was a partial knit for the first five stitches; in the fifth and sixth courses, it was a partial knit for the next five stitches; and so on. The rest of the prototype swatches repeated the partial tubular pattern at a 5-stitch interval.

POF bundling and LED coupling

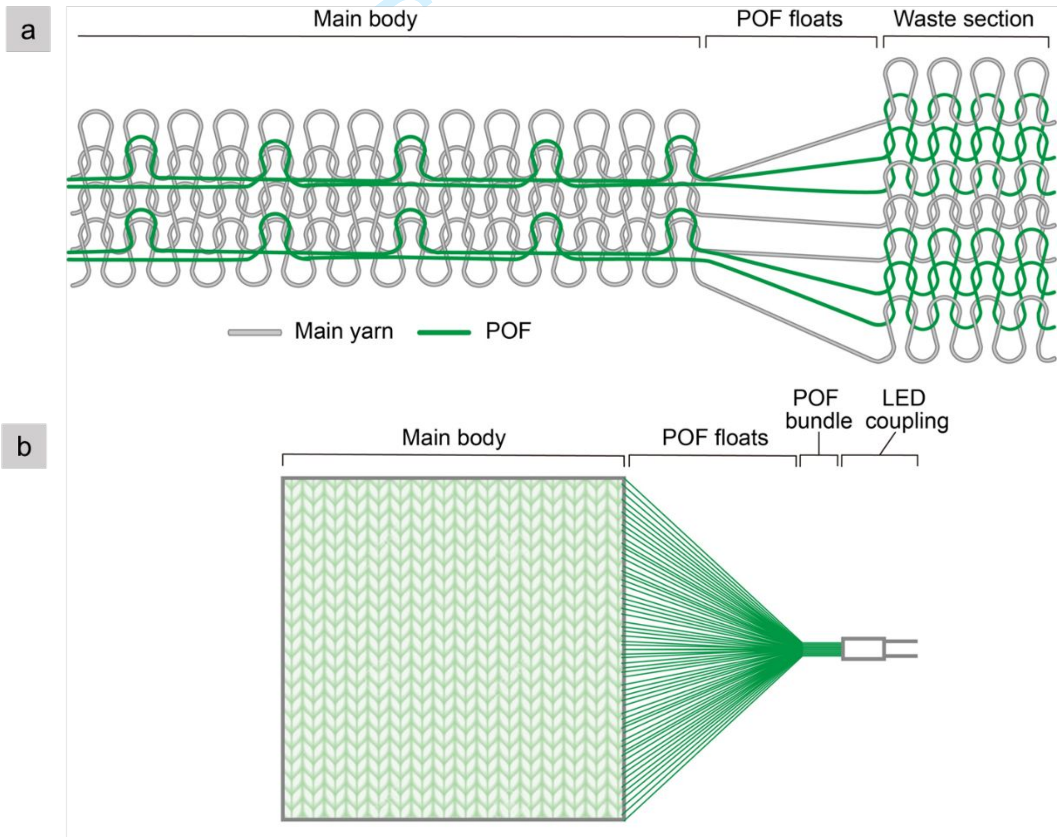

Figure 5 Diagrams showing (a) the 'waste section', which is the part of the POF floats knitted into the main body, and (b) the POF bundle attached to a light source (LED coupling).

To attach a light source to the textile for the illuminative effect, a 'waste section' was intentionally added to the edge of the main body of the knitting structure (Chen *et al.*, 2020). The waste section, shown in Figure 5a, consisted of POF floats and was added to the right side of the structure for the purpose of POF bundling and LED coupling (Figure 5b). The additional

6-stitch waste section was added to the 35-stitch main body of the POF long floats. When the textile swatch was cast off, the waste section was cut and prepared for POF bundling.

Measurement of illuminative effect

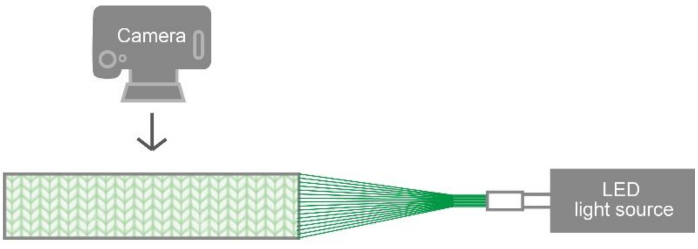

Figure 6 Top view of camera setup of illuminative effect measurement on prototype textile connected with LED light source

The measurement of illuminative effect was conducted in a room with dim light. Figure 6 shows the top view of camera setup for the measurement of illuminative effect. The prototype swatches were connected to an LED light source throughout the measurement process. The LED light source transmits light through the POFs to illuminate the textile. The measurement of surface light emitting effects was captured by a camera setup on top of the prototype textile. The distance between the camera and prototype is 20-30 cm. The camera setting was adjusted according to the level of visible illumination on the camera screen. The levels of illumination in all of the prototype swatches were compared in images taken at 1/4 sec., f/ 1.8, ISO 100. The light emitting effects were then measured by analysing the photos of the illuminated textile swatches. The ratio of the distance from the LED source that illumination travelled from the edge of textile and its diffusion on the swatches was observed in the image. The illumination effect was divided into three levels (strong, weak, or lost). The effect was rated depending on the light intensity observed on the images.

Results and discussion

Seven illuminative POF prototype swatches were created using a hand flat knitting machine. The illuminative effects of seven swatches were showed in Figure 7. Figure 7a to 7c shows the illuminative effect of Group 1 swatches: K1-1 (1 knit x 5 floats), K1-2 (1 knit x 7 floats) and K1-3 (1 knit x 11 floats). Figure 7d and 7e shows the illuminative effect of Group 2 swatches: K2-1 (double plain POF inlaid) and K2-2 (full cardigan POF inlaid. Figure 7f and 7g shows the illuminative effect of Group 3 swatches: K3-1 (double plain POF) and K3-2 (partial knitted double plain POF). The analyses of the prototype swatches indicated that the knit stitches have a direct impact on the illumination capacity of knitted POF textiles. Table III summarises the characteristics of the seven prototypes.

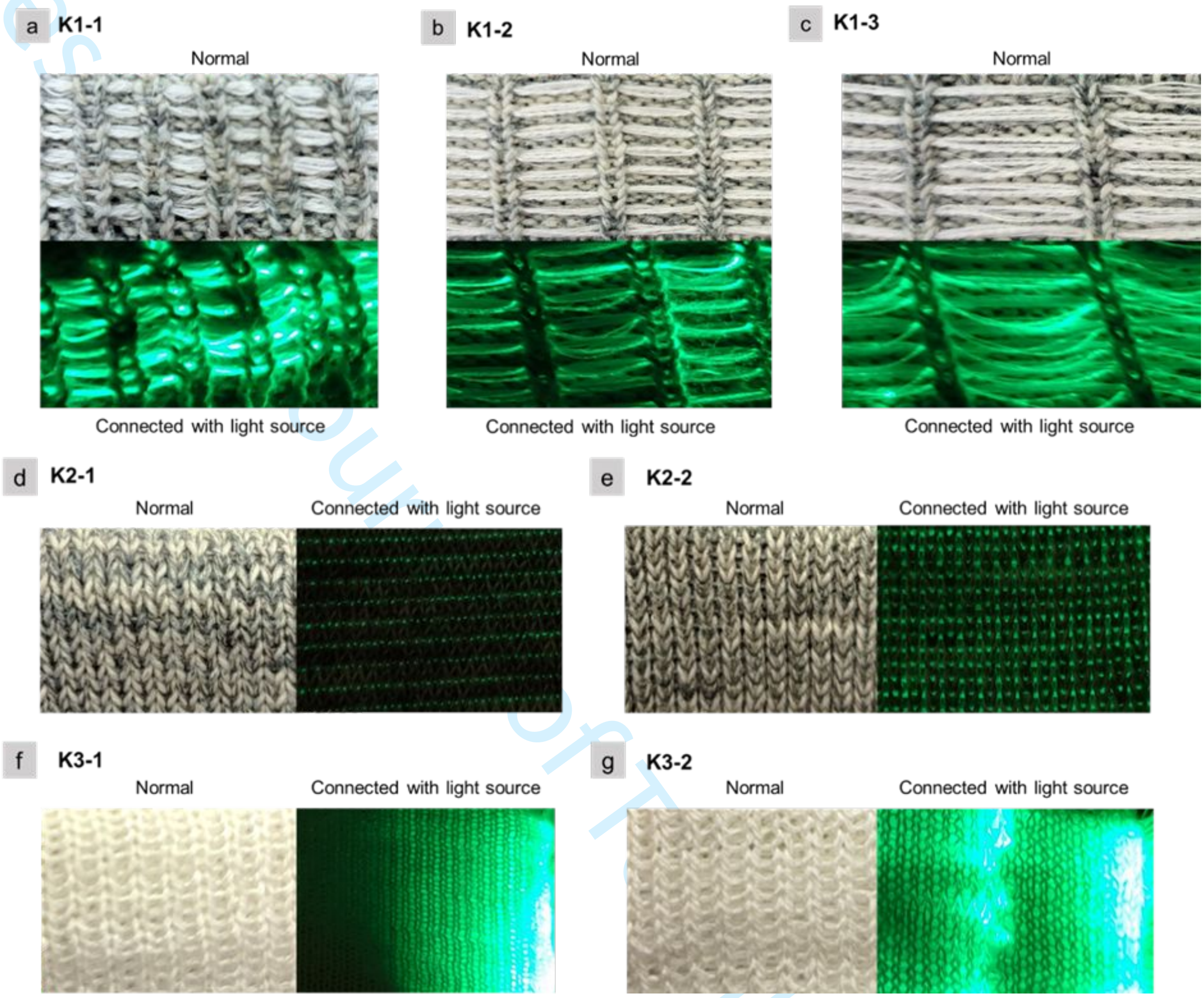

Figure 7 Illumination of prototype swatches: (a) K1-1 (1 knit x 5 floats); (b) K1-2 (1 knit x 7 floats); (c) K1-3 (1 knit x 11 floats); (d) K2-1 (double plain POF inlaid); (e) K2-2 (full cardigan POF inlaid; (f) K3-1 (double plain POF); and (g) K3-2 (partial knitted double plain POF).

Table III Characteristics of the prototype swatches

Prototype Swatch Code	**K1-1**	**K1-2**	**K1-3**	**K2-1**	**K2-2**	**K3-1**	**K3-2**
Illuminative effect	50% Lost 15% Weak 35% Strong	10% Lost 40% Weak 50% Strong	30% Weak 70% Strong	Weak	Strong	50% Lost 10% Weak 40% Strong	Strong
Relaxed horizontal fabric tension (Loops / 5cm)	28	16	13	17	13	16	14

Stretched horizontal fabric tension (Loops / 5cm)	25	15	13	9	7	14	11
Horizontal stretchability (%)	10.71	6	0	47.06	46.15	12.5	21.43
Relaxed vertical fabric tension (Loops / 5cm)	40	34	34	24	18	35	27
Stretched vertical fabric tension (Loops / 5cm)	26	26	20	18	12	28	20
Vertical stretchability (%)	35	24	41	25	33.33	20	25.93
Handle	Soft	Soft	Soft	Soft	Soft	Stiff	Stiff
POF snagged	Possible	Possible	Possible	Unlikely	Unlikely	Unlikely	Unlikely

Knitted POF fabric in intervallic knit and float stitches

The float stitch exposes the POFs on the surface of the fabric. This study examined how the float stitch can be used to integrate POFs into a knitted structure and the limitation of POF long floats in these fabrics. The prototypes were single jersey-based structures that used different combinations of floating distance, with a pattern of two normal knitted courses followed by two courses with different numbers of stitches in an intervallic approach. This study tested three versions of the float stitch, each with a different float length.

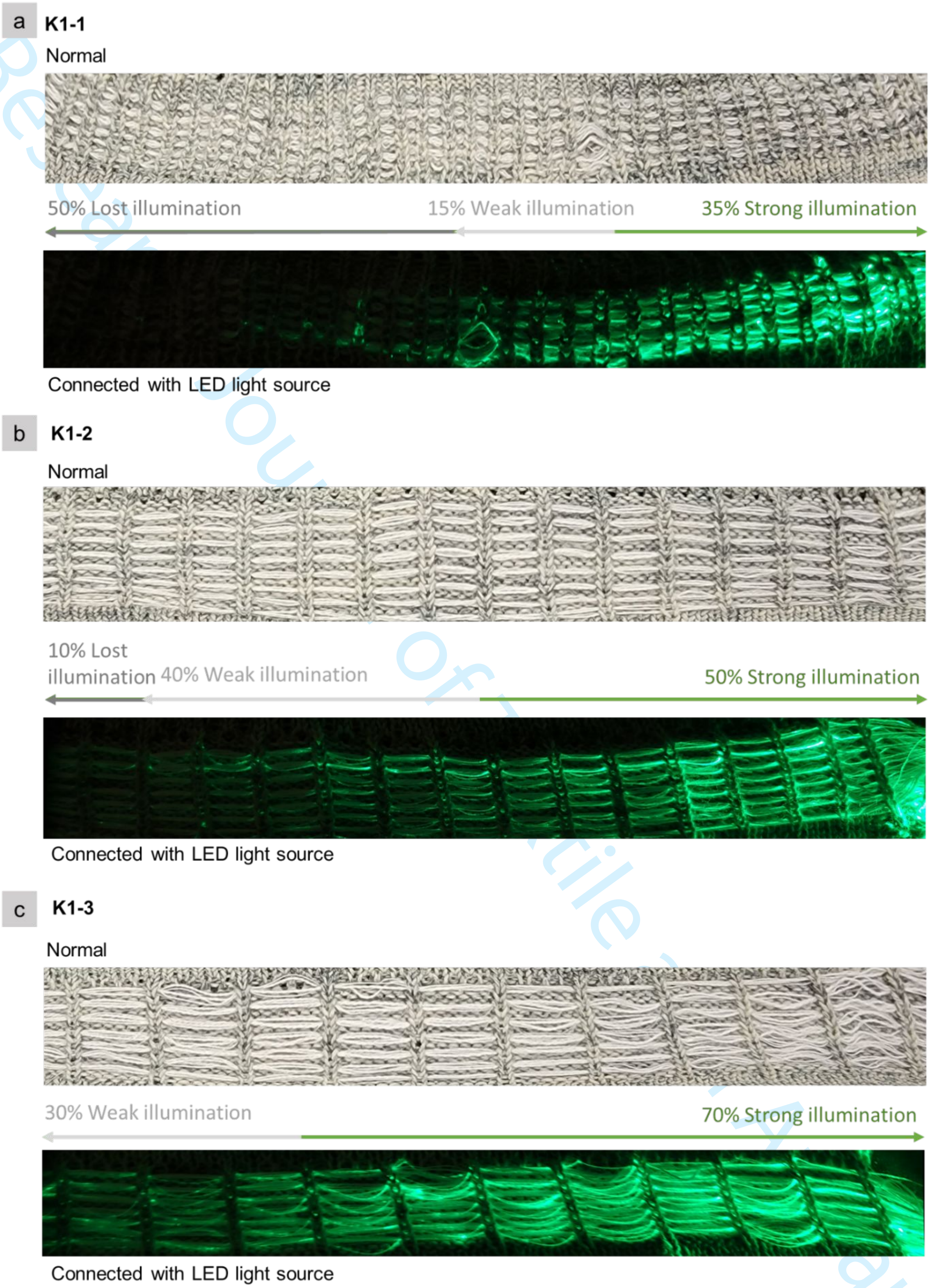

Figure 8 Illuminative effect in the prototype swatches: (a) K1-1 (1 knit x 5 float stitches), (b) K1-2 (1 knit x 7 float stitches) and (c) K1-3 (1 knit x 11 float stitches).

Swatch K1-1 had the most intense knit and float structure with a 5-stitch interval. The light was lost along 50% of the course, 35% of the course had strong illumination and the remaining 15% had weak illumination. The illumination disappeared at about the middle of the swatch (Figure 8a). Swatch K1-2 had a knit stitch at 7-stitch intervals (Figure 8b). Although it was illuminated across 90% of the entire course, only 50% of the course had strong illumination; 40% had weakened illumination and in 10%, the light was lost. Among all of the prototype swatches in Group 1, swatch K1-3 had the longest float (11 floats). This structure created an even surface with the highest exposure of POF and unsurprisingly achieved the most intense illumination. The light travelled along the whole course and had strong illumination for 70% of the entire course, then weakened for the last 30%.

These observations of the illumination of the knitted prototype swatches indicated that longer floats allowed more light to be transmitted along the entire course. In contrast, the sharp bending of POFs in knit structures damaged the fibres and light leaked from the bent fibres. This study found that illumination was disrupted after each knitted stitch, and the light was not able to travel for more than eight to nine stitches along a course.

For prototype swatches in Group 1, the front loop of the POF knit stitch fixed the course. The width of the swatch was limited because of the loss of illumination after each knitted stitch, but increasing the interval between knit stitches extended both the width of the knitted textile and the illuminative effect. Long floats minimised the number of knitted stitches, thus reducing the number of sharp bends in the POFs and increasing the illumination distance. However, the length of POF floats must be controlled to prevent unwanted yarn from being drawn from the surface. Swatch K1-1 had the lowest illumination intensity: the light was disrupted after ten to eleven knitted stitches. Swatch K1-2 had a structure with a short knit and float interval. Swatch K1-3 had the longest sequence of float stitches (11 floats) and the highest illumination intensity.

Overall, this study showed that the intervallic knitting approach, which allows the manipulation of float arrangement and interval distance, can be used to create structures that enhance the illumination of knitted textiles by reducing the number of knit stitches and thus decreasing the amount of POF breakage. Compared to the knitted structures created in previous studies, the Group 1 structures offered an explicit arrangement of knit and float stitches in a structure that could affect the transmission of light. Swatch K1-3 had a similar intervallic knit and float stitch structure as the prototype in Chen *et al.* (2020). It is also notable that when fewer components were used for bundling and illumination, it was possible to create lighter, non-intrusive and easier-to-maintain textiles suitable for more practical applications.

The stretchability of the prototype swatches was also considered. Chen *et al.* (2020) found that the horizontal stretch of the POF fabrics was more limited than the vertical stretch. This study confirmed those results. The unit used to measure fabric stretch was loops per 5 cm. Swatch K1-1 had the highest stretchability of the three prototypes (10.71%); K1-2 had around 6% of stretch and K1-3 had no stretch in the direction of the course. In the vertical direction, the stretchability of the prototype swatches had distinct results: K1-3 could be stretched up to 41%, K1-1 could be stretched up to 35% and K1-2 stretched to nearly 24%. POF is more rigid than knitting yarn, and the tight tension created by the loop formation decreased the stretchability further.

When using a flat knitting process to produce this kind of structure, a supporting yarn was fed into the machine together with the POF. This made it difficult to remove the supporting yarn after sampling, as it was knitted as a loop with the POF. It is recommended that the colour of the supporting yarn used in this structure be considered part of the design of the illuminative textile. Hence, the handle of the prototype swatches was primarily dependent on the main yarn. The technical back of the single jersey structure gave a soft handle. The selection of the main yarn would be an important aspect of the design.

Inlaid POF in double plain and full cardigan structures

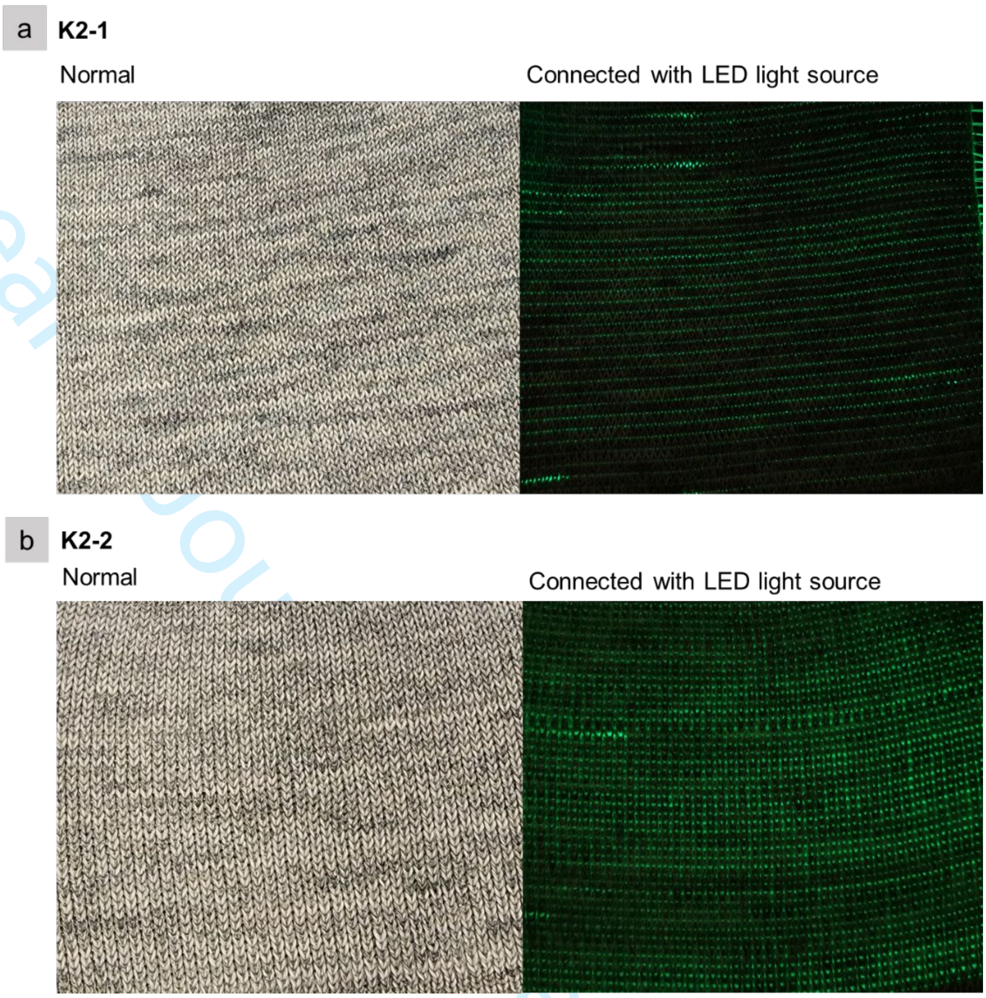

Figure 9 Illumination of prototype swatches: (a) K2-1 double plain and (b) K2-2 full cardigan structure.

With the inlay technique, the POFs can be integrated into a knitted structure without the need for the fibres to form loops. This decreases the damage to the POFs and creates a more even light transmission throughout the swatch. K2-1 was a double plain knitted jersey, which is the most common structure in textiles. In K2-1 (Figure 9a), the main yarn had high coverage of the surface, and thus the illumination from the POFs was hard to observe. Swatch K2-2 (Figure 9b) had a structure built on the knit and tuck stitch. The tuck stitch produces more open knitted textiles, and this looser structure exposed more of the POFs, achieving better illumination. Both swatches had horizontal stretchability of more than 45%, but the vertical stretch of K2-2 (33.3%) was better than that of K2-1 (25%). The inlaid method for integrating POF increased the textile's flexibility, making it easier to form shaped panels, and imposed fewer constraints on the textiles' stretchability. Compared to K2-1, K2-2 had less compact loop formation, giving it a softer handle. One characteristic of textiles made by this method was that the yarns were slippery within the textiles, as the POFs were not knitted. Thus, the POFs were unlikely to snag on the surface. Hence, the handle of the prototype swatches was primarily dependent on the main yarn. In this group of swatches, only one end of the waste section was required for POF bundling. The placement of POF fringes and bundling arrangement could be based on design and application criteria. In addition, the supporting yarns were easy to remove in these two structures, which addresses aesthetic concerns.

POF in double plain and partial knitted structures

Figure 10 Illumination of prototype swatches: (a) K3-1 double plain structure and (b) K3-2 partial knit double plain structure.

In K3-1 (Figure 10a), light leaked from the edge on the side closest to the light source and the illumination was disrupted after travelling a short distance across the swatch. The illumination leakage was caused by the loops in the POFs and affected the light transmission. In K3-1, there was strong illumination across 40% of the entire course; there was a short stretch of weak illumination (10%) and no illumination for the rest area of the swatch (50%). However, the breakage of POFs at the edge of the swatch created concentrated light spots that enhanced the illumination in these areas. In K3-2 (Figure 10b), the illumination was enhanced by a structure that repeated the single unit used in K3-1. The partial knitting structure created a repetitive pattern that increased the light concentration along the entire course. The illumination near the edge of K3-2 was the same as in K3-1, but repeating the knit stitch increased the area of illumination. These findings suggested that patterns of repetitive units can minimise POF breakage, which is important in real applications, as POF breakages disrupt the illumination after a certain distance. This technique provides an alternative method for integrating POFs into knitted double fabrics. It created different concentrated light spots or areas along a course, thus offering an alternative when the light cannot be transmitted to all areas of a textile.

The stretchability of the K3 prototype swatches was also investigated. Swatch K3-1 stretched up to 12.5% and K3-2 stretched up to 21.43% in the horizontal direction. In the vertical direction, K3-1 stretched up to 20% and K3-2 stretched up to nearly 26%. Thus, among the experimental swatches, the partial knit double plain textile had greater stretchability than the conventional double plain textile. Knitting the POF in separate sections increased the concentration of the illuminative effect and created better stretchability in both the horizontal and vertical directions. The structure of swatch K3-2 (partial knitted) achieved illumination across the textile surface with a waste section on one end. Although the breakage of POF in knitted structures has been considered a failure in textile development, it could be the key to creating illuminative textiles, as damaged POFs increase the illumination in the damaged areas. The drawback of this partial knitted structure was that it creates extra courses of POFs with more POF fringes at one end, which increases the thickness of the POF bundles.

As the POFs were knitted together with the main yarn in this technique, a smooth edge was created on the side of the swatch without the POF bundling. In addition, the supporting yarn could not be removed after knitting, as it formed part of the knit structure. This structure gives a hard and rigid hand feel, as the POFs were knitted with a normal yarn throughout the whole swatch. The chances of unwanted POF snagging were low because of the tightly formed loop structure.

Conclusions

Seven illuminative POF prototype swatches were created using a hand flat knitting machine. This study has investigated novel POF knitted textiles with intervallic knit and float stitches, inlaid POF double knit, double plain and partial knit. It is concluded that the integration of POFs in loop structure affected the illumination and the fabric's stretchability. Longer intervallic knit and float stitches offer more exposure of POFs which could contribute to the illumination effects. Besides, the openness of knit structure (full cardigan) could enhance the illumination compare to double plain structure. In addition, even if POFs are knit in loop structure, the repetitive pattern in different sections create an even illumination.

In the prototype swatches of intervallic knit and float stitch, the extent of the illumination was affected by the choice of knit and float stitch sequences. Longer floats expose more POFs, which contribute to the illuminative effects but limits the textile's horizontal stretchability. Breakage caused by abrupt bending of the POFs when forming loops disrupted the light transmission; however, intervallic knit and float stitches decreased the light disruption. Swatches of intervallic knit and float stitches produced good illumination effects and the longer floats exposed more fibres, increasing the illumination. The swatches' horizontal stretchability was affected by the float length. An illuminating effect could be achieved by connecting the POF bundle at one end of the swatch to a light source.

The inlayed POFs produced the most intense and even illumination. The open structure of the full cardigan swatch exposed more POFs than the double plain knitted structure and thus enhanced the illumination.

It is possible to knit POFs in a full needle setting; however, this may compromise the illumination effect and cause partial illumination of the fabric. This study showed that patterns consisting of repeats of the same full needles sets in separate sections decrease the chance of uneven illumination caused by looped POFs. This partial knitting in separate sections was the most successful approach to genuine integration of POF in physically knitted textiles. However, this technique hinders the horizontal stretchability of the textile.

This study highlighted the effects of knit stitches on the illumination of POF textiles. It shed light on how POFs perform when manipulated into different loop formations. Specifically, it found that knitting POFs on industrial hand flat knitting machines is a viable technique. The authors recommend that further studies investigate whether it is possible to knit POFs on computerised knitting machines. In commercial applications, industrial hand flat knitting machines are used for small orders and basic sample development. Future studies using computerised knitting machines will contribute to the mass production of POF textiles, which is necessary for wider applications.

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References

Bai, V. Z., Tan, J., Chen, A. & Ge, L. (2019), "Enhancing the wearablity and accessibility of illuminated POF garment". *International Journal of Clothing Science Technology,* Vol. 32, No. 2, pp. 218-230

Bai, Z., Tan, J., Johnston, C. & Tao, X. M. (2012), "Enhancing the functionality of traditional interior textiles with integration of optical fibers". *Research Journal of Textile and Apparel,* Vol. 16, No. 4, pp. 31-38

Bai, Z., Tan, J., Johnston, C. F. & Tao, X. M. (2015), "Connexion: development of interactive soft furnishings with polymeric optical fibre (POF) textiles". *International Journal of Clothing Science and Technology,* Vol. 27, No. 6, pp. 870-894

Chen, A., Tan, J., Henry, P. & Tao, X. (2020), "The design and development of an illuminated polymeric optical fibre (POF) knitted garment". *The Journal of The Textile Institute,* Vol. 111, No. 5, pp. 745-755

Daishing Pof Co. Ltd. n.d. "*Fiber Optic Textile"*, available at: http://www.dspof.cn/Optical-fiber-cloth (accessed 17 Nov 2021).

Ge, L. & Tan, J. (2021), "Development of three-dimensional effects and stretch for polymeric optical fiber (POF) textiles with double weave structure containing spandex". *The Journal of The Textile Institute,* Vol. 112, No. 3, pp. 398-405

Gorgutsa, S., Berzowksa, J. & Skorobogatiy, M. 2013. 3 - Optical fibers for smart photonic textiles. Kirstein, T. (ed.) *Multidisciplinary Know-How for Smart-Textiles Developers.* Cambridge: Woodhead Publishing.

Harlin, A., Makinen, M. & Vuorivirta, A. (2003), "Development of polymeric optical fibre fabrics as illumination elements and textile displays". *AUTEX Research Journal,* Vol. 3, No. 1, pp. 8

Kim, H., Tan, J. & Toomey, A. (2018), "Co-designing Interactive Textile for Multisensory Environments". *International Conference on Artificial Intelligence on Textile and Apparel*. Springer, pp.205-211.

Kim, H., Tan, J. & Toomey, A. (2019), "User experience and interactive textiles: A textile designer's perspective". *International Journal of Design Management Professional Practice,* Vol. 13, No. 2, pp. 1-10

Militky, J., Kremenakova, D. & Saskova, J. (2018), "Optical Attenuation of Linear Composites Containing SEPOF". *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, pp.012035.

Mohr, B., Beckers, M., Münch, P., Seide, G., Gries, T. & Bunge, C. (2016), "Textile Integration of POF for lighting applications". *Proceedings of the Conference Proceedings: 25th International Conference on Plastic Optical Fibres*. Aston University: Birmingham, UK.

Quandt, B. M., Pfister, M. S., Lübben, J. F., Spano, F., Rossi, R. M., Bona, G.-L. & Boesel, L. F. (2017), "POF-yarn weaves: controlling the light out-coupling of wearable phototherapy devices". *Biomedical optics express,* Vol. 8, No. 10, pp. 4316-4330

Samsara Srl. 2020. "*FIBER OPTIC TABLE RUNNERS FOR SPECIAL ATMOSPHERES: DREAMLUX*", available at: https://lumigram.com/en/smartblog/6_.html (accessed 29 Oct 2021).

Schrank, V., Beer, M., Beckers, M. & Gries, T. 2017. Polymer-optical fibre (POF) integration into textile fabric structures. Christian-Alexander, B., Thomas, G. & Markus, B. (eds.) *Polymer optical fibres.* Duxford, United Kingdom: Elsevier.

Shindo. 2015. "*Plastic Optical Fiber Mesh Knit*", available at: https://www.shindo.com/en/fashion/material/assets/Knitted%20optical%20fiber-E.pdf (accessed 27 Aug 2021).

Tan, J. 2013. *Neophotonics*, The Hong Kong Polytechnic University.

Tan, J. 2015. Photonic fabrics for fashion and interiors. Tao, X. (ed.) *Handbook of Smart Textiles.* Singapore: Springer.

Tan, J., Bai, Z., Ge, L., Shao, L. & Chen, A. (2019), "Design and fabrication of touch-sensitive polymeric optical fibre (POF) fabric". *The Journal of the Textile Institute,* Vol. 110, No. 11, pp. 1529-1537

Tan, J. & Chen, A. 2019. *Fāguāng zhēnzhī wù hé fāguāng zhuāngzhì*. China patent application.

Tan, J., Shao, L., Lam, N. Y. K., Toomey, A. & Ge, L. (2021), "Intelligent textiles: designing a gesture-controlled illuminated textile based on computer vision". *Textile Research Journal,* Vol. No., doi: 00405175211034245.

Wang, J., Huang, B. & Yang, B. J. T. R. J. (2013), "Effect of weave structure on the side-emitting properties of polymer optical fiber jacquard fabrics". Vol. 83, No. 11, pp. 1170-1180doi:

Wang, J., Yang, B., Huang, B. & Jin, Z. (2012), "Design and development of polymeric optical fiber jacquard fabric with dynamic pattern display". *Textile Research Journal,* Vol. 82, No. 10, pp. 967-974

Yang, J.-H., Park, S.-H., Cho, H.-S. & Lee, J.-H. (2013), "A study of luminescence effects of POF-woven fabric display by method of weaving". *Science of Emotion and Sensibility,* Vol. 16, No. 4, pp. 517-526