This is the accepted version of the publication Liu S, Liu Y, Li L. The impact of different proportions of knitting elements on the resistive properties of conductive fabrics. Textile Research Journal. 2019;89(5):881-890. Copyright © The Author(s) 2018. DOI: 10.1177/0040517518758003.

The impact of different proportions of knitting elements on the resistive properties of conductive fabrics

Su Liu[a], Yanping Liu[b], and Li Li[c]*

[a] *Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hong Kong*

[b] *Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hong Kong*

[c] *Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hong Kong*

*Corresponding Author:
Li Li, The Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong. Email: li.lilly@polyu.edu.hk

The impact of different proportions of knitting elements on the resistive properties of conductive fabrics

Abstract

Conductive yarn is the key factor in fabricating electronic textiles. Generally, three basic fabric production methods (knit, woven, and non-woven) combined with two finishing processes (embroidery and print) are adopted to embed conductive yarns into fabrics to achieve flexible electronic textiles. Conductive yarns with knit structure are the most flexible and effective form of electronic textiles.

Electronic textiles present many advantages over conventional electronics. However, in the process of commercialization of conductive knitted fabrics, it is a great challenge to control the complicated resistive networks in conductive knitted fabrics for the purpose of cost saving and good esthetics. The resistive networks in conductive knitted fabrics contain length-related resistance and contact resistance. The physical forms of conductive yarns in different fabrication structures can be very different and, thus, the contact resistance varies greatly in different fabrics. So far, study of controlling the resistive property of conductive fabrics has not been conducted.

Therefore, establishing a systematic method for the industry as a reference source to produce wearable electronics is in great demand. During the industrialization of conductive knitted fabrics, engineers can estimate the resistive property of the fabric in advance, which makes the production process more effective and cost efficient. What is more, the resistive distribution in the same area of knitted fabrics can be fully controlled.

Keywords
conductive knitting, float stitch, tuck stitch, resistance value, length-related resistance, contact resistance

Smart E-textiles is a newly emergent industry thanks to the combination of conductive materials and traditional textiles.[1] Nowadays, wearable electronic textiles have progressed from the research lab into the industry and subsequently been commercialized.[2–6] Conductive yarn is the key factor in fabricating electronic textiles.

Three basic texture methods of production (knit, woven, and non-woven) combined with two main methods of finishing (embroidery and print) are adopted to embed conductive yarns into fabrics to achieve flexible electronic textiles. A knit structure with conductive yarns is the most flexible and effective form of electronic textiles.[7–9] A certain number of researchers have taken great effort in the study of resistive properties of conductive knitted fabrics. Most of the study was focused on the properties of the conductive plain knitted structure, which is the most basic structure in knitting either under free or a certain external load.[10–15] However, it is found that the knitted structure can be an important factor that determines the performance of conductive knitted fabrics.[16–18] Therefore, it is necessary to investigate how the knitted structure influences the conductive performance of knitted fabrics. In the authors' previous research work, an effective system has been established for the resistive impact of different knitted structures based on the construction of different knitting elements from a microscope view.[19,20] It was found that float and tuck stitches, which are the other two elements in knitting technology, can reduce the whole resistance value to a certain degree. In further research, the present study will be carried out on the percentage influence of different knitting elements. With reference to 100% knit fabrics, samples of conductive knitted fabrics with float stitches and tuck stitches are fabricated by considering the proportions of float and tuck stitches in the entire fabric. Corresponding swatches with different structures are prepared and the resistance values are measured. It was found that the percentage of float stitches and tuck stitches can greatly influence the resistive properties of conductive knitted fabrics. With the increase of float or tuck stitches, the value of resistance sharply decreases. Thus, tuck stitches can be a more effective knitting structure to reduce the total value of resistance, while float stitches can be a cost-effective structure because the amount of yarn is reduced greatly.

Opportunities and challenges coexist. The industry does not have a method to calculate and control the resistance of fabrics simply based on current textile knowledge. The wearable electronic products thus cannot be further developed. It is a common challenge to control the complicated resistive networks in conductive fabrics, which contain contact resistances and length-related resistances. The physical forms of conductive yarns in different fabrication structures can be very different and, thus, the contact resistance varies greatly in different fabrics. Thus, the study of the resistive property of conductive fabrics is in great demand for the purpose of cost saving and good esthetics.

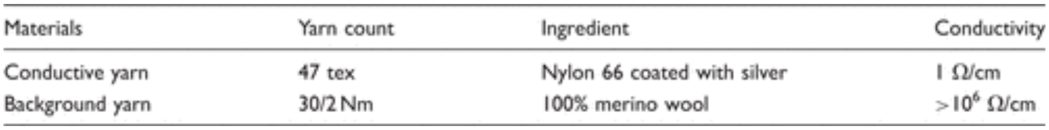
Furthermore, as we know, the cost estimation is very complicated. The price of products is usually double the cost. The price of conductive yarn is commonly around US$300 per kilogram and the usage of conductive yarns for a present heating garment product on the market is about 100 g, which puts great pressure on the sale price.

Therefore, there is a need to establish a systematic method for the industry as a reference source to produce wearable electronics. The relationship between different stitches and the properties of conductive materials needs to be explored. At the same time, there is a demand to investigate how much the yarn cost can be reduced and how much the resistance properties of conductive knitted fabrics can be changed accordingly when the percentage of different knitting elements (knit, float, and tuck) changes. This will provide valuable viewpoints and information for the worldwide wearable business and assist with the industrial production of textile manufactories.

Experimental procedure

Material specifications

The yarns are shown in the Table 1. The yarn core and appearance of both types of yarns (conductive and wool) are shown in Figure 1.



Materials	Yarn count	Ingredient	Conductivity
Conductive yarn	47 tex	Nylon 66 coated with silver	1 Ω/cm
Background yarn	30/2 Nm	100% merino wool	$>10^6$ Ω/cm

Table 1. The materials used for conductive part and background part

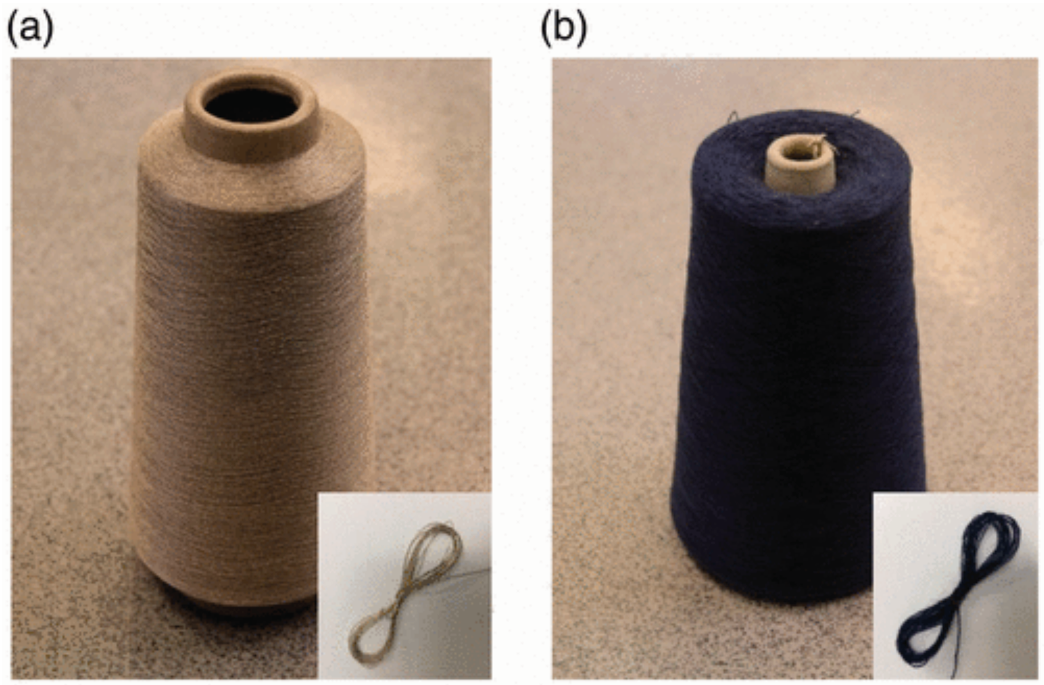


Figure 1. Yarn core and sample: (a) conductive yarn; (b) wool yarn.

Equipment information

The experimental samples were still knitted on a STOLL CMS 822 computerized flat knitting machine (H. Stoll GmbH & Co.KG), as shown in Figure 2. To make the sample specifications uniform, the knitting parameters for producing the samples were as listed in Table 2. In Table 2, the NP value is a stitch cam setting on the STOLL knitting machine, which is related to controlling the tightness of the fabric. For the same knitted structure, a higher NP value means a less dense fabric. The WM value is a parameter of the take-down tension and a higher value means a greater tension.

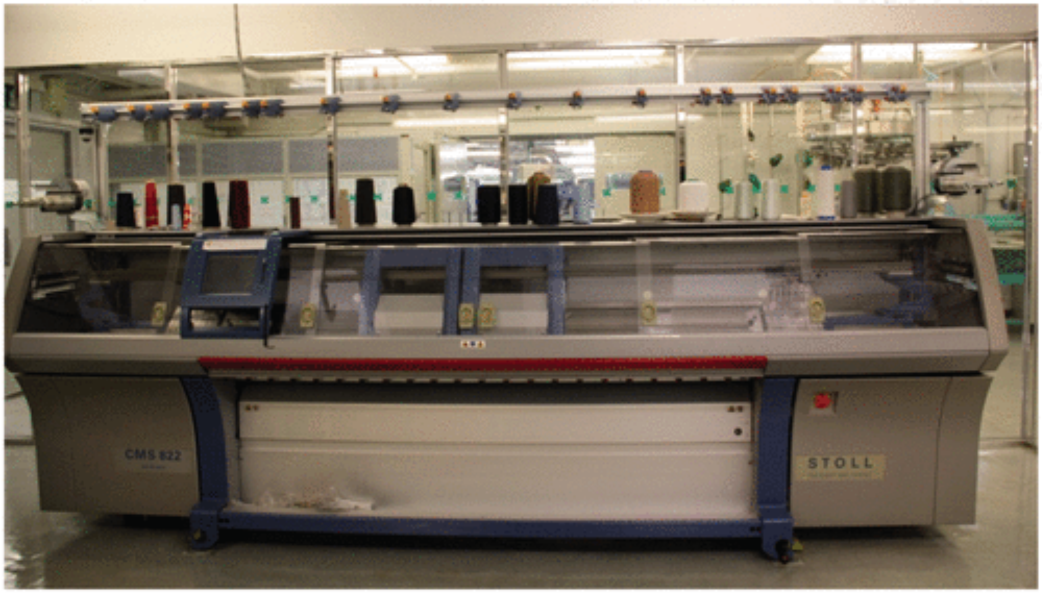
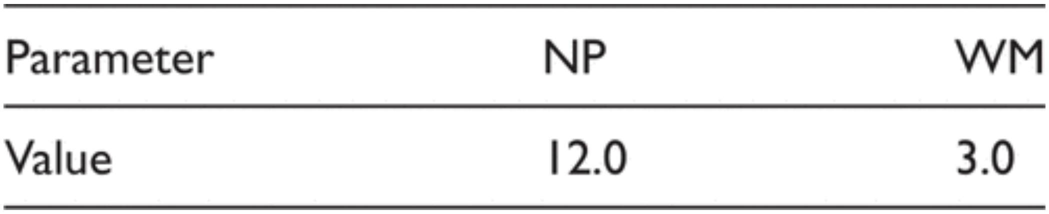


Figure 2. STOLL CMS 822 computerized flat knitting machine.



Parameter	NP	WM
Value	12.0	3.0

Table 2. Knitting machine parameters

Experimental design

Table 3 lists the characterization of different knitting elements (knit, tuck, and float) in different aspects of appearance, stability, yarn cost, application, dimension, and density. It was found that different knitting methods can give the fabric different performances and properties; therefore, the experiments were designed as follows. Seven fabric samples knitted with different proportions of float stitches are fabricated. The fabric samples are uniform in size, with a dimension of 100 courses and 100 wales; Figure 3 shows the knitting notations. Float knitted structures can be knitted by using the float jacquard technique for an esthetically pleasing appearance and dimensional stability. In the figure, the symbols  and  represent the knit and float stitches, respectively. In the present research, it is supposed that the resistance values remain the same when the structures are different but the proportion of knitting elements is the same.

Characterization	Knit	Tuck	Float
Appearance	Plain, smooth	concave-convex	Long float line
Stability	***	*****	*
Yarn cost	100%	≈90%	≈40%
Courses per cm	10	11.76	7.81
Wales per cm	8	7.04	7.69

Table 3. The characterization of different knitting elements

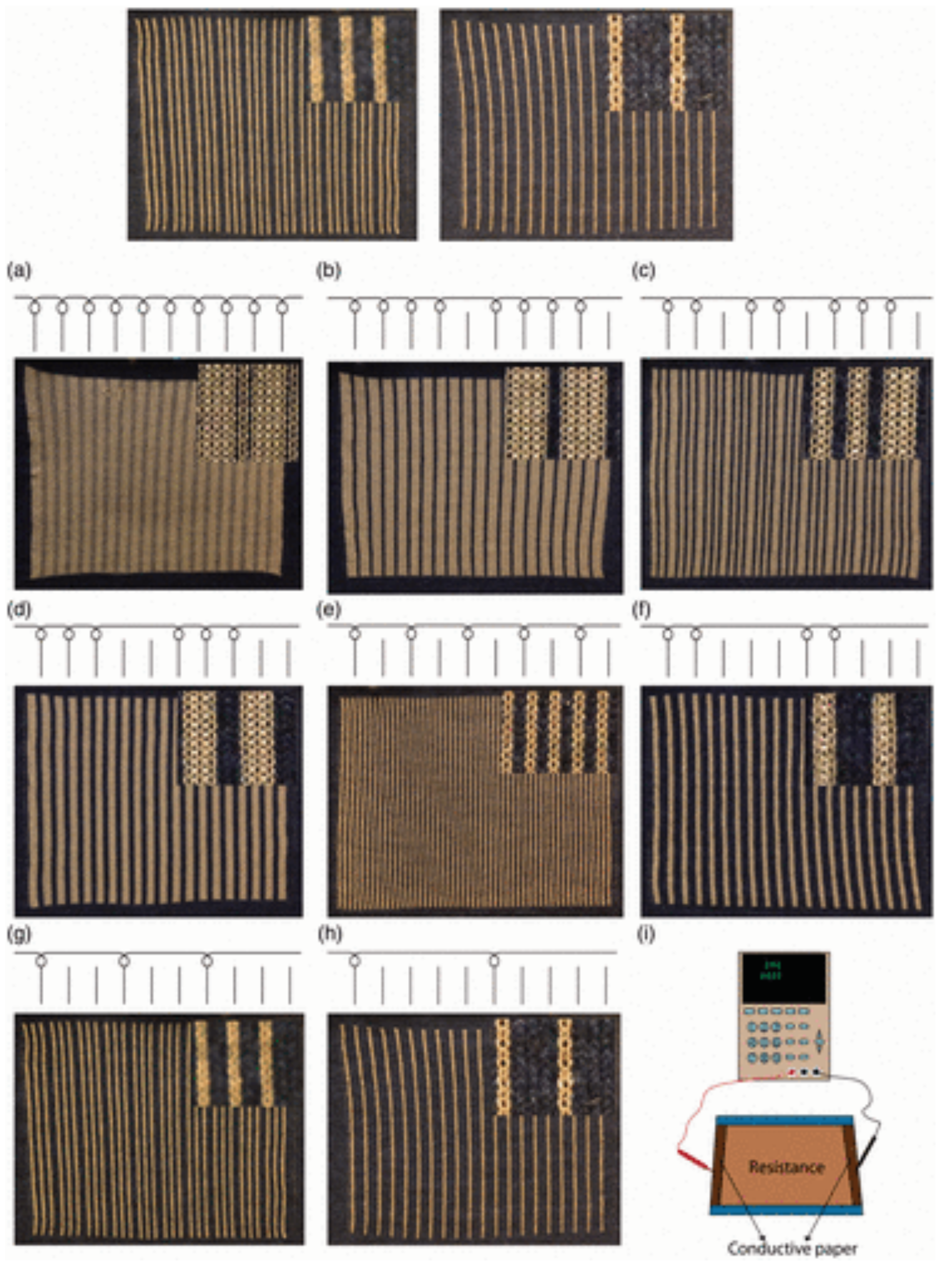


Figure 3. Knitting notations and fabric images of knitted structures with different proportions of float stitches: (a) 0%; (b) 20%; (c) 30%; (d) 40%; (e) 50%; (f) 60%; (g) 70%; (h) 80%; (i) illustration of the testing method.

Seven samples of knitted fabrics with different proportions of tuck stitches are fabricated that have the same dimensions as the fabric samples with float stitches; Figure 4 provides the knitting notations. A limitation of tuck structures is that the proportion of tuck stitches cannot exceed 50%. For a more esthetically pleasing appearance, a double layer structure was adopted and a fine Lycra yarn was used to sew the two layers together with tuck stitches. In the figure, the symbols  and  denote the knit and tuck stitches, respectively.

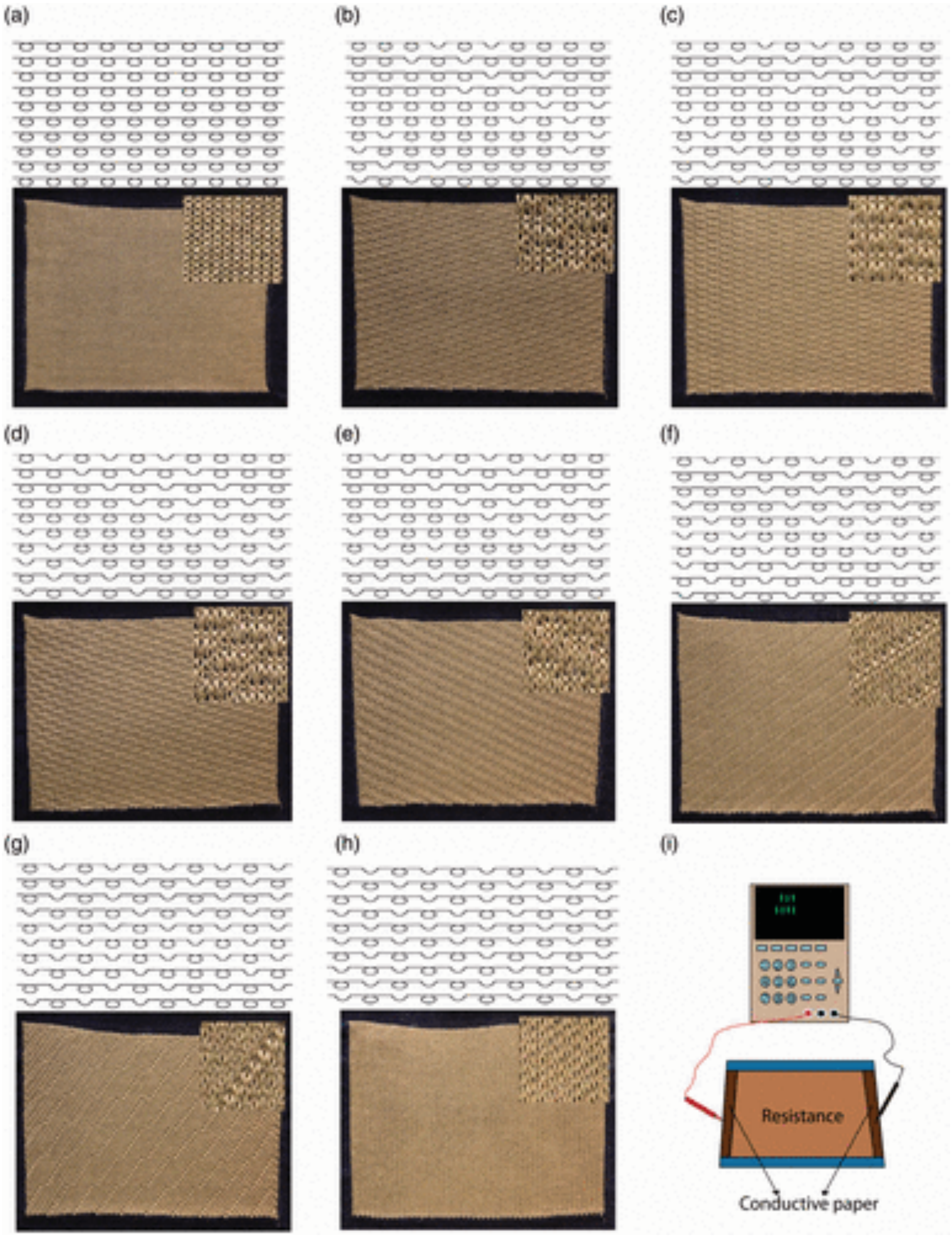


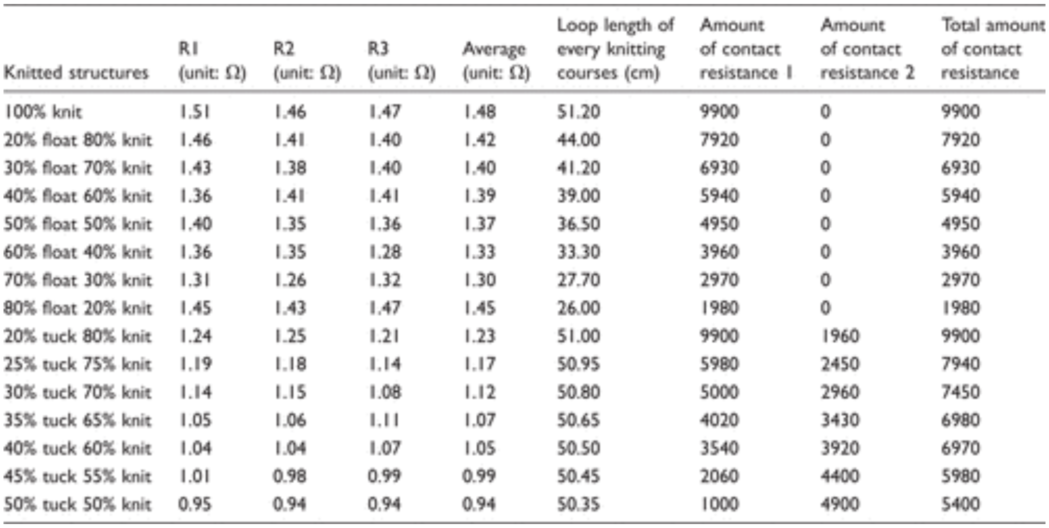
Figure 4. Knitting notations and fabric images of knitted structures with different proportions of float stitches: (a) 0%; (b) 20%; (c) 25%; (d) 30%; (e) 35%; (f) 40%; (g) 45%; (h) 50%; (i) illustration of the testing method.

The fabric views of the different float and tuck knitted structures with different proportions of knit, float, and tuck stitches are shown in Figures 3 and 4, respectively.

It can be observed that the different structures can provide a multitude of fabric surface appearances, which contribute to different thermal knitwear designs. All of the different samples were fabricated with the same three pieces of fabric for reproducibility.

Experimental results

All the knitted samples were placed into a constant temperature and humidity chamber for 24 hours after they were removed from the knitting machine. The resistance of the individual fabric samples was measured with a DAXIN digital control direct current (DC) power supply. The electrical circuit that went through the conductive fabric samples was measured when an output of 1 V was loaded. To obtain stable and effective data, conductive paper was glued onto the edge of each sample, as shown in Figures 3 and 4. The tested resistance values for the samples are listed in Table 4.



Knitted structures	R1 (unit: Ω)	R2 (unit: Ω)	R3 (unit: Ω)	Average (unit: Ω)	Loop length of every knitting courses (cm)	Amount of contact resistance 1	Amount of contact resistance 2	Total amount of contact resistance
100% knit	1.51	1.46	1.47	1.48	51.20	9900	0	9900
20% float 80% knit	1.46	1.41	1.40	1.42	44.00	7920	0	7920
30% float 70% knit	1.43	1.38	1.40	1.40	41.20	6930	0	6930
40% float 60% knit	1.36	1.41	1.41	1.39	39.00	5940	0	5940
50% float 50% knit	1.40	1.35	1.36	1.37	36.50	4950	0	4950
60% float 40% knit	1.36	1.35	1.28	1.33	33.30	3960	0	3960
70% float 30% knit	1.31	1.26	1.32	1.30	27.70	2970	0	2970
80% float 20% knit	1.45	1.43	1.47	1.45	26.00	1980	0	1980
20% tuck 80% knit	1.24	1.25	1.21	1.23	51.00	9900	1960	9900
25% tuck 75% knit	1.19	1.18	1.14	1.17	50.95	5980	2450	7940
30% tuck 70% knit	1.14	1.15	1.08	1.12	50.80	5000	2960	7450
35% tuck 65% knit	1.05	1.06	1.11	1.07	50.65	4020	3430	6980
40% tuck 60% knit	1.04	1.04	1.07	1.05	50.50	3540	3920	6970
45% tuck 55% knit	1.01	0.98	0.99	0.99	50.45	2060	4400	5980
50% tuck 50% knit	0.95	0.94	0.94	0.94	50.35	1000	4900	5400

Table 4. Resistance values, loop length, and amount of contact resistance of conductive fabrics with different proportions of float and tuck stitches

The construction of different knitted fabrics can be observed by micro-computed tomography (micro-CT; vivaCT 40). Micro-CT images for different knitted structures are shown in Figure 5. Because of the deviation in construction for different conductive knitted structures, the loop length for the same dimension, that is, one course with 100 wales, will be different. The experimental measured values are listed in Table 4. On the other hand, contact resistances will be changed accordingly with different constructions as shown in the colored dots in Figure 5. For the interlock of knit stitches, the contact resistances are generated by the overlap of two conductive yarns, as shown in Figure 5(a) and (b) (red dots). For the interlock of the knit stitch and the tuck stitch, the contact resistances are generated by the overlap of three conductive yarns because the tuck stitch is only held on the old knit stitch, as shown in Figure 5(c) (orange dot). The amount of contact resistance in every knitted fabric specified with 100 wales and 100 courses is also listed in Table 4, wherein, contact resistance 1 represents the contact resistance generated by two overlapped yarns and contact resistance 2 represents the contact resistance generated by three overlapped yarns.

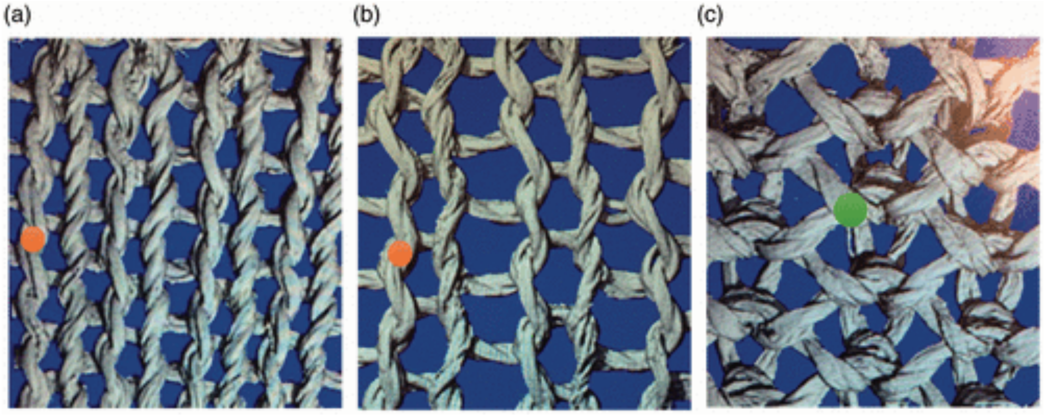


Figure 5. The micro-computed tomography images of different knitted structures: (a) plain knit; (b) 1 × 1 float (50% float stitch); (c) single pique (50% tuck stitch). (Color online only.)

The relationship between the resistance value and proportion of float and tuck stitches in the knitted fabrics is plotted in Figure 6(c). The configuration of float and tuck stitches and their developed geometrical models can be seen in Figure 6(a) and (b), respectively. Correspondingly, the equation to describe the above two models can be referred in my previous papers.[19,20] Therefore, the loop length for different parts of the stitch can be obtained.

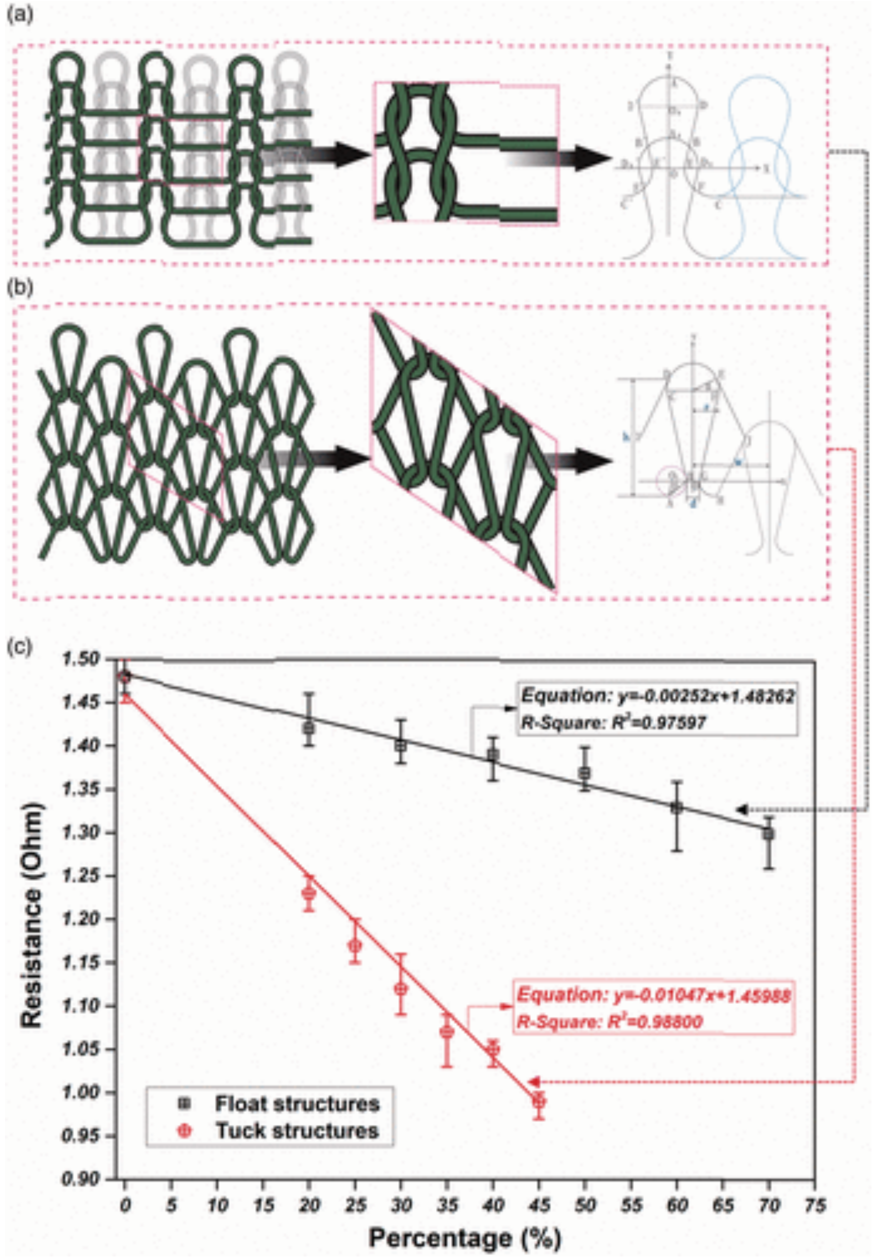


Figure 6. (a) Configuration of the float stitch and its developed geometrical model. (b) Configuration of the tuck stitch and its developed geometrical model. (c) Fitting curves for resistance values of conductive knitted fabrics with different proportion of knit, float, and tuck stitches.[19,20] (Color online only.)

From the experimental results, the resistance value of 100% knit fabric is 1.48 Ω. However, when the proportion of float stitches in the knitted fabric is 50%, the resistance value is reduced to around 1.37 Ω, and with tuck stitches it is 0.99 Ω. When the proportion of float stitches is 70%, the resistance is reduced to about 1.32 Ω. When the proportion of float stitches exceeds a certain degree (70%), the resistance value will increase rather than decline. This is because the long float stitches will destroy the connectivity points. Therefore, in Figure 6, the data point for 80% float stitch is ignored. In the figure, the black squares symbolize the data from the fabric with float stitches, and red circles denote the data from the fabric with tuck stitches. From the plot, it can be seen that the relationship is linear; the fitting equation is provided in equations (1) and (2)

$$y = -0.00252x + 1.48262 \tag{1}$$

$$y = -0.01047x + 1.45988 \tag{2}$$

where x is the percentage of float or tuck stitches in the knitted fabrics and y is the resistance value for corresponding knitted fabrics. Their adjusted R-square values are 0.97597 and 0.98800, respectively.

It can also be observed in Figure 6 that the resistance value significantly declines with increasing number of tuck and float stitches. It was found that tuck stitches are more effective in reducing the total resistance of conductive knitted fabrics, while float stitches are also effective in reducing the resistance of conductive knitted fabrics if the cost of conductive yarns is reduced because the loop length is much shorter than that of the knit and tuck stitches.

Figure 7 shows the relationship between the loop length of every knitting course and the proportion of float or tuck stitches. It can be observed that there was no obvious change in loop length according with the increase of the proportion of tuck stitches in knitted fabrics. However, when the proportion of float stitches increases, the loop length of knitted fabrics decreased dramatically. The equation to fitting the relationship is provided in equations (3) and (4)

$$y = -0.001831x + 51.29815 \tag{3}$$

$$y = -0.31256x + 51.03684 \tag{4}$$

where x is the proportion of float or tuck stitches in the knitted fabric and y is the loop length of every knitting course for corresponding knitted fabrics. Their adjusted R-square values are 0.9352 and 0.98716, respectively.

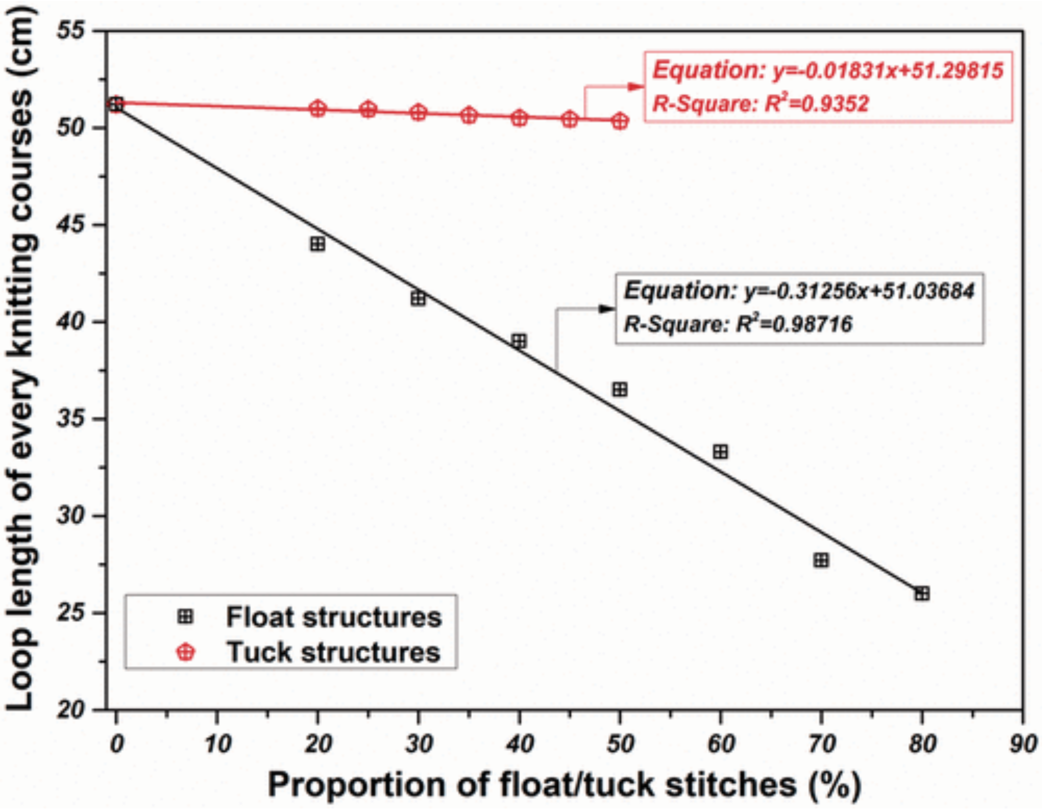


Figure 7. Relationship between loop length and proportion of float/tuck stitches in knitted fabrics.

To investigate the impact of contact resistance on the whole resistance of knitted fabrics, the amount of contact resistance in the whole fabrics was considered. As discussed before, in float knitted structures, the contact resistances were generated by two overlapped conductive yarns (contact 1). The fitting curve among loop length, amount of contact resistance, and resistance value (Figure 8) is provided by equation (5); the adjusted *R*-square is 0.987

$$f(x, y = 1.095 + 0.007074x + 2.202 \times 10^{-6}y) \qquad (5)$$

where *x* is the loop length of every knitting course, *y* is the amount of contact resistance, and *f*(*x, y*) is the resistance value for corresponding knitted fabrics.

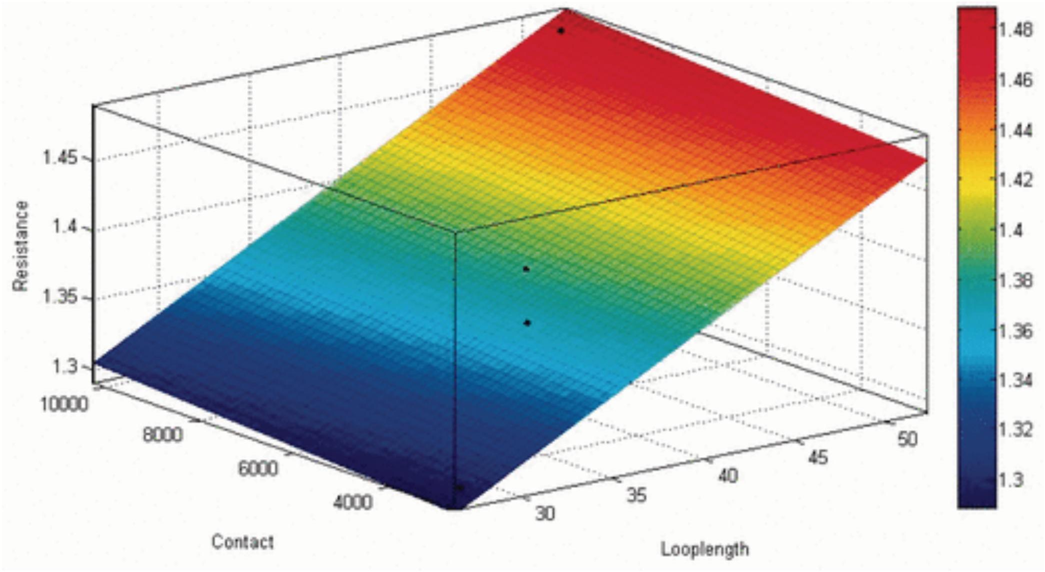


Figure 8. Relationship among loop length, amount of contact resistance, and resistance value.

For the case of different tuck knitted structures, it has been observed that loop length was not changed obviously. Therefore, the impact of loop length was ignored in this case. For the different contact resistance was considered, the fitting curves among amount of contact resistance 1, amount of contact resistance 2 and whole resistance values (Figure 9) are provided by equation (6); the adjusted *R*-square is 0.9778

$$f\,(x, y) = 0.8984 + 5.719 \times x10^{-5}x \ + 1.457 \times 10^{-6}y \qquad (6)$$

where x is the amount of contact resistance 1, y is the amount of contact resistance 2, and $f(x, y)$ is the total resistance value for corresponding knitted fabrics.

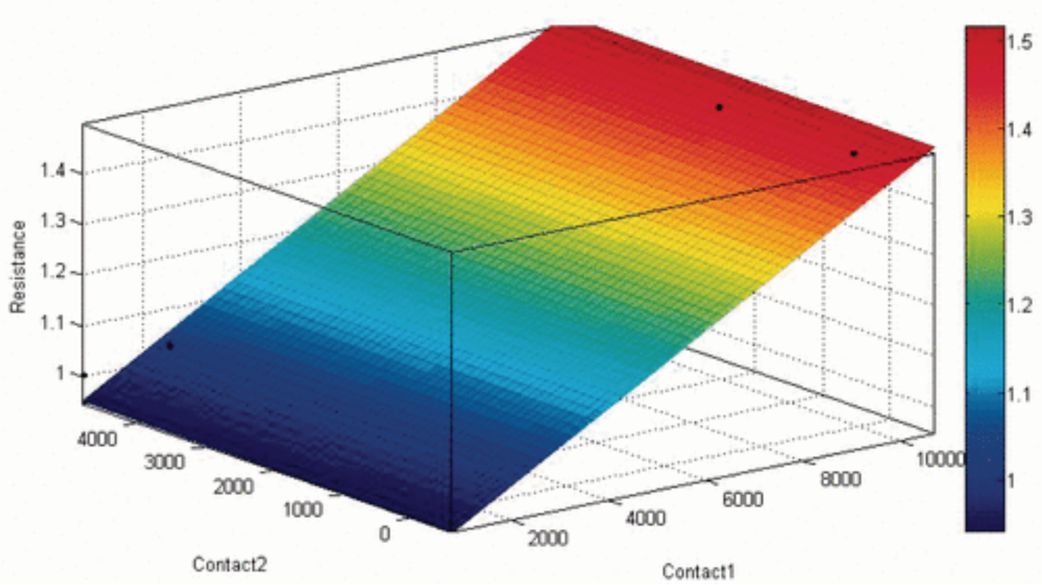


Figure 9. Relationship among amount of contact resistance 1, amount of contact resistance 2, and whole resistance values.

Conclusion

The present study mainly provides powerful macroscopic evidence that different knitwear structures could impact the resistivity of conductive knitted fabrics. That is, with an increase in the proportion of tuck and float stitches, the resistance appears to obviously follow a trend of decrease. The relationship between conductive resistance and proportion of tuck and float stitches is plotted in Figure 6(b), in which a linear relationship is observed. Compared to float stitches, tuck stitches can reduce the total resistance to a larger degree. This is concluded to be because the tuck structured fabric has more contact resistance, which will reduce the total value of resistance. However, float stitches are the optimal means of reducing the resistance of knitted fabrics when less yarn is necessary or used. In addition, for knitted structures that use float stitches, the proportion of stitches should not exceed 70%, so that stable connectivity or an optimal structure can be obtained.

The relationship between yarn cost and resistance was obtained, which will provide a widely useful database for the wearable textile industries. It can be applied to the development of conductive knitted products, which will adopt a variation of knitting methods to improve the performance and function of different electrical textile products. Therefore, the work will add to the innovative development of smart textiles. This study will also serve as the basis for future studies and may be extended to other potential applications in the future. The application can be concluded as follows.

1. When the area is fixed, one can adjust the proportion of tuck or float stitches in the knitted structures to reduce the total resistance value and the tuck stitch can reduce the resistance value to a larger degree.
2. When the required resistance value is fixed, we can change the knitted structures to adjust the proportion of tuck or float stitches so that the knitting area can be different.
3. When the required resistance value is fixed, the float structures can make the yarn cost reduce greatly, which will result in savings.

Declaration of conflicting interests

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

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the HK RGC General Research Fund (Grant/Award Number PolyU 154031/14H).

References

1. Zeng W, et al. Fiber-based wearable electronics: a review of materials, fabrication, devices, and applications. *Adv Mater* 2014; 26: 5310–5336.
2. Castano LM and Flatau AB. Smart fabric sensors and e- textile technologies: a review. *Smart Mater Struct* 2014; 23: 053001.
3. Clevertex. Report on intelligent textiles. 2015.
4. Schwarz A, et al. A roadmap on smart textiles. *Text Progr* 2010; 42: 99–180.
5. Stoppa M and Chiolerio A. Wearable electronics and smart textiles: a critical review. *Sensors Basel* 2014; 14: 11957–11992.
6. Coyle S, et al. BIOTEX—biosensing textiles for persona- lised healthcare management. *IEEE Trans Inform Technol Biomed* 2010; 14: 364–370.
7. Atalay O, Kennon WR and Demirok E. Weft-knitted strain sensor for monitoring respiratory rate and its elec- tro-mechanical modeling. *IEEE Sensors J* 2015; 15: 110–122.
8. Duran D and Kado lu H. Electromagnetic shielding char- acterization of conductive woven fabrics produced with silver-containing yarns. *Text Res J* 2014; 85: 1009–1021.
9. Martin T, et al. Towards a design framework for wear- able electronic textiles. In: *Proceedings of the Seventh IEEE International Symposium on Wearable Computers*, White Plains, NY, USA, 21-23 October 2003, pp. 190–199.
10. Li L, et al. A resistive network model for conductive knitting stitches. *Text Res J* 2009; 80: 935–947.
11. Li L, et al. Electromechanical analysis of length-related resistance and contact resistance of conductive knitted fabrics. *Text Res J* 2012; 82: 2062–2070.
12. Li L, et al. Electromechanical analysis of length-related resistance and contact resistance of conductive knitted fabrics. *Text Res J* 2012; 82: 2062–2070.
13. Wang J, et al. Electromechanical properties of knitted wearable sensors: part 1–theory. *Text Res J* 2014; 84: 3–15.
14. Wang J, et al. Electro-mechanical properties of knitted wearable sensors: Part 2–parametric study and experi- mental verification. *Text Res J* 2014; 84: 200–213.
15. Zhang H. Electro-mechanical properties of knitted fabric made from conductive multi-filament yarn under unidir- ectional extension. *Text Res J* 2005; 75: 598–606.

16. C¸ eken F, et al. The electromagnetic shielding properties of some conductive knitted fabrics produced on single or double needle bed of a flat knitting machine. *J Text Inst* 2012; 103: 968–979.
17. Liu R, Wang S and Lao TT. A novel solution of moni- toring incontinence status by conductive yarn and advanced seamless knitting techniques. *J Eng Fabrics Fibers* 2012; 7: 50–56.
18. Li L, et al. A novel design method for an intelligent cloth- ing based on garment design and knitting technology. *Text Res J* 2009; 79: 1670–1679.
19. Liu S, et al. Smart E-textile: resistance properties of con- ductive knitted fabric–single pique. *Text Res J* 2017; 87: 1669–1684.
20. Liu S, et al. The impact of float stitches on the resistance of conductive knitted structures. *Text Res J* 2016; 86: 1455–1473.