engineering proceedings

Proceeding Paper

Optimization of Heating Performance of the Rib-Knitted Wearable Heating Pad †

Sandeep Kumar Maurya, Apurba Das and Bipin Kumar *

Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India
* Correspondence: bipin.kumar@textile.iitd.ac.in

† Presented at the 4th International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles, Nottingham, UK, 8–10 November 2022.

Abstract: Textile structures such as knitting, weaving, braiding, and nonwoven can be used to produce wearable heating pads. Knitted fabric has unique properties such as stretchability, flexibility, and comfort among these textile structures. However, traditional knitted heating pads are manufactured by employing a straightforward three-structure design comprised of a plain, rib, and interlock with yarn that is entirely conductive. The usage of fully conductive materials in industrial applications has been restricted primarily as a result of their more expensive price tag and higher power requirements. Herein, we reported a rib (knitting structure)-based wearable heater with localized conductive yarn. A 14-gauge V-bed knitting machine is used to prepare a localized heating pad with a slight variation in the loop length. The rib-knitted structure (R1) with the lowest loop length showed a 47.4 °C average surface temperature at 9 Volt DC power source. The laboratory-based prototype of the heating pad is also designed for alleviation of joint and muscle pain in the affected area of the body.

Keywords: smart textiles; wearable heating pad; knitted structures; heat therapy; conductive textiles

check for updates

Citation: Maurya, S.K.; Das, A.; Kumar, B. Optimization of Heating Performance of the Rib-Knitted Wearable Heating Pad. *Eng. Proc.* **2023**, *30*, 1. https://doi.org/10.3390/engproc2023030001

Academic Editors: Steve Beeby, Kai Yang, Russel Torah and Theodore Hughes-Riley

Published: 19 January 2023

1. Introduction

Nowadays, conductive yarn or fabrics are utilized for smart wearable electronic textiles. Textile-based wearable heaters have drawn attention to the application of heat therapy for the reliving of joint and muscle pain. A higher skin temperature increases the heat circulation and blood flow in a specific area of our body. Heating devices can be divided into four categories: electrical-, phase change material-, chemical-, and fluid-based heating [1]. Electrical heating is the most preferred for wearable applications since it requires less time to reach an equilibrium temperature. Therefore, many researchers focused on textile-based electrical heating products such as gloves, belts, and pads for heat therapy applications [2–4]. Equation (1) can be used to calculate the amount of heat that is produced when an electric current flows through a conductor.

$$Heat\ dissipated\ (H) = I^2 \times R \tag{1}$$

where I and R are the current flowing in the conductor and the resistance of the conductor, respectively.

Recently, textile-based wearable heaters have gained a lot of attention owing to their intrinsically flexible, soft, breathable properties and efficient production techniques. Various techniques for incorporating heating components into woven [5,6], knitted [7,8], nonwoven [9], and embroidered [10] fabrics have been found in the literature. The woven structure lacks flexibility due to the horizontal and vertical interlacement of yarns, limiting the yarn mobility in the structure. Heating fabric made up of nonwoven fabric has a limited use owing to the high electrical resistance of conductive fabric. The knitted-based heating fabric has a significant advantage over other methods in terms of its flexibility, stretchability, and comfortability. Liu et al. [11] designed and fabricated the three types of knitted heating fabrics (KHFs), plain, rib, and interlock fabric, using silver-plated conductive yarn and polyester spun yarn. They concluded that the interlock structure was superior to the plain and rib-knitted structures in terms of the heating performance. The structural elements of the knitted structure play an important role for optimizing the heating performance. Kexia sun et al. [12] reported that float and tuck stiches decrease the resistance value of conductive knitted fabric. Consequently, the surface temperature of the combination of a float and tuck knitted heating pad was higher than that of the 100% knitted structure.

The literature has given very little justification on the optimization of the heating performance of the knitted-based heating pad. Herein, we reported a rib (knitting structure)-based wearable heater with localized conductive yarn. This study investigated the surface temperature of the heating pad with a slight variation in the loop length in the knitted structure.

2. Materials and Methods

Low twisted cotton yarn (74 tex) and silver coated nylon yarn (30 tex) were used to fabricate the heating pad by using a V-bed knitting machine (14 gauge). Cotton yarn was used as a nonconductive material, while silver coated yarn was used as a conductive material. The rib-knitted structure was prepared with three courses of localized conductive yarn after six courses of non-conductive yarn, as shown in Figure 1a–e. Four samples of heating pads, such as R1, R2, R3, and R4, were prepared with a varying loop length. The specification of the samples is illustrated in Table 1.

Table 1. Sample specifications.

Sample Code	Sample Appearance	Electrical Resistance (Ω)	Areal Density (g/m^2)	Loop Length (mm)	Courses Per Inch (CPI)	Wales Per Inches (WPI)	Stich Density ($loops/inch^2$)
R1		51 ± 2	414 ± 10	4.82	27	33	891
R2		63 ± 2	346 ± 10	5.12	22	30	660
R3		75 ± 2	330 ± 10	5.81	18	28	504
R4		80 ± 2	309 ± 10	6.21	16	26	416

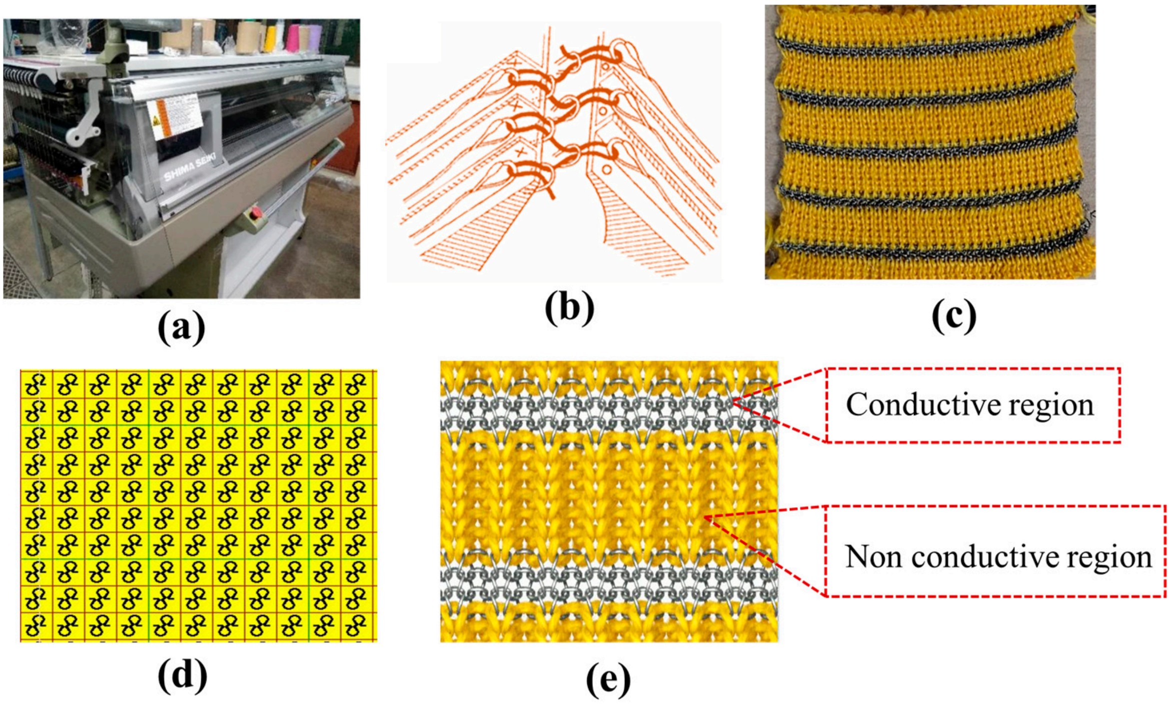

Figure 1. Fabrication of knitted structures (heating pad), (**a**) V-bed knitting machine, (**b**) needles arrangement on V-bed, (**c**) actual image of the heating pad, (**d**) computerized design for rib structure, (**e**) mimetic view of the samples.

3. Results and Discussion

Analysis of Surface Temperature of Knitted Structures

The average surface temperature of the rib-knitted heating pad was analyzed by a thermal infrared camera (Fluke ti450 pro) with an under specified voltage source. The DC source (IT6720-100W) was used to power the heating pad's active component. The sample was kept at a distance of 40 cm from the camera, which was fixed on a tripod with 95% emissivity.

The surface temperature of the fabric was investigated at a 9-volt DC power source at room temperature. The rib structure (R4) with a loop length of 6.21 mm showed a 31.4 °C average surface temperature. At the same input power source, the heating performance of the rib structure increased by 51% with a loop length of 4.82 mm, as shown in Figure 2a. This can be explained by the tightness factor of the knitted structures. The tightness factor of the knitted fabric is calculated by the following Equation (2) [13].

$$Tightness\ factor\ (TF) = \frac{\sqrt{Tex}}{l} \tag{2}$$

where l is the loop length of the rib structure in cm and Tex is the linear density of the yarn.

The fabric sample (R1) with the shorter loop length exhibited a more tightness factor, i.e., 11.36 (Table 2), resulting in a more compact and less conductive yarn being required on the active part of the sample. Thus, knitted structures (R1) exhibited a lower electrical resistance, i.e., 51 Ω, than the other samples. Consequently, the amount of current flowing through the knitted structures (R1) increases, leading to an increase in the fabric's surface temperature. A sample (R1) is utilized to design the heating pad to test the viability of the knitted structure. The heating pad is applied to the elbow, wrist, and calf regions of the body part at a 9 V/2.5 A DC power source, as shown in Figure 2b–d.

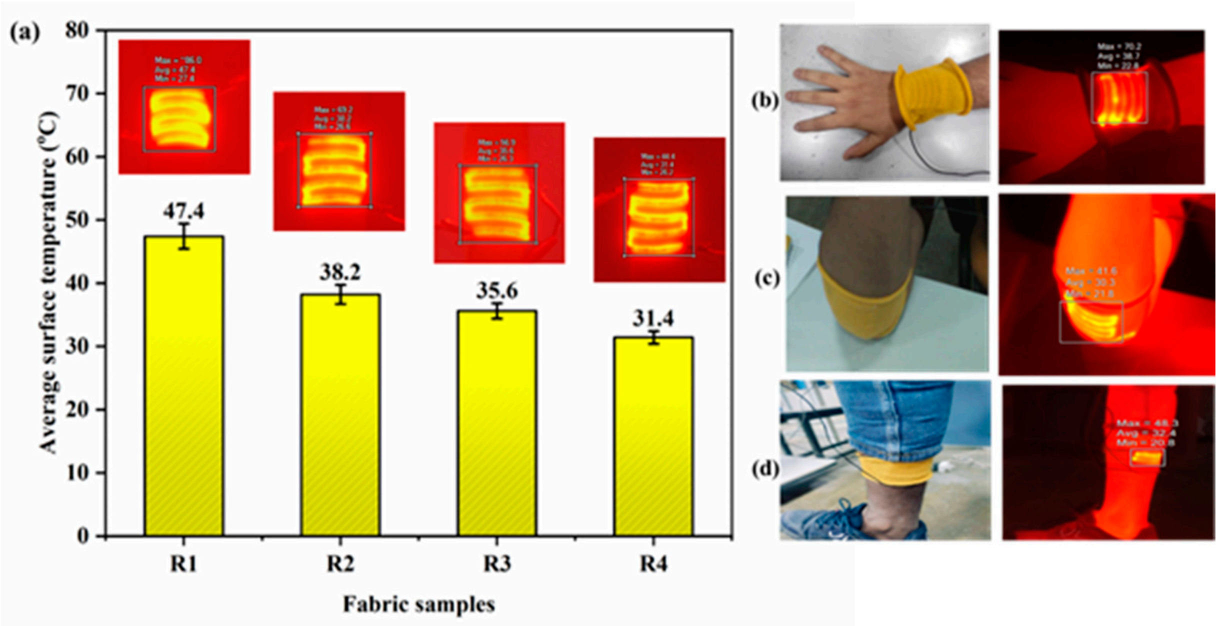

Figure 2. (**a**) Result of the surface temperature of knitted structures at 9 volts and knitted-based localized heating pad developed in the lab for joint and muscle pain in the (**b**) wrist, (**c**) elbow, and (**d**) calf areas.

Table 2. Tightness factor of the rib-knitted structures.

Sample Code	R1	R2	R3	R4
Tightness factor	11.36	10.69	9.43	8.82

4. Conclusions

The objective of this study was to optimize the surface temperature of the heating pad by varying the loop length of the knitted structure, a subtle alteration in the structure of the loop that has a significant impact on the surface temperature of the heating pad. The sample (R1) with the lowest loop length with a compact structure showed a good heating performance. The prototype of the heating pad is designed for the alleviation of joint and muscle pain in the affected area of the body. The study's findings indicate that the loop length of the knitted fabric is a critical component in optimizing the surface temperature.

Author Contributions: Conceptualization, methodology, validation, investigation, and writing—original draft preparation, S.K.M.; writing—review and editing and supervision, B.K. and A.D. All authors have read and agreed to the published version of the manuscript.

Funding: The author would like to acknowledge financial support from the Indian Institute of Technology Delhi.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, F.; Gao, C.; Kuklane, K.; Holmér, I. A review of the technology of personal heating garments. *Int. J. Occup. Saf. Ergon.* **2010**, *16*, 387–404. [CrossRef] [PubMed]
2. Hamdani, S.T.A.; Fernando, A.; Maqsood, M. Thermo-mechanical behavior of stainless steel knitted structures. *Heat Mass Transf.* **2016**, *52*, 1861–1870. [CrossRef]
3. Kumar, B.; Das, A.; Sharma, A.; Krishnasamy, J.; Alagirusamy, R. Cyclic bursting loading on needle-punched nonwovens: Part I–Distention behavior. *Indian J. Fibre Text. Res. (IJFTR)* **2018**, *43*, 20–24.

4. Pragya, A.; Singh, H.; Kumar, B.; Gupta, H.; Shankar, P. Designing and investigation of braided-cum-woven structure for wearable heating textile. *Eng. Res. Express* **2020**, *2*, 015003. [CrossRef]
5. Sezgin, H.; Bahadır, S.K.; Boke, Y.; Kalaoğlu, F. Investigation of Heating Behaviour of E-textile Structures. *Int. J. Mater. Text. Eng.* **2015**, *9*, 491–494.
6. Muthukumar, N.; Thilagavathi, G.; Kannaian, T.; Periyasamy, S. Development and Characterization of Metal Woven Electric Heating Fabrics. In *Functional Textiles and Clothing*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 119–127.
7. Hao, L.; Yi, Z.; Li, C.; Li, X.; Yuxiu, W.; Yan, G. Development and characterization of flexible heating fabric based on conductive filaments. *Measurement* **2012**, *45*, 1855–1865. [CrossRef]
8. Liu, S.; Yang, C.; Zhao, Y.; Tao, X.M.; Tong, J.; Li, L. The impact of float stitches on the resistance of conductive knitted structures. *Text. Res. J.* **2016**, *86*, 1455–1473. [CrossRef]
9. Xu, J.; Xin, B.; Du, X.; Wang, C.; Chen, Z.; Zheng, Y.; Zhou, M. Flexible, portable and heatable non-woven fabric with directional moisture transport functions and ultra-fast evaporation. *RSC Adv.* **2020**, *10*, 27512–27522. [CrossRef] [PubMed]
10. Petcu, I.; Agrawal, P.; Curteza, A.; Brinks, G.; Teodorescu, M. A comparative study of heating elements used for the development of textile heaters. In Proceedings of the 12th AUTEX World Textile Conference, Faculty of Textile Technology of the University of Zagreb, Zadar, Croatia, 13–15 June 2012.
11. Liu, H.; Li, J.; Chen, L.; Liu, L.; Li, Y.; Li, X.; Li, X.; Yang, H. Thermal-electronic behaviors investigation of knitted heating fabrics based on silver plating compound yarns. *Text. Res. J.* **2016**, *86*, 1398–1412. [CrossRef]
12. Sun, K.; Liu, S.; Long, H. Structural parameters affecting electrothermal properties of woolen knitted fabrics integrated with silver-coated yarns. *Polymers* **2019**, *11*, 1709. [CrossRef] [PubMed]
13. Maurya, S.K.; Uttamrao Somkuwar, V.; Garg, H.; Das, A.; Kumar, B. Thermal protective performance of single-layer rib-knitted structure and its derivatives under radiant heat flux. *J. Ind. Text.* **2021**, *51*, 8865S–8883S. [CrossRef]