FIBRES & TEXTILES in Eastern Europe
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Research Article • DOI: 10.2478/ftee-2024-0013 FTEE • 32(2) • 2024 • 33–40

Textile Connector for Smart Textile Applications

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Abstract

Textile signal lines are some of the more significant parts of an electronic system incorporated in modern smart garments. These applications often need to make lines that are disconnectable. The article presents the construction of two textile connectors that can connect direct current textile electro-conductive lines. These connectors are mostly made of textile materials and are an alternative to conventional connectors or connectors using snap fasteners. The article presents basic research on the electrical properties of the connectors proposed. The present research examined the influence of the size and shape of the connector contacts on their resistance, measured after each disconnection and reconnection of both parts of the connectors. The article also presents research on the dependence of the electrical resistance of the connectors on the pressure force of their textile contacts. The test results presented, and their statistical analysis confirmed the suitability of the connectors presented for applications in e-textiles.

Keywords

Textile connectors, smart clothing, textronics, e-textiles, wearable electronics.

1. Introduction

Nowadays, there is an increased interest in smart garments. This popularity is due to the evolution of electronics, in particular wearable electronics. This resulted in increased work on smart clothing, which can be used, for example, in monitoring the health parameters of aged people [1–3], newborns [4–6] or people working in a hazardous environment (firefighters, miners, etc.) [7,8]. In these applications, electrical connections between electronic modules used in smart clothing are often needed. These connections are very often required to be detachable, which forces the use of various types of electrical connectors. Standard connectors used in electronics are generally rigid. Their use increases the stiffness of the garment, reducing the comfort of its use. For this reason, work is underway to develop both flexible textile signal lines [9–13] and electrical connectors, for the construction of which textile materials will be used to the maximum extent.

Currently, work is being carried out on fixed and detachable joinings between electronic circuits placed in smart textiles [14]. The following article concerns detachable connections. Some of them are snap fasteners (also called poppers, press studs, and gripper snaps). These connectors are among the most popular in the e-textile prototypes described. Leśnikowski [15] reported the usefulness of snap fasteners as connectors for low and medium-bandwidth signal transmission lines. Although useful for creating electrical connectors [15], snap fasteners cannot be used in all cases. Using these elements as connectors requires cutting out the holes in the electro-conductive textile paths where the snaps are mounted. Therefore, they are only suitable for connecting electrically conductive paths of considerable width. Using these elements is problematic in the case of narrow paths several millimetres wide. This type of connector is often not advisable for design reasons and the expected aesthetics of the product. Another kind of tested connector proposed for e-textile applications is pogo pins equipped with magnets [16,17]. These connectors are specially designed for the connection of electronic circuits not permanently incorporated into clothing [16,17].

Many e-textile prototypes usually use conventional connectors, for instance, having the form of pin headers [14,18]. Most contacts proposed for e-textile applications, including those cited above, are not made of textile materials and have significant dimensions and stiffness. This may reduce the ergonomics of using clothing with these connectors. This is especially noticeable when a large number of connectors are required. In most cases, the clothing designer wants to hide additional elements that transform conventional clothing into smart clothing as much as possible. Therefore, the design of future connectors for e-textile applications should make maximum use of flexible textile materials. The following article describes the construction of a connector that uses textile materials to a large extent and is an alternative to using snap fasteners as electrical connectors. This design allows the connector to be camouflaged in clothing.

The connector proposed connects two sections of the textile electro-conductive line. This line can be used as a line supplying low-current power to electronic modules placed in smart clothing. For example, it can connect flexible photovoltaic panels to a battery [19]. The connector presented in the article reduced the number of rigid elements to two. This solution constitutes significant progress towards the construction of a fully textile connector. The amount of textile materials used distinguishes the connector from those previously described in the literature.

The simplest line created from fabric contains two electro-conductive paths. These can be placed on the opposite

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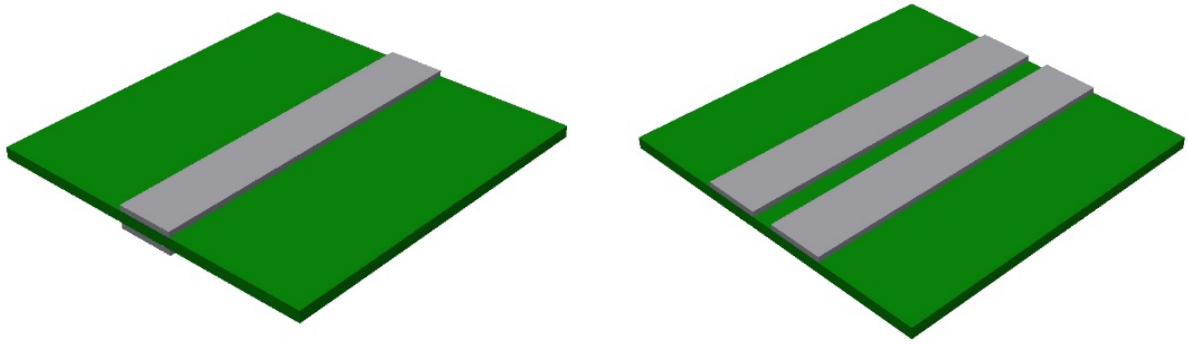

a) Signal and ground paths are placed on the opposite side of the substrate. b) Signal and ground paths are placed on the same side of the substrate.

Fig. 1. View of the simplest signal line created from fabric

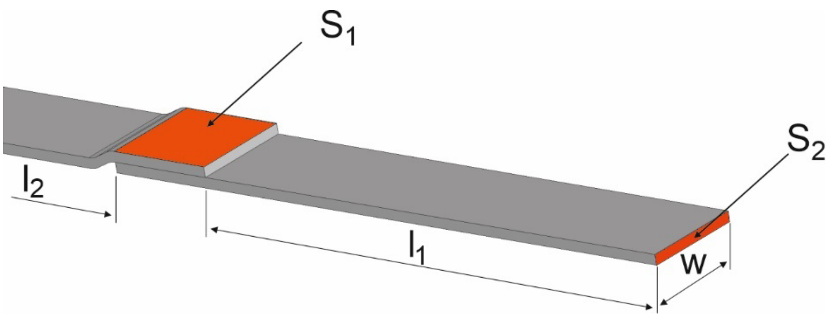

Fig. 2. Connection between the two parts of connected paths

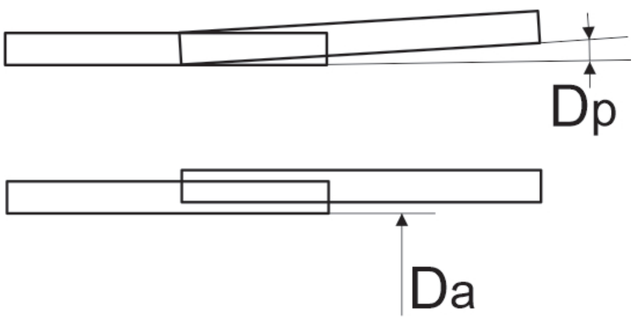

Fig.3. Main possible inaccuracies in the connection of electro-conductive paths in the textile connector: parallelism (Dp) and deviation from the axis (Da)

(Fig.1a) or the same side (Fig.1b) of the line's substrate. The quality of the electrical connection depends, among other things, on the contact force of electro-conductive paths and their mutual arrangement. Therefore, the article, among others, presents research on the impact of these factors on the quality of that connection.

As mentioned earlier the connectors presented were designed to connect textile lines conducting direct low currents. For this application, the most important parameter characterizing the quality of the connector is the connection resistance of the connected paths.

The resistance of a conductor is related to its geometric dimensions, which can be expressed mathematically through the formula:

$$R = \rho \frac{l}{S}, \qquad (1)$$

Where ρ is the conductor resistivity, l the length of the conductor, and S is the transverse cross-sectional area of the conductor. The joined textile paths typically overlap to increase the contact surfaces. This can be seen in Figure 2.

The total resistance of the two connected paths (shown in Figure 2) can be expressed by the following relationship:

$$R = R_{p1} + R_{p2} + R_j, \qquad (2)$$

Where R_{p1} and R_{p2} are resistances of paths of length l_1 and l_2, and R_j is the junction resistance.

Assuming that both connected paths have the same width, thickness and similar length $l_1 \cong l_2$, we can write:

$$R = 2R_{p1} + R_j. \qquad (3)$$

From (1) and (3) and assuming ideal contact between the connected paths, we obtain:

$$R = 2\rho \frac{l_1}{S_2} + \rho \frac{h}{S_1}, \qquad (4)$$

Where h is the thickness of the paths.

Due to the flexibility of the textile contact elements, some inaccuracies may occur when connecting them. Two main possible inaccuracies when connecting two flat electro-conductive textiles are shown in Figure 3.

The first inaccuracy occurs when the electro-conductive paths being connected are not parallel to each other. The second is when the connected paths do not lie on one axis.

In both cases, these inaccuracies cause a reduction in the contact area (s_1 in

Figure 2) of the electro-conductive paths. Formula (4) shows that this will increase the connector resistance, which means deterioration of its electro-conductive properties. Studies on the impact of these switching inaccuracies are presented later in the article.

The connectors described in the article are used for connecting the lines presented in Fig.1a. The line choice from Fig. 1a was dictated by the lower probability of short-circuiting its conductive paths during the connection. For the line shown in Figure 1b, the possibility of a short-circuit of electro-conductive tracks resulting from an inaccurate connection of both parts of the connector presented is much higher.

An additional advantage of the connector proposed compared to snap fasteners is that it does not affect the structure of the connected textile lines, as is the case with snaps requiring holes to be made in the connected paths. These holes reduce the area s2 (Fig. 2) of the connected paths, which, according to formula (4), increases the total resistance of the connector.

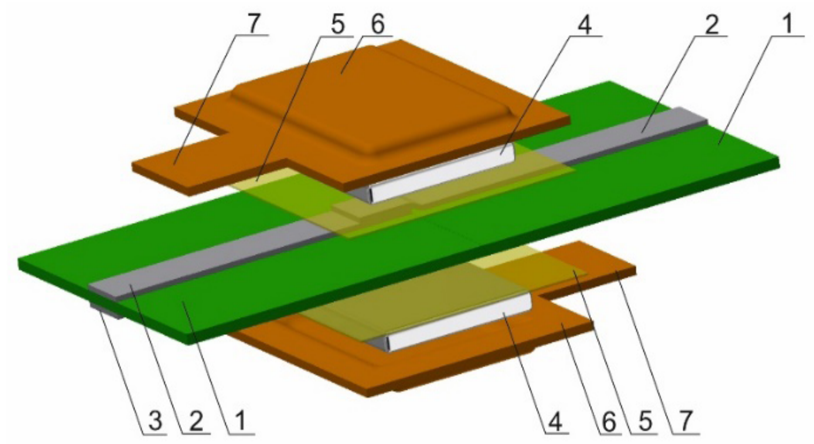

Fig. 4. Textile connector with rectangular contacts

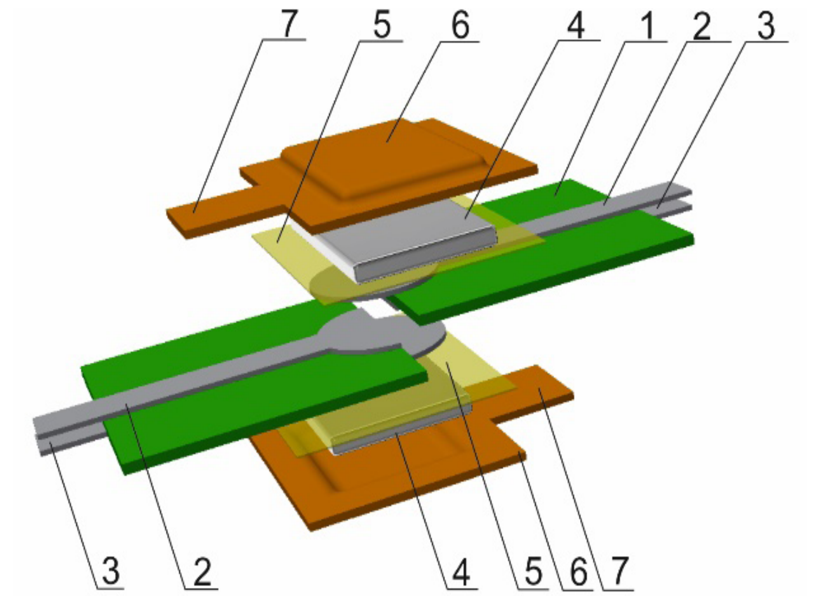

Fig. 5. Textile connector with circular contacts

2. Materials and Methods

In the first step of the research, three connectors, shown in Figure 4, were made. In these connectors the shape of the connected electro-conductive paths does not change, i.e. the connection place of both tracks is a rectangle (Fig.4). Then, these connectors were tested. After analyzing the results, an attempt was made to improve its properties by producing a second version. In this version, the contacts have a larger surface and a round shape. The round shape of the contacts in the second version of the connector was intended to minimize the impact of the inaccuracy of connecting both parts of the connector, called parallelism (Dp in Fig. 3), on its resistance. Finally, two different connectors were designed and manufactured. The construction of these textile connectors is presented in Figures 4 and 5. Both connectors are designed to connect electro-conductive paths made of flat electro-conductive textile materials, e.g. fabrics, and are an integral part of the signal line. Figures 4 and 5 show two fragments of signal lines (for a better view, the connector in Figure 5 is shown in a disconnected state). These lines consist of the textile substrate (1), signal (2) and ground (3) textile patches. The width of the electro-conductive paths in both connectors was 5 mm. Electroconductive fabric paths (2) and (3) were glued to the substrate (1) with thermo-tape, widely used in the textile industry.

In the connectors proposed, the electro-conductive textile paths overlap. The contact area in the first connector is 25 mm^2, and in the second it is 47 mm^2. Two neodymium magnets (4) provide the appropriate clamping force to ensure proper electrical contact between connected electro-conductive parts. Neodymium magnets are placed between the insulating (5) and covering (6) fabric. These fabrics are sewn together and also to the substrate of the connected signal lines. The insulating fabric (5) is thinner than the other fabrics. This increases the magnetic attraction force between the magnets placed in each part of the connector, improving the connection quality. Although the neodymium magnets used in the prototype connectors are not flexible, the connector design proposed does not exclude using flexible magnets. An example view of a part of the connectors (substrate and electroconductive paths only) is shown in Fig.6. Example views of the whole

Fig. 6. Example views of a part of the connector prototypes (substrate and electro-conductive paths only)

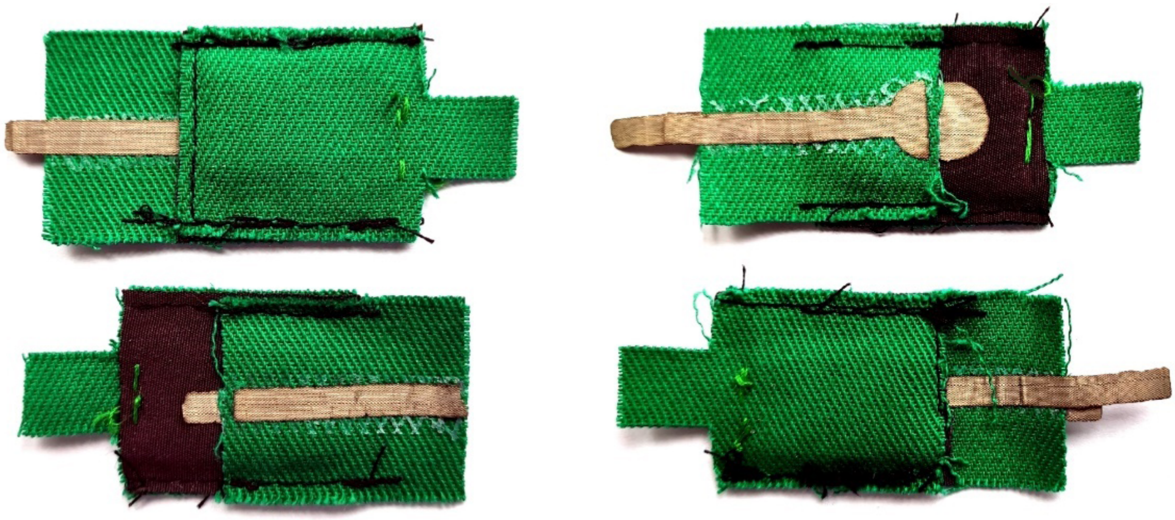

Fig. 7. Example views of the bottom and upper side of the connector's parts

connector are shown in Fig.7. The adopted dimensions of the substrate (35×30 mm) on which the electro-conductive paths were placed mean that the length of the connector after connecting both parts is 75 mm and its width - 30 mm. Of course, the adopted dimensions are not critical and can be changed depending on needs. The thickness of the connectors depends mainly on the magnets' thickness. The thickness of the tested prototypes when both parts of the connector were connected was 6 mm. The proposed design allows for the production of thinner connectors. However, this requires thinner magnets resulting in a lower pressing force between contacts' connectors.

The conductive parts of the connectors were made of electro-conductive nickel-coated polyester fabric. The basic parameters of this fabric are shown in Table 1.

The basic parameters of the neodymium magnets used are shown in Table 2.

The materials used to build the connector are widely available on the market. Due to the previously reported anisotropy of electro-conductive fabrics [20–22], all electro-conductive paths were cut at the same angle to the weft and warp threads. For improved dimensional repeatability, the textile components of the connectors were cut using a laser cutting machine.

The basic parameters of fabrics used for non-conductive connector elements are shown in Table 3.

3. Measured parameters

The basic parameter characterizing the ability of a connector to conduct direct current is its resistance when connecting both parts. Another parameter is the current carrying capacity, expressed as the maximum current the connector can carry without overheating. Since the amount of heat emitted by a conductor is directly proportional to its resistance, the research assumed resistance as the basic parameter of the connector characterizing its suitability for conducting direct current.

All resistance measurements were carried out at 20°C and with 65% relative humidity. An Agilent 34410A multimeter operating in the 4-wire mode was used to perform these measurements. During the measurements, both parts of the connector were connected. Both paths on the ends of the connector were short-circuited and connected to the Agilent multimeter's leads.

As part of the research, measurements of the disconnecting force of both parts of the connectors were also performed. A Hounsfield[â] testing machine was used for these tests.

4. Results and discussion

In the first research stage, connectors consisting only of a substrate and two electro-conductive paths were used for testing. These simplified connectors are shown in Figure 6. In this research phase, the resistance between two connected connector parts was measured in dependence on the force applied to the contact point. This information is

Material	Trade name/ Producer	Thickness	Surface resistivity	Metal amount	Surface mass	Weave	Warp density	Weft density
-	-	mm	Ohm/sq	g/m²	g/m²	-	Yarns/cm	Yarns/cm
Ni/Cu Nylon Ripstop	3050-525/ Laird	0.127	0.07	27-39	71-92	Twill	55	40

Table 1. Basic parameters of electroconductive fabric used in the research conducted

Magnetic material	Magnet length	Magnet width	Magnet thickness	Magnet weight	Maximum force of attraction
-	mm	mm	mm	g	N
N38	25	15	2	5,63	26.2

Table 2. Basic parameters of the neodymium magnets used in the connectors tested

Fabric no.	Element no. (Fig.1)	Raw material	Weave	Thickness	Surface mass	Warp density	Weft density	Electro-conductive
	-	-	-	mm	g/m²	threads/ cm	threads/ cm	-
F1	1, 6, 7	cotton	twill	0.62	287	30	19	No
F2	5	polyester	plain	0.36	158	56	28	No

Table 3. Basic parameters of fabrics used for non-conductive connector elements

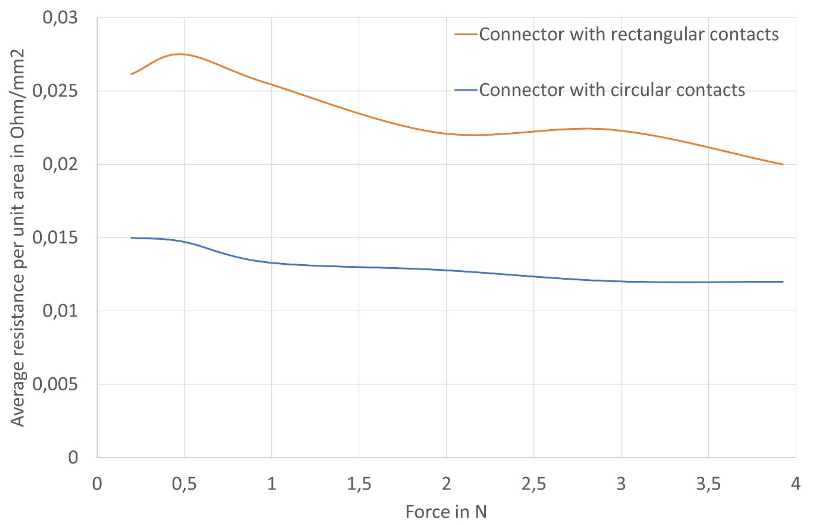

Fig. 8. Comparison of changes in the average resistance per unit area of connectors with a rectangular and circular contact area versus the clamping force of both their parts

intended to enable the selection of an appropriate magnet for the connector. It could also be useful in future research about connectors using flat electro-conductive textiles as contacts.

The contact area of the connector (for example, S1 in Figure 2) was loaded with weights of different masses to obtain various compressive forces. After placing a weight of a certain mass on a pair of contacts, the contact resistance was measured. These measurements were repeated ten times for each connector and each compressive force. During the analysis of the measurement results, the average resistance per unit area was used. This eliminates the impact of differences in the dimensions of both connectors tested (resulting, among others, in different contact surfaces) on their resistance. The average resistance per unit area value was obtained from the formula:

$$R_s = \frac{R_{avg}}{S} \qquad (5)$$

Where R_{avg} is the average value of the measured resistance values, and S is the contact area.

The results obtained for the connector with rectangular and round pads are shown in Figure 8.

The graph shown in Figure 8 shows that the average resistance per unit area of the connector with rounded contacts changes less under a compressing force than for the connector with rectangular contacts. This allows to use thinner magnets (with a lower attraction force) without significant resistance deterioration of the connector.

A good quality connector should ensure the lowest possible resistance between its contacts. It should also ensure the stability of this resistance in conditions of repeated disconnection and connection of its parts. Therefore, in the next research phase, prototypes of connectors that incorporated all of the components were evaluated.

Tests in this phase were mainly aimed at checking whether the connectors proposed ensure correct electrical contact each time their parts are connected.

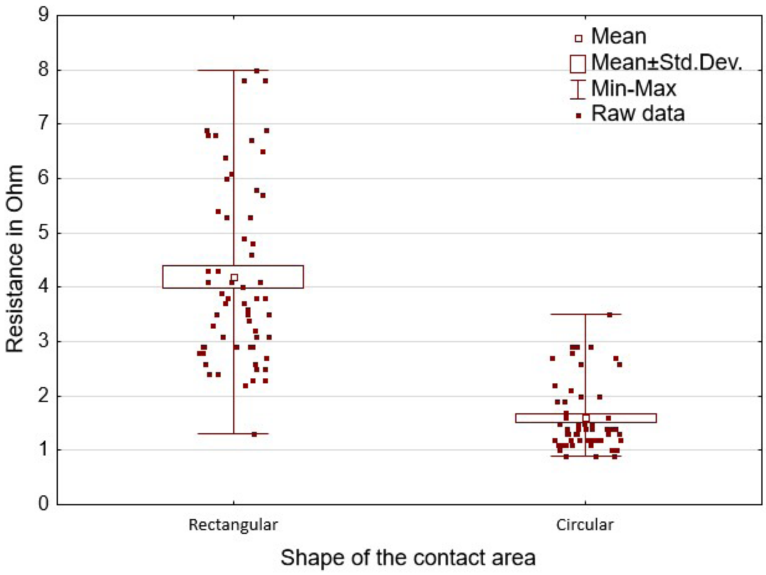

Fig. 10. Dispersion of the resistance per unit area of the connectors tested due to repeated disconnection and connection

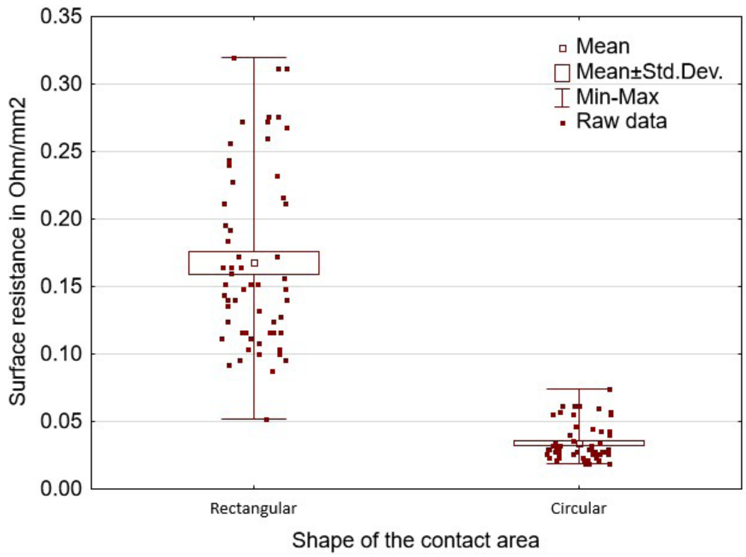

Fig.11. Dispersion of the resistance per unit area of the connectors tested due to repeated disconnection and connection

During these tests, connector resistance was measured after each disconnection and reconnection of both connector parts. These measurements also aimed to check whether the second connector proposed with a bigger round shape of the contacts had better electrical properties than a connector with rectangular contacts. Twenty resistance measurements were made for each connector tested (three with rectangular contacts and three with circular contacts). The results obtained are presented in Figure 10. The resistance results obtained were converted to resistance per unit area using formula (5) to eliminate the influence of different contact surfaces on connectors tested. The results are presented in Figure 11.

The results shown in Figure 11 show that the connector with bigger circular contacts is characterized by lower resistance per unit area than the connector with rectangular contacts. This resistance is also more stable during multiple reconnections. Due to the connectors' relatively high resistance, they can only be used as connectors in low-current systems. Of course, if large connector dimensions are acceptable, the resistance can be reduced by increasing the contact areas and the width of the electro-conductive traces.

A statistical analysis of the results obtained was also performed to confirm the above observations. Non-parametric tests were used instead of the multifactor analysis of variance (ANOVA). This was due to the failure to meet the assumptions of analysis of variance (lack of normality of distributions in groups determined by variables and lack of homogeneity of variance). The effect of the contact shape of the connectors on the changes in resistance per unit area due to repeated reconnections was checked. For this purpose, the non-parametric Mann-Whitney U test was used [23]. This test is a non-parametric statistical test used to compare two groups. Using this test, it was checked whether the difference between the average resistance per unit area calculated for both types of connectors does not differ statistically significantly. The null hypothesis (H0) in a Mann-Whitney U test assumes that the two populations tested are equal. For this test, the null hypothesis (H0) assumed equality of the average resistance per unit area for both connector types. In other words, the null hypothesis assumed no influence of the contact shape on the connector's average resistance per unit area. The test result was the p-value of the probability that the assumed null hypothesis is true. Assuming a significance level of $\alpha = 0.05$, based on the probability obtained from the test $p = 5.89\times10^{-21}$, the H0 hypothesis should be rejected. This means that the contact shape of the two kinds of connectors tested has a statistically significant effect on the average resistance per unit area of the connector, caused by multiple reconnections.

In the last research stage, measurements of the force needed to disconnect both connector parts were also performed. As a result of these measurements, a disconnecting force value of 7.1 N was obtained with a coefficient of variation of 2.3%.

5. Conclusions

As part of the research presented, a new electrical textile connector was proposed for use in Smart textiles. The connector proposed can be used in e-textiles to connect textile conductive lines connecting various electronic systems or to connect lines supplying power to these systems. The connectors proposed are an alternative for snap fasteners, among others. They may be useful in situations where snaps are not advisable e.g. when making holes in textile materials is not advisable or when we want to mask the presence of a connector in clothing. The article presents the construction and testing of two connectors differing in the shape of the contact point of the connection paths. As a result of the research conducted and statistical analysis, the following conclusions were drawn.

- The connectors proposed in the article are suitable for connecting textile electro-conductive traces, conducting low-current.
- The circular contact of the two connected lines and larger contact area, compared to the rectangular one, reduce the dispersion of the resistance values obtained during repeated disconnection and connection.
- To ensure better connection quality, the contact surface on the connector should be round and as large as possible.
- The values of the disconnecting force obtained confirm the suitability of the connectors proposed for smart clothing.

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

This research received no external funding.

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