From Design to Function: Inkjet-Printed Conductive Patterns for Smart Textiles

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Original scientific paper**

Smart textiles enable the integration of sensors and conductive pathways into flexible wearable systems for real-time monitoring. Within the national WIBRANT project, an innovative wearable smart brace for non-invasive monitoring and rehabilitation of muscular disorders was developed. This study focuses on the development of conductive patterns on a stretchable knitted fabric using inkjet printing with commercial PEDOT:PSS conductive ink. Printing parameters were first optimized on hydrophobic photo paper and subsequently adapted to the textile substrate. The influence of printed line length and number of deposited layers on electrical resistance was evaluated, while optical microscopy was used to assess print quality and ink distribution. The results demonstrated well-defined conductive patterns without significant bleeding. Electrical resistance increased with line length, whereas increasing the number of printed layers reduced resistance. The optimized process was successfully applied to produce a sensor matrix and a functionally designed conductive pattern for integration into the smart muscle brace.

Keywords: *muscle injuries; flexible electronics; conductive printing; sensory systems; ink-jet technology*

Izvorni znanstveni rad**

Od dizajna do funkcije: vodljivi uzorci tiskani ink-jet tehnologijom za pametni tekstil

Pametni tekstili omogućuju integraciju senzora i vodljivih puteva u fleksibilne nosive sustave za praćenje u stvarnom vremenu. U okviru nacionalnog projekta WIBRANT razvijena je inovativna nosiva pametna ortoza za neinvazivno praćenje i rehabilitaciju mišićnih poremećaja. Ovo istraživanje usmjereno je na razvoj vodljivih uzoraka na rastezljivom pletivu primjenom ink-jet tiska s komercijalnom vodljivom tintom PEDOT:PSS. Parametri tiska najprije su optimirani na hidrofobnom fotopapiru, a zatim prilagođeni tekstilnoj podlozi. Ispitan je električni otpor s obzirom na duljinu otisnutih linija i broj nanesenih slojeva, dok je optička mikroskopija primijenjena za procjenu kvalitete otiska i raspodjele tinte. Rezultati su pokazali jasno definirane vodljive uzorke bez značajnog razlijevanja tinte. Električni otpor povećavao se s duljinom linije, dok se povećanjem broja otisnutih slojeva smanjivao. Optimizirani postupak uspješno je primijenjen za izradu senzorske matrice i funkcionalno dizajniranog vodljivog uzorka za integraciju u pametnu mišićnu ortozu.

Ključne riječi: *ozljede mišića; fleksibilna elektronika; vodljivi ispis; senzorni sustavi; ink-jet tehnologija*

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1. Introduction

Muscle injuries in elite sports represent a prevalent challenge, often accounting for one-third of all sports-related injuries. These injuries can result in extended recovery periods, affecting both athletes' performance and team dynamics. Rapid and effective rehabilitation solutions are crucial to minimize downtime and prevent recurrence [1,2]. Wearable technology has recently gained significant attention due to its various applications in health and environmental monitoring, energy storage, as well as for entertainment purposes. The modern definition of wearable technology includes devices that can collect physiological and environmental data in real-time in a portable and wearable manner. Designing such products requires ensuring that wearable systems include sensors for detecting and collecting information, circuits for signal routing, devices for storing or transmitting information, power supplies and connecting conductive elements, as well as a suitable flexible or stretchable substrate. Wearable technology has emerged as a promising approach, offering non-invasive, real-time monitoring and personalized rehabilitation solutions [3].

Among various innovations, smart textiles (e-textiles) stand out for their ability to integrate sensors, circuits, and conductive pathways into wearable systems. E-textiles generally consist of three basic components that combine textiles and electronics at different levels of integration [3,4]:

- Sensors, which are designed to detect and record external stimuli, such as monitoring heart activity (e.g., ECG). Sensors represent the main textile component, typically made from conductive yarns or highly flexible substrates obtained through various technologies, such as surface coatings with metallic nanoparticles or conductive polymers.
- Electronic modules, which are intended for signal recording and processing. They include components like batteries, which cannot yet be fully miniaturized and can be removed before washing. A lot of research is focused on improving the durability and robustness of these modules, which would allow for easier adaptation and maintenance of electronic components in everyday life.
- Electronic circuits/connectors, which serve as a bridge between the sensors and the electronic module. By using silver fibre yarns, conductive paths and sensor electrodes can be seamlessly woven into the textile material. Additionally, electronic circuits can be embroidered or printed using conductive fluids [1].

Ink-jet printing, a cutting-edge method in textile production, enables precise deposition of conductive materials onto flexible substrates.

State-of-the-art inks for ink-jet printing include:

(i) metallic nanoparticle-based inks, such as silver and copper nanoparticles, which offer high conductivity. Silver nanoparticle inks are especially popular for their excellent electrical properties and low resistivity, making them ideal for wearable applications. Gold nanoparticles, while more expensive, are prized for their chemical stability and biocompatibility, finding use in high-performance medical textiles and bioelectronics. However, these materials often require high-temperature sintering, which may limit their use on heat-sensitive textile substrates.

(ii) Carbon-based materials, including graphene and carbon nanotube (CNT) inks, are increasingly applied for their excellent electrical, thermal, and mechanical properties. These materials allow for the development of multifunctional textiles capable of advanced sensing and energy storage.

(iii) Conductive polymers, such as polyaniline (PANI) and polypyrrole (PPy), provide another promising category of inks due to their intrinsic conductivity and mechanical flexibility. They can be used to create lightweight and stretchable conductive layers compatible with wearable textiles. PEDOT:PSS, a conductive polymer, is particularly suited for these applications due to its stability, flexibility, and eco-friendly properties.

(iv) Hydrogel-based conductive inks are also emerging, offering biocompatibility and potential use in wearable bioelectronic applications. By combining these advanced inks with the precision of inkjet printing, researchers can fabricate highly functional conductive layers, enabling the seamless integration of electronics into textile materials for next-generation smart wearables [5-7].

Ink-jet printing technology offers significant advantages for smart wearable electronics, including high design freedom, compatibility with a wide range of materials, and reduced environmental impact compared to traditional methods. It allows for the production of lightweight, flexible, and customizable patterns that seamlessly integrate into textiles without compromising comfort or durability.

Current trends in this field emphasize the development of multifunctional textiles capable of energy harvesting, wireless communication and advanced sensing capabilities. Inkjet printing stands out as an

adaptable, scalable and cost-effective solution for these innovations [6, 7].

Electrical resistance in printed flexible wearable electronics on textiles is a critical performance parameter, as it determines the efficiency and reliability of the electronic functionality. Factors affecting the electrical resistance are [5-7]:

(i) Material type:
- conductive polymers (e.g., PEDOT:PSS): Typically exhibit sheet resistance in the range of 100–1,000 Ω/sq for single layers, depending on doping and thickness. Multilayer coatings can lower this resistance.
- metallic nanoparticles (e.g., silver, gold, copper): Feature much lower resistivity (silver: ~1.6 μΩ·cm, gold: ~2.2 μΩ·cm), resulting in sheet resistances of 1–10 Ω/sq for optimized layers.
- carbon-based materials (e.g., graphene, CNTs): Offer intermediate resistance values, with sheet resistance typically ranging between 10 and 500 Ω/sq, depending on dispersion quality and printing parameters.

(ii) Ink Layer Thickness:
- thicker layers reduce resistance but may compromise flexibility and adhesion. Optimizing the number of printed layers can balance these factors.

(iii) Substrate Properties:
- textiles with high surface roughness or porosity can disrupt ink deposition, increasing resistance. Pre-treatment of fabrics (e.g., plasma or chemical coating) helps improve uniformity.

(iv) Post-Treatment:
- sintering or curing processes significantly impact resistance. Metallic nanoparticle inks typically require high-temperature sintering (~200°C for silver), while PEDOT:PSS can be thermally treated at lower temperatures (~90°C).

This study, part of the national WIBRANT project, aims to develop an innovative, wearable, and flexible smart brace that enables non-invasive, real-time telediagnostics and telerehabilitation for muscular disorders. By employing ink-jet technology, traditional conductive fibres can be replaced, using commercial conductive polymer ink. In addition, the surface morphologies of printed textiles were studied to visualize the effect of coating on the formation of a continuous conductive pattern. Electrical characteristics of the conductive patterns were determined as a function of the length, and number of printed layers.

2. Experimental work

Hydrophobic paper: photo glossy paper for ink-jet printing with grammage 180 g/m^2, size A4 (210 x 297 mm), supplied by Activejet.

Textile substrate material: Flexible and stretchable knitted fabric composed of 62% polyamide, 20% cotton, and 28% elastane, selected for its high elasticity and stretch recovery. The fabric was sourced from Inplet d.o.o., Slovenia.

Conductive ink: Commercial PEDOT:PSS ink (Poly (3,4-ethylenedioxythiophene):Polystyrene sulfonate) Clevios P Jet 700N by Heraeus, with the chemical structure shown in Fig.1, offers high conductivity (650 S/cm) and compatibility with inkjet printing. The ink was thermally cured to enhance adhesion and conductivity.

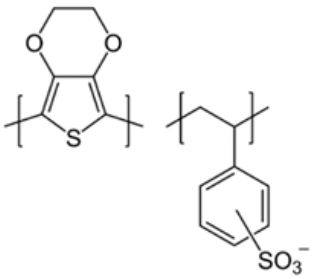


Fig.1 Chemical structure of PEDOT:PSS ionomer

Printing equipment: Dimatix Materials Printer (DMP-2800 Series) with piezoelectric printheads (Fig.2).

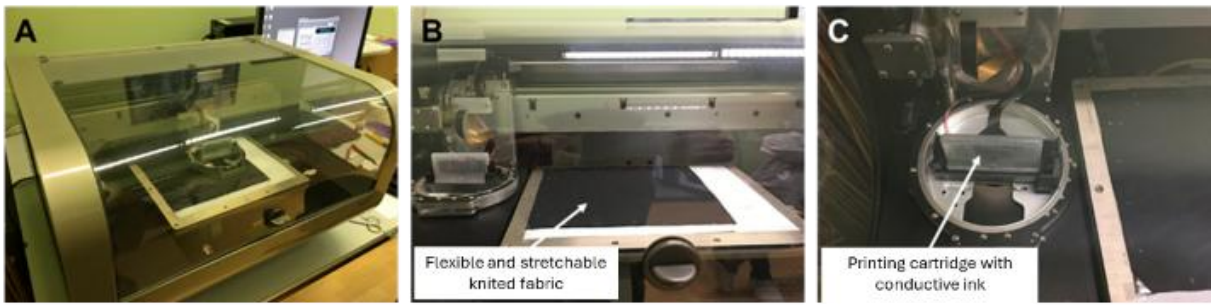


Fig.2 A – Fuji Dimatix ink jet printer, B – printing surface, C – single use printing cartridge

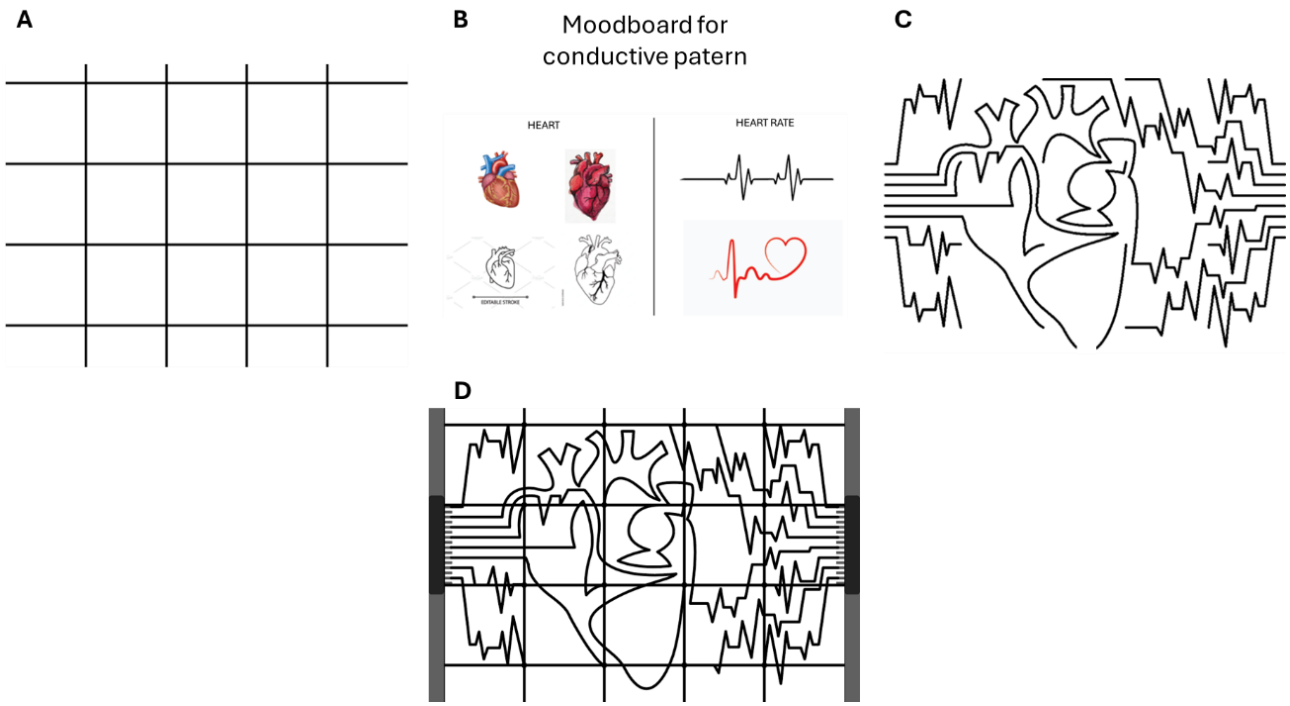


Fig.3 A – Designed sensor pattern, B – Mood board for development of conductive pattern, C – Designed conductive pattern, D – Sensor matrix also integrated with conductive pattern connecting the sensor points to the connectors

Printing parameters were optimized for drop size (10 pL), resolution (612 dpi), and nozzle voltage (40 V) and frequency (80 Hz), to achieve sharp, continuous conductive lines. During the printing all 16 printing nozzles were used, angle of the printing head was 9.4° and the distance between the printing head and substrate was 1.2 mm.

Design of conductive patterns: The conductive matrix design incorporated functional and aesthetic elements, using Adobe Illustrator CS 6 to create an appealing "heartbeat" pattern representing the muscle brace's purpose for conductive pattern (Fig.3). The design integrated a 4 x 4 cm sensor grid, represented the pattern for multi-point data acquisition (16 measuring points).

Printing and post-treatment process: Initial tests were conducted on hydrophobic paper to determine optimal parameters for ink deposition. These parameters were adjusted for knitted fabric, ensuring pattern continuity and print quality. After printing the samples were thermally treated at 90°C for 15 minutes to enhance wash durability and conductivity, using drying chamber (Sterimatic, ST-11, Instrumentarij, Zagreb).

Analytical Methods: Electrical resistance was measured using a digital multimeter, resistance values were used to calculate the sheet resistance of printed patterns. Print quality and ink dispersion were evaluated using optical microscope (Kern, camera ODC 825) and microscope Bresser USB, to examine the morphology and sharpness of printed lines.

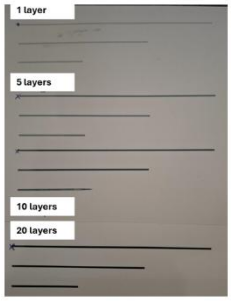
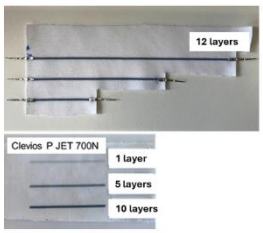
3. Results and discussion

In the presented research the conceptual design of a conductive pattern was inspired by the idea originated from the biggest and most vital muscle, without which life is impossible – the human heart. Due to the rhythmic contraction of the heart, a pulse is generated, which was decided to incorporate into the pattern as well (Fig.3B). The conductive pattern as well as sensor matrix were designed using the graphic software Adobe Illustrator, with prototype dimensions of 200 x 150 mm. The sensor matrix (Fig.3A) consisted of horizontal and vertical lines spaced 4 cm apart, forming a measurement matrix with 16 measuring points. The intersections of the vertical and horizontal lines represented points that were precisely 4 x 4 cm apart and served as sensor points for detecting dimensional changes in the elastic textile material. By stretching the textile and altering the distance between the intersection points, changes in electrical resistance is signaled to the computer. The connections between the measurement points and the connectors for computer represented the new graphic design of conductive pattern (Fig.3C). The intersection points of the sensor matrix also served as output points for the conductive lines, connecting the sensor points to the connectors (Fig.3D).

To assess the precision and success of printing with the conductive PEDOT:PSS fluid, hydrophobic photo paper was employed as the reference material. This substrate allows for the fabrication of highly precise

conductive lines with excellent reproducibility. Tab.1 illustrates the printed patterns on photo paper. Various line lengths were printed, and different numbers of printed layers were applied as the electrical resistance can be regulated by adjusting the number of layers. It demonstrates that inkjet printing technology enables the successful deposition of multiple layers on top of each other without the conductive PEDOT:PSS fluid spreading, thereby allowing controlled conductivity. For successful printing, it was necessary to first adapt and optimize the printer settings (nozzle voltage, frequency, resolution).

Tab.1 Images of printed conductive ink lines on hydrophobic photo paper and knitted fabric and the measured electrical resistance of lines with different length and different number of layers

Hydrophobic photo paper	Knitted fabric
	

Layers	Printed line length (cm)			Layers	Printed line length (cm)		
	5	10	15		5	10	15
Electrical resistance (kΩ)							
1	0	0	0	**12**	31.5	40.2	70.1
5	490	980	1300	**45**	2.11	3.05	3.46
10	63	77	74.1				
20	1.5	2.4	2.7				

The knitted fabric used to produce the brace is flexible and porous that can pose challenges when printing precise patterns and ensuring uniform thickness and conductivity of the applied layers. The porosity of the fibres and the resulting capillary action can lead to uneven absorption of the conductive fluid during printing and reduced sharpness of the printed patterns. The knowledge gained from printing PEDOT:PSS conductive fluid on photo paper to a real sample of flexible knitted fabric was applied. As part of this process, preliminary tests by printing straight lines of varying lengths and different numbers of layers, as shown in Tab.1, was performed. It can be seen that the inkjet printing technique for PEDOT:PSS conductive fluid is also suitable for textile materials. However, additional optimization of the printhead settings and printing parameters was necessary beforehand.

The printed layers exhibit sharpness, which is crucial for ensuring the reliability of the measured signals. Furthermore, it is possible to apply thicker layers through multi-layered printing without the formulation bleeding beyond the contours of the print.

In the printed pattern of PEDOT:PSS conductive fluid on the knitted fabric, the same trend of increasing electrical resistance with increasing length of the printed lines as seen with printing on photo paper was observed. However, compared to the measured electrical resistance values of conductive lines printed on photo paper, achieving similar electrical resistance on knitted fabric requires a greater number of printed layers of PEDOT:PSS conductive formulation.

To analyse the fluid application and evaluate the printing quality regarding pattern sharpness and the potential bleeding or spreading of the fluid beyond the pattern contours, microscopic analysis on the prepared samples of PEDOT:PSS conductive fluid printed on photo paper and knitted fabric was performed. Under the microscope, as shown in Fig.4, the knitted fabric reveals a left-to-right interlacing of yarns. When PEDOT:PSS conductive fluid is printed onto the knitted fabric, yarn coloration can be observed. The varying coloration of individual yarns suggests that an additional reinforcement system of yarns is integrated into the fabric, which differs in raw material composition due to its varying absorption of PEDOT:PSS fluid. Upon unravelling the knitted fabric, the inclusion of a “weft” yarn was identified, in this case, an elastane yarn, which enhances the fabric's elasticity. Fig.4 also depicts the edges of the PEDOT:PSS conductive fluid print, showing high print quality, as no fluid bleeding beyond the pattern contours is observed. Under higher magnification, the microscopic analysis of the PEDOT:PSS conductive fluid printed on the knitted fabric reveals that the fibres of the fabric absorb the formulation well. The absorption is uniform across the entire surface of the fibres.

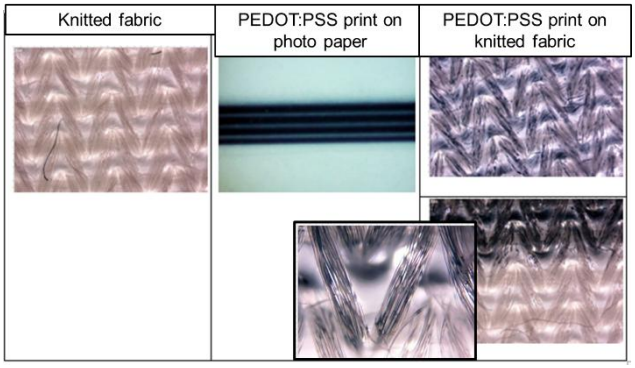


Fig.4 Microscopic images of knitted fabric, PEDOT:PSS print on photo paper as well as on knitted fabric (magnification: knitted fabric – 40x, photo paper – 20x)

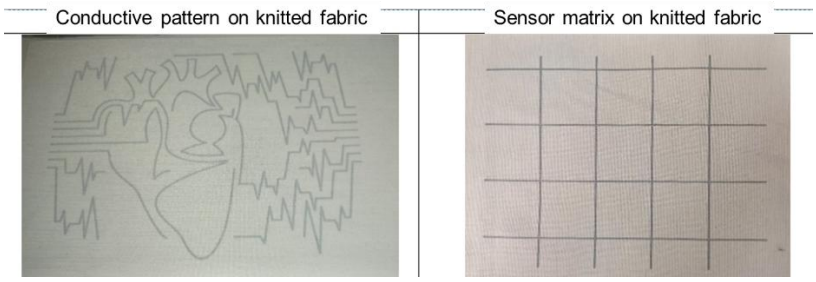


Fig.5 The final printed product of the "HEARTBEAT" conductive matrix and the sensor matrix

Post-treatment of printing inks is essential in the printing process on textile materials, as it allows the fluid to penetrate and bind to the fibres, thereby increasing the durability of the product for subsequent use. The post-treatment of the PEDOT:PSS conductive fluid print on the knitted fabric was carried out in a dryer at 90°C, with monitoring of the electrical resistance before and after treatment. The results show that the post-treatment slightly increases the electrical resistance, (2,11 kΩ before treatment and 3,26 kΩ after the treatment), which leads to a reduction of electrical conductivity. It was assumed that during the post-treatment process, water present in the PEDOT:PSS conductive fluid evaporated from the surface of the knitted fabric, which affected the measurement, resulting in a slight increase in electrical resistance and the migration of the fluid into the interior of the fibres.

Following all the presented research on the printing of PEDOT:PSS conductive ink on knitted fabric, Fig.5 shows the final printed product of the sensor matrix and the "HEARTBEAT" conductive matrix, which together form the sensor part of the muscle brace designed within the WIBRANT project.

4. Conclusion

In summary, conductive pattern on textile material using an inkjet printer and PEDOT:PSS conductive ink was successfully developed. The results showed that by applying multiple layers of fluid, electrical resistance could be effectively controlled. The high print precision on photo paper was achieved, and transferred to the textile. Printing on knitted fabric required additional optimization, however, the fibres of the knitted fabric absorbed the formulation well, ensuring homogeneous conductivity without fluid bleeding beyond the pattern contours. The results confirmed the quality of the print and uniform fluid application, what is essential for the continued development of conductive textiles. The results confirm that thermal curing improved the binding of the fluid into the fibres, which is important for wash resistance. A higher number of layers improved conductivity and reduced electrical resistance, which is important for future applications in the textile industry, where wear resistance and electrical conductivity are crucial.

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