ARTICLE

Textile-Based Sensor Design Through Machine Knitting: The SensorKnit Framework

Shihab Asfour [1,*]

[1] University of Miami, Department of Industrial Engineering, 1251 Memorial Drive, 268 McArthur Engineering Building, Coral Gables, FL 33146, USA

Abstract

This paper presents the development of three innovative types of textile sensors, each harnessing the resistive, piezoresistive, and capacitive properties of various fabric configurations. These sensors are created through the process of digital machine knitting using conductive yarn, a programmable and flexible manufacturing technique traditionally employed in the production of clothing, accessories, and footwear. This method offers fine-tuned control over the structural and electrical properties of the fabric, enabling precise manipulation of its behavior. By designing specific knit patterns that integrate conductive and dielectric materials, we were able to systematically influence the electrical resistance of the textiles, adjusting their characteristics through algorithmic control. This programmable approach to material fabrication opens new possibilities for creating customizable textile-based electronic systems. We further explore practical applications of these knitted sensors in both wearable technologies and smart home environments, demonstrating their versatility and adaptability in real-world settings. These use cases highlight how the sensors can be integrated seamlessly into everyday objects, enhancing their functionality with embedded sensing capabilities. While electronic textiles have been widely researched in interaction design and related fields, our work uniquely emphasizes the relationship between the microstructure of the knit—such as the loop configuration and material placement—and the resultant electrical properties of the fabric. By focusing on this microstructural-electrical interaction, we contribute to a deeper understanding of how textile design choices at the fiber level can directly impact the performance and functionality of e-textile systems.

Keywords: digital fabrication, additive manufacturing, textile-based sensing, machine knitting technology, material engineering

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1 Introduction

Materials play a foundational role in how we engage with our surroundings. Recently, there has been a growing focus on fabricating multimaterial structures, particularly within the fields of digital fabrication and additive manufacturing. The advancement of conductive materials has enabled the creation of interactive and responsive objects, moving beyond static designs [1, 2]. Previous studies have introduced innovative materials and fabrication techniques that allow for novel interactions, with textiles and soft materials gaining particular attention due to their nonlinear behavior and extensive potential for wearable technology.

Prior research has made strides in using direct ink writing to 3D print conductive elements onto textiles to create sensors and actuators. However, issues such as cracking in conductive traces and challenges in large-scale manufacturing persist.

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***Corresponding author:**
✉ Shihab Asfour
sasfour@miami.edu

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An alternative approach is to integrate conductive components directly into the fabric using multimaterial yarns through methods like weaving, knitting, or embroidery [3]. While these techniques aren't typically classified as 3D printing, they share similarities with additive manufacturing by building up fabric through the layering of yarns. With recent developments in computer-aided design (CAD), the complexity of textile geometries has expanded, and the manufacturing process has become highly customizable. Thus, weaving, knitting, and embroidery are increasingly seen as additive manufacturing techniques for textiles.

Nearly two decades ago, Margaret Orth and colleagues at the MIT Media Lab introduced the Musical Jacket, an interactive garment featuring touch-sensitive controls woven with conductive yarn. This milestone sparked ongoing research into electronic textiles (e-textiles) in the field of human-computer interaction (HCI). Subsequent work demonstrated how fabric manipulation techniques like sewing, embroidery, and knitting could be used to embed electronics into textiles. For example, Project Jacquard developed a comprehensive woven textile system, from designing specialized conductive yarn to producing garments with embedded capacitive sensors.

Building on the rich history of e-textile innovation, this article introduces three sensor designs—both resistive and capacitive—developed using digital machine knitting. Machine knitting, commonly employed to produce garments like shirts and sweaters, has advanced significantly in recent years, allowing for the creation of complex multilayer or 2.5D knit structures using various materials. Compared to embroidery, knitting is more scalable for larger textiles, and unlike weaving, it supports 2.5D structures. Furthermore, in contrast to ink-based 3D printing for conductive traces, knitting offers superior flexibility, durability, and scalability without being constrained by specific design limitations [4].

In this study, we present the design and fabrication of textile sensors created through machine knitting, utilizing silver-coated conductive yarn. By precisely controlling the knit structure at the stitch level, we can fine-tune the fabric's overall resistance. Special geometries, such as conductive yarn pockets, enable the creation of both resistive and capacitive sensors. Thanks to the versatility of the machine knitting process, these sensors can be seamlessly integrated into nonconductive fabrics in a single knitting procedure. We discuss the sensor designs, sensing mechanisms, fabrication processes, and performance evaluations in detail.

While considerable research has been conducted on 3D printing of conductive materials, our work aims to bring machine knitting closer to the principles of additive manufacturing. With further advancements in responsive yarns, we believe that these knit designs could be adapted not only for sensing but also for actuating and displaying information on fabrics, contributing to the future of interactive textile design.

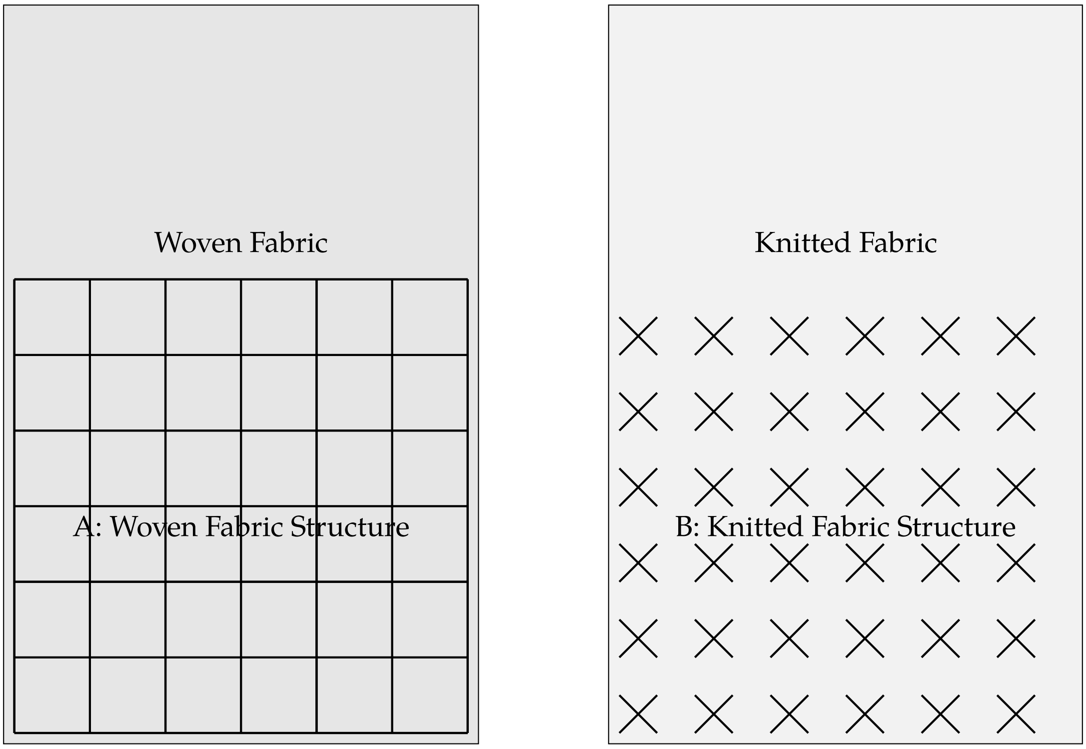
2 Related Works

The integration of electronics into textiles has a long-standing history in human-computer interaction (HCI). Researchers have developed various methods for embedding sensors and actuators into fabrics to create interactive user interfaces, expressive artwork, and promote social engagement. Generally, these fabrication techniques fall into two main categories: extrinsic methods (such as coating or laminating) and intrinsic methods (such as embroidery, weaving, or knitting). For example, Buechley and Eisenberg utilized lamination to bond conductive fabrics with non-conductive ones, while Atalay et al. combined dielectric silicone with fabric to create sensors. On the intrinsic side, Project Jacquard thoroughly explored integrating conductive yarn directly into fabric to form capacitive sensors within garments.

Building upon these works, our research investigates digital knitting as a scalable method to create customizable sensors. This approach allows precise control over the electrical properties of knitted fabric down to the stitch level.

Knitting has been an integral part of human culture for centuries. Many hobbyists, artisans, and artists have experimented with incorporating conductive materials into their knitting projects, using it to create functional sensors. Kurbak's work demonstrates how antennas and capacitors can be knitted using copper wire, while Hannah Perner-Wilson shared her knitted stretch sensors on public platforms like Instructables. Similarly, Stitching World's projects have showcased knitted capacitors. Our study introduces several knit patterns for resistive and capacitive sensors, along with a detailed analysis of their performance [5].

The textiles we encounter daily are predominantly created through weaving or knitting. While weaving uses an "over-and-under" yarn structure, knitting involves forming loops through loops. Unlike woven



fabrics, which require multiple yarns, knitted textiles can be made from a single continuous yarn. This looped structure also enables the creation of 2.5D and 3D geometries by varying the knitting stitches.

Digital machine knitting is a programmable and automated process that forms interlocking loops from one or more yarn threads. In contrast to hand knitting, which typically uses two long needles, machine knitting utilizes a series of hooks (or needles) to form the loops. The yarn is fed into the machine from a cone, passes through a tensioning device, and then into the knit object via a yarn carrier. Modern knitting machines can accommodate multiple yarn carriers, allowing parallel or sequential knitting with different yarns. For further details on how machine knitting operates, McCann et al. provide an in-depth explanation, and additional resources are available in Spencer and Sadhan's works. Atef has also created animations to illustrate needle movements during the knitting process [6].

The knitting machine we used for this project is a V-bed model from Matsuya. A V-bed knitting machine features two needle arrays, known as the back and front beds. This configuration enables the production of two-layered fabric that can be joined to form tube-shaped pieces or connected intermittently to produce flat sheets. This dual-bed design offers significant flexibility in fabric shape creation, which we leveraged to combine both tube and sheet geometries for sensor pockets.

To instruct the knitting machine on how to form loops, specialized design software is used. Although the software is unique to each machine, the general principles are applicable across brands. The interface is divided into two grid-based sections. On the left side, users can design the overall shape of the knit piece, assigning a specific knit operation (such as knit, tuck, or transfer) to each grid position using color codes. Since the machine operates with two beds, most operations are duplicated for the front and back beds.

On the right side, more detailed instructions are provided for each knitting line, also using color codes. Each color corresponds to specific machine parameters, such as yarn carrier selection, knitting speed, and stitch tension. These settings allow precise control over the final knitted piece. For further guidance on the machine's color coding system, Matsuya provides online resources [7].

3 Material Selection for Sensor Fabrication

In electronics, the creation of various components relies on the precise control of conductive and dielectric material geometries. In this study, we apply that same principle to machine knitting, developing tunable knit capacitors and resistors that enable specific sensing functionalities, particularly useful in interaction design.

Much like bricks are essential in building a house, conductive yarn forms the backbone of a textile resistor. Following the approach introduced by Project Jacquard, numerous types of conductive yarn structures are available in the market. For our design, we selected a yarn sourced from Alibaba.com, consisting of silver-coated fibers intertwined with non-conductive yarn. This yarn struck an ideal balance between conductivity and resistance (measured at 1 ohm/mm), which is crucial as we were designing resistors alongside other components.

A closer examination of these conductive fibers using scanning electron microscopy revealed a dielectric core covered with a thin layer of silver nanoparticles ranging from 20 to 200 nanometers in size. Unlike traditional metallic core yarns that risk losing conductivity if broken, these silver-coated fibers maintain electrical contact within the knit structure, ensuring both durability and consistent electrical performance.

Once the right conductive yarn was selected, we explored how the knit pattern itself could influence the overall electrical properties. We produced several test samples, varying the number of loops in each direction to create "wires" of different lengths and widths. Our findings showed that resistance increases in direct proportion to the length of the knitted sample and decreases inversely with its width. This relationship held true across three different knit patterns: jersey, interlocking, and ribbed [8].

L represents the number of loops along the length, W is the number along the width, and the constant 2.63 was calculated based on experimental data. It's important to note that this constant may vary depending on factors like stitch tension, which affects how much contact exists between loops. For consistency, we used the same yarn type and maintained a constant tension throughout our experiments [9].

One of the key differences between knitted and woven fabrics is that knitted textiles retain elasticity, even if the yarn used is not inherently stretchy. This spring-like behavior, due to the "looped" structure of knitting, is not always desirable—particularly when designing resistors, where stability in resistance values is required. To resolve this, we introduced bonding yarn into the knit.

Bonding yarn, typically a thermoplastic polyurethane (TPU) that melts at temperatures between 45°C and 160°C, is widely used in the knitting industry for creating non-elastic textiles such as shoes and bags. We knitted the bonding yarn along with conductive and non-conductive yarns in the same process. Initially, the fabric retains its elasticity, but after a brief application of heat through ironing, the bonding yarn melts and eliminates the stretchiness. This process ensures that the resulting textile is flexible but not elastic, allowing the resistors to perform consistently.

On the other hand, there are cases where elasticity is required. By knitting with spandex yarn, we can control the fabric's stretch. Tightening the stitch tension ensures that the inherent elasticity of the spandex becomes more dominant than the natural flexibility of the knit loops. We utilized spandex, sourced from Supreme Corporation, to construct a stretch sensor as part of this study.

Armed with this selection of yarns and materials, we explored various knitting architectures to develop effective sensing mechanisms for interaction design.

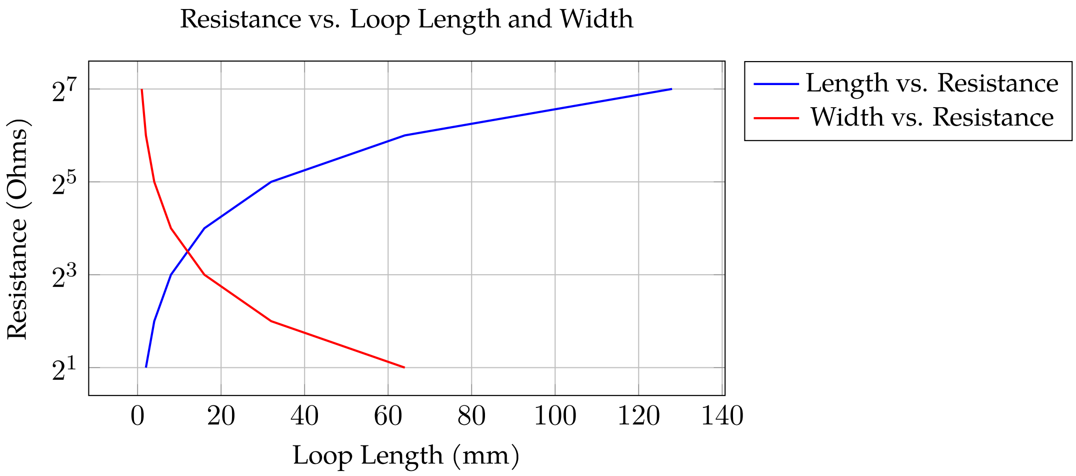
Industrial knitting machines provide the capability to adjust several key parameters, such as stitch tension, take-down speed, and cam speed. These settings are typically modified on a course-by-course basis, which allows for precise control over the knitting process.

The principles behind this programming, enable the detailed customization needed to produce high-performance textile sensors.

4 Rheostats

We developed two types of sliding rheostats that work by modulating resistance. The basic concept involves creating two conductive strips from yarn embedded in the fabric, allowing the resistance to change depending on the length of the circuit path. The first design resembles a belt made from knitted polyester. Two conductive strips run parallel along the belt, and resistance is adjusted by using a metallic buckle to bridge the two strips. The resistance can be fine-tuned by modifying the number of rows formed by the conductive yarn. The second design operates similarly, but the shorting is done using a neodymium magnet. Instead of knitting a single sheet using two beds, we created a spandex pocket designed to hold a ball magnet. The user can modify the resistance by moving the magnet with a magnetic tool. This design's advantage is that the resistance remains stable even after the magnet is removed.

Above Figures illustrate the knitting patterns used for these designs. In both cases, the conductive yarn



is introduced into the knitting process through the yarn carrier. In Figure, the design creates a pocket by sequentially knitting on both the front and back beds. Figure features an interlocking structure similar to that in Figure, where knitting alternates between the front and back beds. Different tension settings were used for the conductive yarn compared to the other yarns, with the machine settings adjusted to 300 for conductive yarn and 360 for other yarns. This ensures that the conductive loops are tightly connected.

Both rheostat designs were constructed using one thread of 400 denier ultra-high-molecular-weight polyester (sourced from Alibaba.com), one thread of 450 denier silver-coated conductive yarn, and one thread of 150 denier thermoplastic polyurethane (TPU) yarn. After knitting, the TPU was melted by ironing the fabric at approximately 100°C.

The first rheostat is constructed as a belt made from polyester, with two parallel conductive strips knitted into the fabric. This design allows for resistance adjustment through a metallic buckle that shortens the conductive strips at various points along the belt. By altering the position of the buckle, the effective length of the conductive path changes, which in turn adjusts the resistance. This design offers flexibility in resistance tuning by varying the number of yarn loops, which impacts the resistance range of the belt. This allows for dynamic adjustments based on the buckle's placement, making it suitable for applications requiring variable resistance settings.

The second rheostat utilizes a magnetic mechanism to control resistance. It features a spandex pocket knitted to hold a neodymium magnet. The resistance is adjusted by moving the magnet along the fabric, which shorts different sections of the conductive yarn strips. This design provides a stable resistance value as the magnet remains in place, even if the magnetic tool is removed. The use of spandex adds elasticity to the fabric, which can be beneficial in applications where consistent resistance values are required, despite changes in external conditions.

Both rheostats are created using advanced machine-knitting techniques. The knitting patterns for the belt-like rheostat involve parallel strips of conductive yarn, while the magnetic mechanism design includes a spandex pocket to house the magnet. The fabrication process involves carefully controlling yarn tension and knitting settings to ensure proper integration of conductive and non-conductive materials. Heat treatment was applied to melt the TPU yarns, providing a stable and flexible final product.

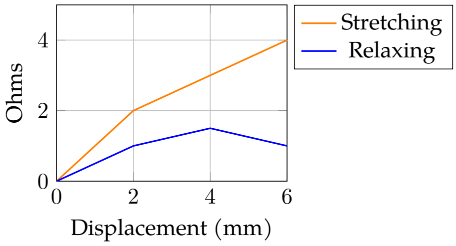
To validate the functionality of these rheostats, we tested their resistance-changing capabilities. The results confirmed that both designs effectively modulate resistance in a predictable manner, aligning with the theoretical models. This demonstrates the feasibility of using machine-knitted fabrics to create adjustable resistive components, paving the way for their integration into interactive and wearable technologies.

Overall, these rheostats exemplify how textile-based sensors can be designed with dynamic and adjustable properties through innovative knitting techniques, offering new possibilities for creating adaptable electronic components within textile structures.

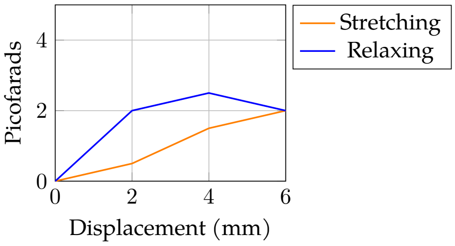
5 Stretch Sensor

Knitted fabrics exhibit some elasticity due to their interlocking loop structure, but they do not quickly return to their original shape after being stretched. To address this, we used spandex yarn to create an elastic

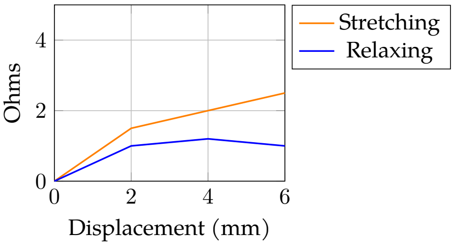
(A) Ohms vs. Displacement



(B) Picofarads vs. Displacement



(C) Ohms vs. Displacement



fabric with low hysteresis, ensuring rapid recovery after stretching. The stretch sensor's design features conductive yarn pockets knitted on top of the spandex base. These pockets overlap when the fabric is in its relaxed state, forming conductive pleats. As the fabric stretches, the pleats move apart, reducing the contact surface between them and increasing the resistance. Once released, the fabric quickly returns to its original shape thanks to the spandex.

The knitting process for the stretch sensor. The sensor is created using a two-bed knitting technique, with the front bed knitting the conductive pockets and the back bed producing the spandex base. While the front bed is knitting, the loops on the back bed remain stationary. This allows for the formation of pockets once the yarn is transferred between the two beds.

The stretch sensor was produced using four threads of 150 denier polyester (sourced from Supreme Corporation), one thread of 400 denier spandex yarn, and one thread of silver-coated conductive yarn. After being removed from the knitting machine, the fabric was ironed at approximately 100°C to flatten the conductive pockets into flaps.

The stretch sensor was tested using an ADMET universal testing machine configured for fabric tensile testing. The fabric was secured at both ends, with alligator clips attached to the top and bottom conductive panels, and a multimeter was used to measure resistance. The fabric was then stretched in 1 mm increments, and resistance values were recorded. Data collection ceased when the distance between the panels exceeded 13 mm, as the conductive panels were no longer in contact at that point. The sensor exhibited a linear relationship between stretch distance and resistance, which was expected, as the overlap between the conductive panels determines total resistance. Additionally, no hysteresis was observed during testing.

the stretch sensor is a textile-based component designed to measure elongation or deformation through changes in resistance. This sensor leverages the unique properties of knitted fabrics and conductive yarns to provide accurate and responsive measurements of fabric stretch.

The stretch sensor utilizes a combination of spandex and conductive yarns to achieve its functionality. The sensor is constructed using a knitted fabric where the base is made from spandex yarn, chosen for its elasticity and ability to quickly return to its original shape after being stretched. This elastic base is essential for creating a fabric that can accommodate and measure stretching without permanent deformation.

On top of the spandex base, multiple pockets of conductive yarn are knitted into the fabric. These pockets overlap and form conductive pleats. When the fabric is stretched, these pleats move apart, which reduces the contact surface area between them and consequently increases the resistance. This change in resistance correlates directly with the amount of stretch experienced by the fabric.

The design of the stretch sensor involves a two-bed knitting process. The front bed of the knitting machine is used to create the conductive pockets, while the back bed forms the spandex substrate. This two-bed approach allows for the integration of both materials in a single knitting pass. The pockets are strategically designed to overlap when the fabric is laid flat, creating a network of conductive pleats that are sensitive to stretching.

The knitting process ensures that the conductive yarns are properly embedded within the fabric, and the spandex provides the necessary elasticity. The sensor is knitted such that the conductive pockets are aligned with the spandex, allowing the sensor to maintain its structure and functionality even as it is stretched.

The fabrication process for the stretch sensor involves several steps:

Knitting: The sensor is knitted using a combination of 150 denier polyester yarn for the base, 400 denier spandex yarn for elasticity, and silver-coated conductive yarn for the sensing component. The use of different yarn types is crucial for achieving the desired mechanical and electrical properties. Heat Treatment: After knitting, the fabric is carefully ironed at approximately 100°C to flatten the conductive pockets into flaps. This heat treatment ensures that the pockets are properly aligned and integrated into the fabric structure. Characterization

To characterize the stretch sensor, it was subjected to tensile testing using an ADMET universal testing machine. The sensor was clamped at both ends and stretched incrementally. Resistance measurements were taken at various stages of stretching. The results showed a linear relationship between resistance and the amount of stretch, confirming that the sensor accurately reflects changes in fabric deformation. No hysteresis was observed, indicating that the sensor returns to its original resistance value consistently after stretching.

The stretch sensor is particularly useful in applications where precise measurement of fabric deformation is required, such as in wearable technology, interactive textiles, and responsive environments. Its ability to provide accurate and reliable measurements of stretch, combined with its integration into flexible and elastic fabrics, makes it a valuable component in the field of e-textiles and human-computer interaction.

6 Conclusion

In this paper, we explored the integration of conductive yarn into machine-knitted textiles to develop novel sensor designs for interactive systems. By leveraging the flexibility of knitting techniques, we demonstrated the ability to fabricate both resistive and capacitive sensors that can be finely tuned through variations in geometry, material choice, and knitting patterns. Two key contributions of this work include the design of sliding rheostats, capable of modulating resistance through mechanical manipulation, and stretch sensors that exhibit predictable, linear changes in resistance in response to deformation.

Through the use of programmable knitting machines, we achieved scalable, customizable fabrication processes that allow for precise control over sensor properties. This approach opens up opportunities for seamless integration of textile-based sensors into wearable devices and other interactive environments. The rheostats and stretch sensors produced in this study serve as foundational building blocks for future applications in human-computer interaction, wearable technology, and soft robotics.

Moving forward, further refinement of the knitting parameters and material composition will enhance the performance of these sensors, particularly in terms of durability, sensitivity, and response time. This work lays the groundwork for more complex sensor architectures and highlights the potential of digital knitting as a versatile tool for crafting interactive, responsive textiles.

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None.

Conflicts of Interest

No conflicts of interest have been declared by the authors.

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