Nanosensors for Soft Robotics Exoskeletons

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Abstract: This paper presents a multi-layered piezoelectric nanosensor designed for robotic exoskeletons, aimed at enhancing neuro-muscular rehabilitation. Green-driven methods were used to achieve biocompatibility throught the incorporation of carbon-based nano-inks, reduced graphene oxide, and an optimized piezoelectric layer to enhance electrical conductivity under mechanical stress. These components are integrated with a triboelectric layer composed of a teflon-copper core. Electrical characterization tests demonstrate that the proposed sensor exhibits robust performance and high reliability, both critical issues for hand grasping sensing under rehabilitation scenarios.

1 INTRODUCTION

The advent of robotic-driven neurological physiotherapy has been significantly reducing recovery times in rehabilitation scenarios. In particular, the precise actuation and sensing capabilities integrated in robotic-based exoskeletons facilitate the mobility of affected limbs through highly intense and repetitive therapies. This enhances the precision of the treatment and provides a straightforward method for generating quantitative data necessary for assessing patient progress. An important body of work in the literature has demonstrated significant clinical-based improvements in upper-limb mobility in post-stroke patients, while using such robotic devices (Abdullah et al., 2011).

Several devices have been specifically designed for patients with hand motion impairments. These devices include orthoses, exoskeletons, and terminal effector devices (Mayer et al., 2022). Orthoses provide static support, whereas motorized exoskeletons enable both passive and active therapeutic exercises under the supervision of a physiotherapist (Jackson and Abdullah, 2023). In general, exoskeleton control systems are organized into three hierarchical levels: perception, control, and execution. This structure facilitates precise responses based on data collected from the environment, the device, and the user's interactions (Neťuková et al., 2022).

The integration of precise sensing capabilities is key to provide active assistance able to adapt to the patient (Pan et al., 2023). In this arena, biocompatible nanosensors have opened new alternatives for precise sensing with ease and flexible integration. In this regard, nanosensors integrated into wearable devices, such as gloves or exoskeletons, can provide real-time feedback on hand grasping strength, pressure distribution, and finger movement (Luo et al., 2024). This level of detailed monitoring is crucial for tailoring rehabilitation exercises to the specific needs of the user, ensuring optimal recovery and functionality. Additionally, the incorporation of nanosensors into these devices allows for the development of more sophisticated control algorithms, which can improve the accuracy and responsiveness of assistive technologies (Yang et al., 2024).

This paper reports the development of a bio-nanosensor fabricated using green-based methods for synthesizing nanomaterials, aimed at decreasing tox-

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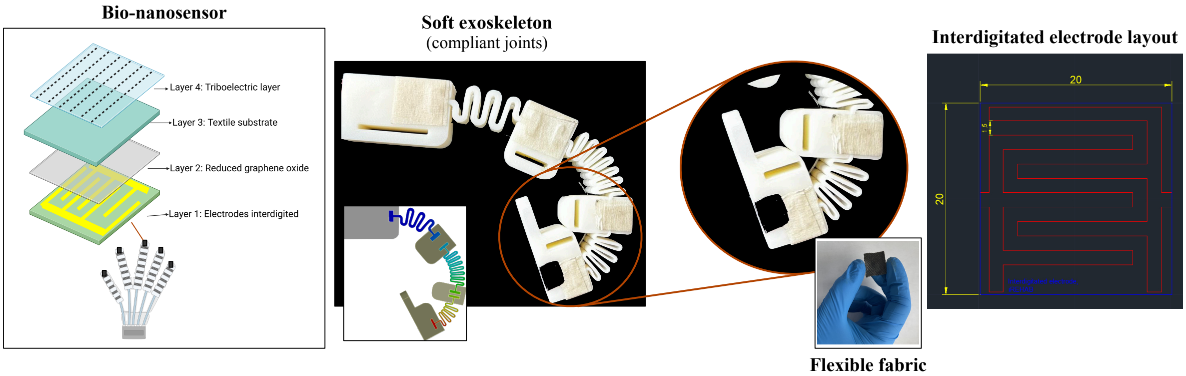

Figure 1: Bio-nanosensor design layers and integration with a hand-based soft robotic exoskeleton to support tactile pressure sensing in grasping-driven rehabilitation.

icity and maximize its bio-compatibility with the human skin. The sensor has multiple layers to mimic cutaneous mechanoreceptors with piezoelectric and triboelectric layers. Electrical characterization is presented, demonstrating the potential of these flexible sensing devices synthesized in a small footprint, while providing accurate sensitivity and precision.

2 METHODS

Figure 1 depicts the multilayered architecture of the sensor composed by 4 stacked layers. A flexible fabric was used to allow proper integration with the exoskeleton prototype developed in previous work reported in (Bonilla et al., 2023). As shown, the first two layers constitute the main piezoelectric sensor. The interdigitated electrode structure, fabricated through screen printing with carbon-based inks, imparts conductivity to the sensor.

A flexible textile substrate is employed, highlighting the applicability of sustainable and flexible materials for wearable technology. This electrode is paired with a layer of reduced graphene oxide, synthesized using an environmentally friendly method, to improve the sensor's performance. The subsequent layer is a triboelectric layer, integrated to enhance the sensor with surface texturing capabilities, which are crucial for exoskeletons designed for hand rehabilitation.

2.1 Piezoelectric Layer Fabrication

The fabrication process is described as follows:

- Substrate preparation: A flexible and durable textile substrate is selected for its suitability in wearable technologies.

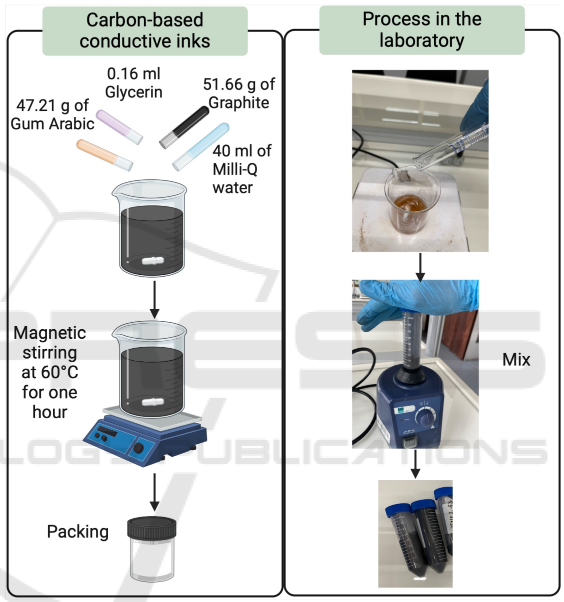

Figure 2: Conductive ink manufacturing process.

- Electrode patterning: Interdigitated electrodes are directly printed onto the textile substrate using conductive carbon-based inks through the screen-printing technique. This method allows precise control over the electrode patterns and thicknesses. Figure 2 details the fabrication process of these conductive inks, highlighting the formulation and application steps involved.
- Graphene-oxide application: Reduced graphene oxide, produced via an environmentally friendly reduction process, is subsequently applied to the interdigitated electrodes. This coating is crucial for enhancing the piezoelectric properties of the sensor. Figures 3 and 4, provide a detailed explanation of the synthesis process for this nanomaterial.

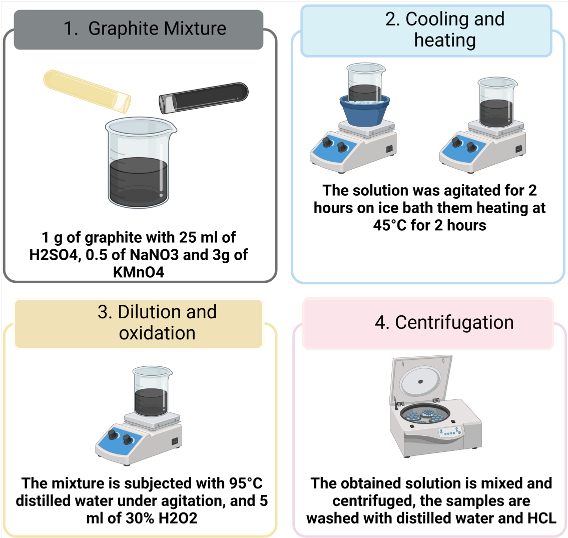

Figure 3: Graphene oxide manufacturing process.

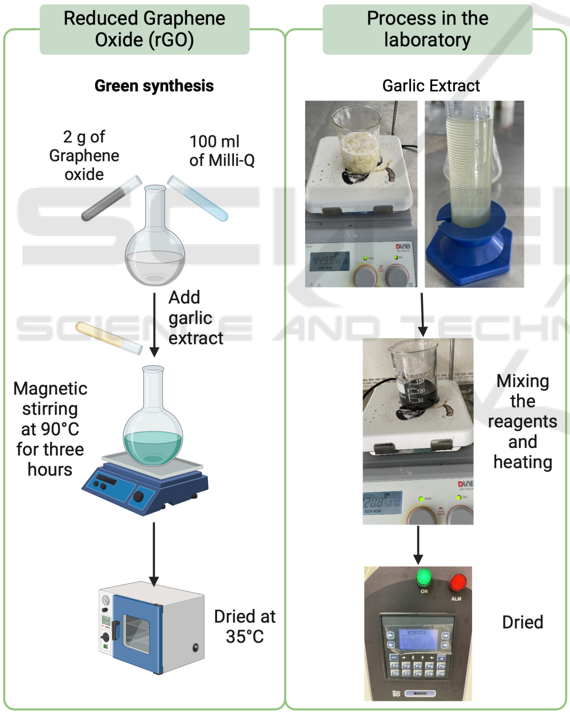

Figure 4: Reduced graphene oxide manufacturing process.

2.2 Triboelectric Layer Fabrication

The triboelectric layer comprises fine teflon fibers with an embedded copper core. This specific structure is selected to generate the triboelectric effect, with Teflon providing the requisite triboelectric properties and the copper core enhancing electrical conductivity and overall layer effectiveness.

2.3 Assembly

All layers are carefully aligned in the correct order and bonded using environmentally friendly biocompatible adhesives. This ensures both the biocompatibility and functionality of the sensor. Proper alignment is critical to ensure cohesive performance when integrated into the exoskeleton.

3 RESULTS

3.1 Conductive Inks Characterization

The electrical properties of inks applied to paper and plastic substrates are crucial, significantly influencing their suitability for flexible devices. To simulate realistic usage conditions, the inks were bent and fixed at angles of 180°, 120°, 90°, 45°, and 30°. Electrical resistivity was measured using the four-point probe method, and conductivity was subsequently calculated.

The four-point probe method is a widely accepted technique for determining the electrical resistivity of materials. It utilizes four aligned electrodes: the two outer electrodes supply a constant current to the material, while the two inner electrodes measure the voltage across them. This arrangement minimizes typical errors due to contact resistance and the resistance of the electrodes, ensuring accurate resistivity measurements of the material under test (Ossila, 2024).

Figures 5 and 6 present the electrical properties of the inks under bending for both substrates. The inks exhibited no significant change in electrical properties under bending, indicating their excellent adaptability to mechanical deformations. This adaptability is vital for applications requiring high flexibility without compromising electrical functionality. The robustness and reliability of these conductive inks demonstrate their potential for use in sensors and other flexible electronic devices, where maintaining electrical integrity is critical for overall functionality and performance. These findings suggest that the design of flexible electronic components can leverage the durability and reliability of these inks under various mechanical conditions.

The results demonstrate reliable stability of the electrical conductivity of conductive inks deposited on both paper and plastic substrates under various bending conditions. In both cases, a slight increase in conductivity is observed as the bending angle decreases from 180° to 30°. This trend indicates that the ink maintains proper conductivity even under significant mechanical deformation, which is crucial for

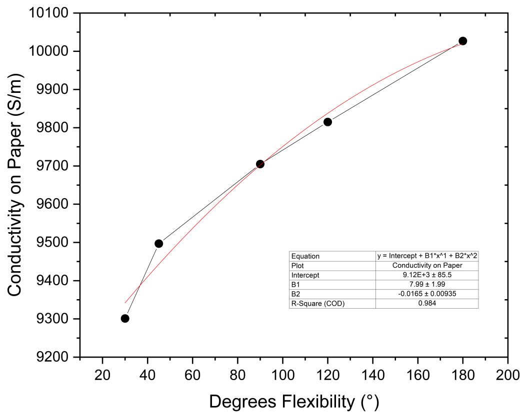

Figure 5: Conductivity on paper substrate.

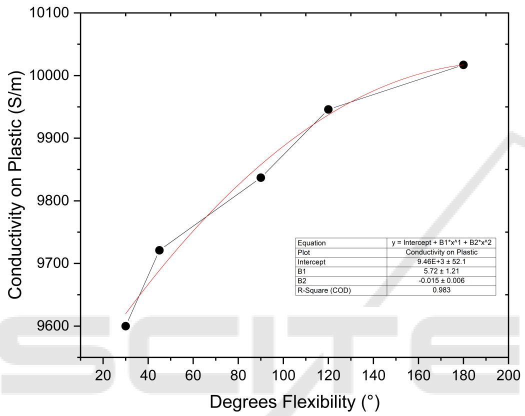

Figure 6: Conductivity on plastic substrate.

applications involving flexible or foldable devices.

3.2 Electrical Characterization Piezoelectric Layer

Figure 7 presents the sensing mechanism of the proposed piezoresistive sensor layer. Unlike flat, hard, and planar bulk metal layers, the coated textile layers exhibit pores and roughness. The contact area between the reduced graphene oxide-coated textile and the bottom electrodes changes with variations in external pressure. When a compressive force is applied to the sensor surface, the porous structures deform, bringing the reduced graphene oxide-coated textile into closer contact with the interdigital electrodes.

This deformation increases the number of conducting pathways between the graphene oxide and the carbon nano-ink electrodes, resulting in larger contact areas and an enhanced current under applied voltage. Upon unloading, the materials return to their original states, reducing the available conduction pathways and consequently decreasing the current.

Electrical signal testing was conducted to evaluate

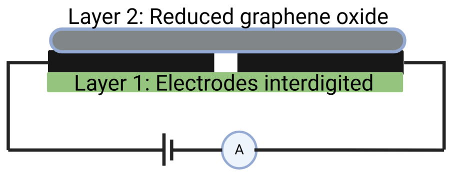

Figure 7: Current measurement configuration.

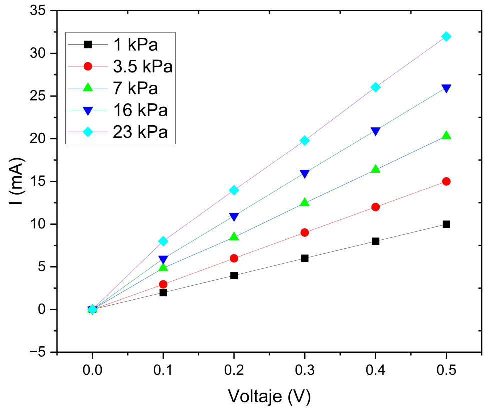

Figure 8: Measurement of voltage and current relationship of the piezoelectric layer.

the sensing performance of the textile sensor devices. As shown in Figure 8, the current-voltage (I-V) curves of the piezoresistive sensor exhibit highly linear relationships under static pressure loading. This linearity indicates that the rGO-coated textile and the carbon nano-ink electrode textile form ohmic contacts. Additionally, the piezoresistive sensor demonstrates high sensitivity and reliability across a wide range of applied pressures.

Figure 8 shows the I-V characteristics of the piezoresistive layer under various applied loads, with pressures ranging from 1 to 23 kPa. The data were obtained by measuring the current at different applied pressures while varying the voltage from 0 to 0.5 V. The I-V curves clearly show that an increase in voltage results in a corresponding increase in current for all tested pressure levels.

The sensor's sensitivity is evident from the increasing slope of the I-V curves with higher applied pressures. For instance, the curve for 1 kPa pressure is relatively low compared to that for 23 kPa, indicating a more significant response at higher pressures. This feature highlights the sensor's capability to distinguish between varying magnitudes of pressure, making it suitable for applications requiring precise pressure sensing. The linearity of the I-V curves under each applied pressure confirms the formation of ohmic contacts by the piezoresistive layer, which is crucial for the reliability and repeatability of measurements. This linearity also simplifies the calibration of the sensor in real-world environments, facilitating the integration of devices utilizing this technology. These results validate the construction of the piezoresistive sensor and its application in highly accurate and sensitive pressure monitoring, which is essential for medical devices and advanced robotic systems.

4 CONCLUSIONS

Multilayered piezoelectric sensors offer significant potential for enhancing robotic exoskeletons used in neuromuscular rehabilitation. The incorporation of carbon-based nano-inks and reduced graphene oxide makes these sensors environmentally friendly and biocompatible, suitable for direct skin contact.

The piezoelectric and triboelectric layers of the sensor are highly sensitive and capable of distinguishing between different levels of applied pressure. Such sensitivity is crucial for replicating the sophisticated mechanoreceptive capabilities of human skin, thereby enhancing the rehabilitative effectiveness of the exoskeleton. Also, the electrical characterization of the sensor demonstrates its viability under mechanical deformation and stability in functional performance. These are critical considerations for wearable technologies that must withstand various dynamic physical stresses. Additionally, the linear I-V characteristics under applied pressures facilitate easier integration and calibration within exoskeleton frameworks, broadening its utility in physio-therapeutic applications.Future research should focus on real-world testing to assess the long-term durability of the sensor and its integration with other biomedical monitoring technologies.

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