

Nanoplatfoms for Neuroscience— NeuroNanotech

Deliverable D1.4

First integrated electromyography and impedance skin sensor

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EXECUTIVE SUMMARY

This deliverable presents the development and validation of the integrated soft sensing platform developed by Tel Aviv University (TAU) within Work Package 1 (Ultimate Sensing) of the NeuroNanotech project. The work contributes to Tasks 1.2 and 1.4 by developing flexible printed sensors for electromyography (EMG), impedance measurements, and strain sensing.

TAU established a fabrication process for soft, screen-printed carbon electrode arrays that are thin, flexible, and mechanically compliant, enabling conformal contact with biological tissue. The electrodes were characterized through bench testing and validated in healthy volunteers using skin-surface measurements on the face and neck. These electrode arrays were compared with conventional gel electrodes, demonstrating comparable stimulation thresholds, user comfort, and safe skin contact without visible irritation. Although dry electrodes exhibited higher contact impedance, their overall electrophysiological performance supports their suitability for wearable sensing and stimulation applications. In parallel, TAU integrated a flexible printed piezoresistive strain sensor. The sensor demonstrated reproducible electromechanical performance during bench testing and successfully detected facial movements in a proof-of-concept on-skin experiment.

Overall, this deliverable establishes a multifunctional soft sensing platform that combines electrophysiological recording, impedance sensing, and strain sensing within a flexible printed architecture. These results provide a foundation for the continued development and optimization of wearable and implantable bioelectronic interfaces within the project.

METHODS and RESULTS

1. Sensor fabrication and characterization

Fabrication process for soft dry electrode arrays was established and based on screen-printed conductive inks on polyurethane films (PU) as described previously [Levit et al. 2023]. Briefly, silver traces are screen-printed on PU films first, followed by aligned screen-printing of carbon electrodes (Creative

Materials, C 124–50T) and curing at 60 °C for 10 min. The arrays are passivated with a double-sided adhesive PU film (Delstar EU94DS), leaving the electrode sites exposed (Fig. 1A).

The resulting arrays are custom made, thin, flexible, and conformable to skin. AFM analysis showed a carbon surface roughness of 615 ± 51 nm (Fig. 1B). Cross-sectional FIB-SEM imaging revealed distinct electrode array layers (Fig. 1C): Carbon (16.7 μ m), silver traces (8.8 μ m), and PU layer (54.3 μ m).

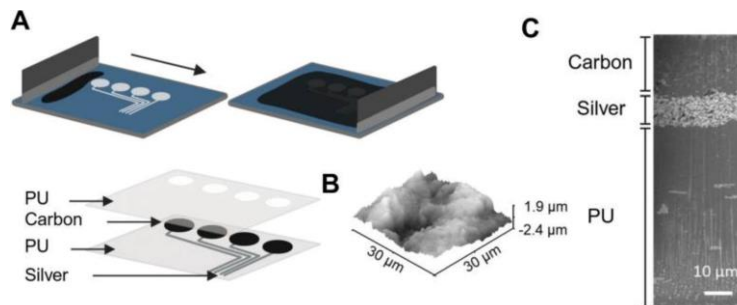


Figure 1. Dry electrode fabrication, surface morphology, and structural characterization. (A) Schematic illustration of the electrode fabrication process. (B) AFM 3D topography of the carbon electrode showing surface roughness. (C) FIB-SEM cross-sectional imaging showing the layered structure.

2. Human Skin Testing (IMPEDANCE): Dry Versus Gel Electrodes

The performance of dry printed electrodes against standard gel electrodes was evaluated in healthy human subjects. Contact impedance and stimulation efficacy were compared across 12 participants. EMG signals on human volunteers were recorded using a wireless data acquisition unit (DAU; X-trodes Ltd., Herzliya, Israel). Contact impedance was measured with skin electrochemical impedance spectroscopy using an impedance analyzer (MFIA, Zurich Instruments) under 2-terminal (2T) measurement at a frequency range of 1–1000 Hz.

Figure 2B shows the Nyquist plots of contact impedance (normalized to contact area) of one subject. As expected, dry electrodes showed higher normalized impedance compared with gel electrodes. To examine group-level trends, impedance and stimulation efficacy were quantified and compared across 12 subjects. However, no significant differences were observed between electrode types in stimulation thresholds or perceived pain at threshold. No skin irritation was observed after electrode removal. The only parameter showing a significant difference was the constant phase element exponent (ndI), which was higher for gel electrodes (p-value <0.01, effect size 0.560). The results support the feasibility of TAU's dry printed electrodes for skin-surface electrophysiological applications.

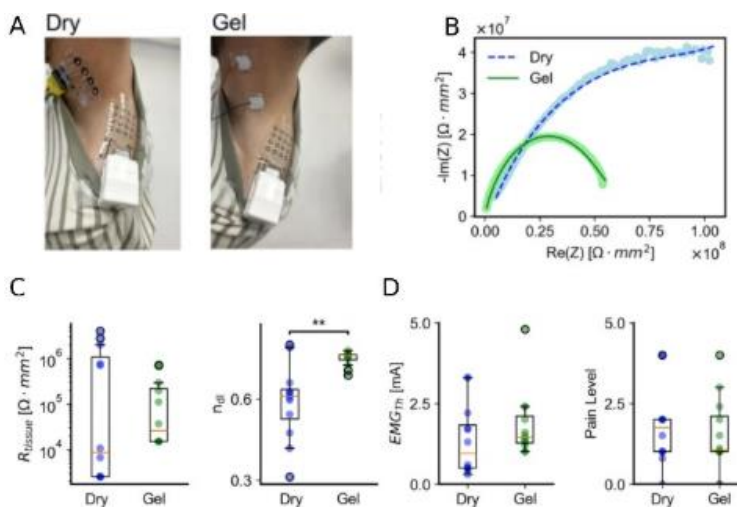


Figure 2. Dry versus gel electrodes comparison. (A) Photograph of electrode placement on the neck. (B) Area-normalized Nyquist impedance plots for dry and gel electrodes, with experimental data points (dots) and corresponding model fits (lines). (C) Boxplots showing tissue resistance and constant phase element exponent across subjects; (D) sEMG activation thresholds and corresponding pain levels at threshold.

The results support the feasibility of TAU's dry printed electrodes for skin-surface electrophysiological applications.

3. Human Skin Testing (STRAIN): development and characterization

TAU developed a soft printed piezoresistive strain sensor (Fig. 3) designed for co-located movement monitoring alongside EMG electrodes. The sensor array consists of four independent sensors fabricated on a PU substrate, with silver interconnects and a PEDOT/carbon-black piezoresistive sensing layer.

Bench-top stretching experiments demonstrated a clear piezoresistive response. Resistivity increased monotonically with applied force and strain, reaching approximately a 3.4-fold increase at 20% strain. Repeated measurements showed low variability, supporting the reproducibility of the response. Mechanical characterization showed an approximately linear stress–strain relationship within the tested range, with an estimated Young’s modulus of 13.2 MPa, suggesting that the printed sensing layer did not substantially compromise the stretchability of the soft polymer platform.

As an initial on-skin proof of concept, two sensors were placed around the lips and connected to an Arduino-based acquisition system. The sensors recorded real-time resistance changes during facial movements, including speaking, smiling, and relaxation.

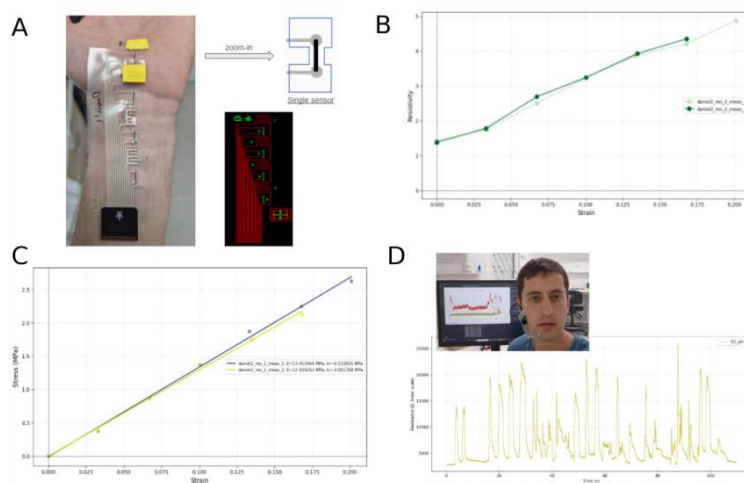


Figure 3. Printed soft strain sensor for skin-mounted movement monitoring. (A) Four-channel piezoresistive strain sensor array fabricated on a PU substrate with silver interconnects and a PEDOT/carbon-black sensing layer. (B) Resistivity increases with strain, showing an approximately 3.4-fold response at 20% strain. (C) Stress–strain fitting indicates an estimated Young’s modulus of 13.2 MPa, comparable to the PU

substrate. (D) On-skin proof-of-concept measurement around the lips demonstrates real-time resistance changes during facial movement.

4. Biocompatibility and safety

Initial healthy skin testing showed no visible irritation following electrode removal. Since the current electrode materials and fabrication processes are based on previously established materials, no new biocompatibility or safety validation tests are needed.

5. Summary

TAU has advanced its WP1 contribution by developing and validating soft printed sensors on thin polyurethane films. The dry electrode platform was shown to support impedance measurement, recording, stimulation, and skin-surface electrophysiology, with human testing demonstrating comparable stimulation thresholds and pain levels to gel electrodes and no visible skin irritation. TAU also developed a printed strain sensor with reproducible resistance changes under stretch and real-time detection of facial movement.