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Bioelectric Electrode For Wound Repair And Monitoring Using Sensor Methodology

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Abstract: This project aims to accelerate wound healing through the application of controlled micro-level electrical currents and continuous impedance monitoring. Microcurrent therapy has been shown to promote cellular migration, collagen synthesis, and angiogenesis, which are essential for tissue regeneration. An impedance sensor is integrated into the system to monitor the healing progression by measuring tissue impedance variations over time. Additionally, a web-based platform has been developed to upload and analyze wound images using a machine-learning model to determine the wound stage. This integrated approach provides both physiological (impedance) and visual (image-based) insights for accurate and continuous wound assessment.

***Index Terms* - impedence sensor, electrodes, buck converter, microcontroller, mobile camera.**

I. Introduction

Wound management is a critical aspect of healthcare, especially for chronic and diabetic wounds that exhibit delayed healing. Traditional wound care methods rely on physical dressing and manual assessment, which can be subjective and inconsistent. To overcome these challenges, recent research focuses on electrotherapy and biosensing to promote faster and more predictable wound recovery.

Microcurrent therapy involves the application of extremely low electrical currents (typically less than 600 µA) that mimic the body's natural bioelectric fields. These currents enhance cellular migration, ATP production, and collagen synthesis. Simultaneously, impedance monitoring serves as a non-invasive diagnostic tool to assess tissue health and hydration levels during recovery. As the wound heals, the impedance decreases due to the formation of new, conductive tissue

In this project, a compact hardware module is designed to deliver microcurrent stimulation and record impedance data. In parallel, a web-based platform allows users to upload wound images, where an AI model classifies the wound stage based on visual features. This integrated approach bridges physiological and visual data for precise wound analysis.

II. Working principle

The microcurrent generator applies a stable and safe current (<600 µA) to stimulate cellular repair. Simultaneously, the impedance sensor measures tissue impedance at predefined intervals. The acquired data is transmitted wirelessly to the web interface, where it is plotted to observe healing trends.

As tissue regenerates, impedance values typically decrease due to increased moisture and reduced inflammation. In parallel, the web portal allows the user to upload images captured at regular intervals, which are processed using a Convolutional Neural Network (CNN) model to determine wound stages: Inflammatory, Proliferative, or Maturation.

III. Methodology

3.1 System Design

3.1.1Microcurrent Generation Unit:

The microcurrent generation unit is the therapeutic core of the system. It is designed to deliver a low-level direct current (typically between 20 µA and 600 µA) to the wound site using biocompatible electrodes. The current level is precisely controlled by a microcontroller such as the ESP32 or Arduino, which modulates the output through a digital-to-analog converter (DAC) and a constant current driver circuit.

The system ensures stable current flow regardless of tissue impedance variations, maintaining consistent stimulation throughout the treatment period. The applied current mimics the body’s natural endogenous electric fields, thereby accelerating cell migration (galvanotaxis), fibroblast activity, and collagen synthesis, which are critical for tissue regeneration.

The output intensity can be adjusted according to the wound type and patient comfort level. Safety mechanisms are implemented to limit the current below 600 µA, preventing any thermal or electrical discomfort. This controlled stimulation helps restore the “current of injury,” a natural bioelectrical potential difference disrupted when the skin is wounded

3.2 Impedance Sensing Unit:

The impedance sensing unit functions as a **diagnostic module** that monitors the physiological changes occurring during wound recovery. The measurement is based on **bioimpedance spectroscopy**, where an **alternating current (AC)** signal, typically between **1 kHz and 10 kHz**, is applied across the wound region through a pair of electrodes.

As the wound heals, the tissue’s **electrical impedance decreases** due to the increase in ionic concentration, tissue hydration, and cellular regrowth. The sensor captures these impedance variations and sends the data to the microcontroller for real-time analysis. The microcontroller processes the signal using analog-to-digital conversion and stores or transmits the results wirelessly to the web server for visualization.

This non-invasive monitoring technique provides valuable information on tissue composition and healing rate, reducing the need for frequent manual inspections or invasive sampling. The impedance readings are graphically represented as a trend over time, allowing clinicians or users to assess wound healing progress quantitatively.

3.3 Web-Based Monitoring and Analysis Platform:

The third component is a web-based monitoring system that integrates both sensor data and image-based wound analysis. The platform is developed using HTML, CSS, and JavaScript for the front-end interface, and a Flask or Django framework for the back-end server. It serves as the communication bridge between the hardware and the user.

The platform allows users to upload periodic wound images captured by a camera or smartphone. These images are processed through a Convolutional Neural Network (CNN) model trained to classify wounds into specific healing stages: Inflammatory, Proliferative, and Maturation. The web interface displays both the impedance readings and image-based analysis results on a dashboard, giving a comprehensive overview of wound recovery.

Additionally, the platform stores data in a secure database, enabling long-term tracking of wound progress and supporting telemedicine applications. This digital interface transforms traditional wound care into a data-driven, remotely accessible, and intelligent monitoring system.

3.4 Data Processing

The data processing workflow is a key element of the proposed system, ensuring accurate interpretation of both electrical and image-based parameters.

Impedance Data Processing: Raw impedance data from the sensor are filtered to remove electrical noise and then averaged over multiple readings to enhance measurement stability. The system plots impedance versus time to visualize the wound's recovery curve. A decreasing impedance trend indicates improved tissue integrity, moisture balance, and collagen formation, whereas stable or increasing impedance may suggest delayed healing or infection.

Image-Based Analysis: The uploaded wound images are resized and normalized before being passed through the CNN model, which extracts spatial and color features associated with wound conditions such as redness, exudate, and tissue granulation. The trained model classifies each image into one of the wound healing stages — Inflammatory, Proliferative, or Maturation. The system then compares this classification with the impedance data trend to validate the healing stage and ensure consistency between electrical and visual indicators.

Data Visualization and Reporting: The processed data are visualized on the web dashboard through real-time charts and healing progress bars. Users can view current impedance levels, healing stage, and overall progress percentage. The data are also stored in a cloud database for historical trend analysis, allowing healthcare professionals to evaluate treatment effectiveness over time.

3.5 Safety & Calibration

Since the system directly interacts with biological tissues, safety and calibration are critical aspects of design and implementation.

Safety: To ensure safe operation, the maximum current output of the device is strictly limited to 600 µA, well below the pain threshold of human skin. The circuit includes current-limiting resistors, isolation amplifiers, and short-circuit protection mechanisms to prevent overcurrent or accidental electrical shocks. All electrodes are made from biocompatible materials such as silver or stainless steel, minimizing the risk of irritation or chemical reaction with skin tissue.

Calibration: Before application on any biological sample, the device undergoes calibration using known resistive loads (e.g., precision resistors ranging from 500 Ω to 10 kΩ) to verify accuracy in current delivery and impedance measurement. The calibration process ensures that the measured impedance corresponds correctly to known values and that the microcurrent generator maintains a consistent output level across varying loads.

Periodic recalibration is recommended to maintain measurement precision, especially when used in long-term experiments. Additionally, environmental factors such as electrode temperature and contact pressure are controlled to reduce measurement variability.

IV. Block Diagram

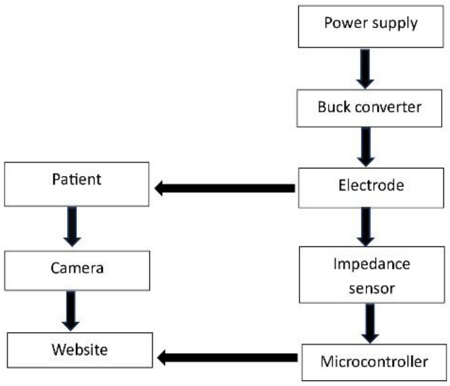

Fig 4: Block Diagram

V. Result and Discussion

The developed system was experimentally tested to evaluate the performance of the microcurrent stimulation, impedance monitoring, and AI-based wound stage classification modules. The experiments were conducted under controlled laboratory conditions using simulated biological tissue and photographic wound datasets for analysis. The results demonstrate that the proposed integrated approach effectively enhances wound healing while providing accurate, real-time monitoring of tissue recovery.

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Healing Day	**Measured Impedance (kΩ)**	**Healing Observation**	**Wound Stage (from Image Analysis)**
Day 1	9.8	Initial inflammation with open tissue	Inflammatory
Day 3	8.6	Slight reduction in redness, beginning of tissue repair	Early Proliferative
Day 5	6.9	Granulation tissue visible, moderate moisture level	Proliferative
Day 7	5.1	Reduced exudate, tissue regeneration evident	Late Proliferative
Day 9	3.7	Formation of epithelial layer, wound contraction observed	Maturation
Day 11	2.9	Almost healed surface, restored skin barrier	Healed / Maturation

were conducted under controlled laboratory conditions using simulated biological tissue and photographic wound datasets for analysis. The results demonstrate that the proposed integrated approach effectively enhances wound healing while providing accurate, real-time monitoring of tissue recovery.

5.1 Experimental Observations

The microcurrent generator delivered a controlled output current between **20 µA and 600 µA** across the wound region. The impedance of the tissue was measured daily, and the corresponding values were recorded to track the healing progression.

As healing advanced, the impedance values consistently **decreased**, indicating increased tissue hydration and collagen deposition. The impedance data was correlated with the wound's physical condition as identified by image-based analysis.

VI. Conclusion

This study presents an innovative wound healing and monitoring system that integrates DC microcurrent stimulation, impedance analysis, and smart web-based wound assessment. The results validate that microcurrent therapy enhances tissue repair and accelerates wound closure. The impedance-based monitoring provides quantitative feedback on the healing process, while the web platform enables convenient and remote wound stage evaluation. The proposed system has strong potential for clinical applications, especially for diabetic ulcers and chronic wounds, offering a cost-effective and scalable solution for modern healthcare. Future enhancements may include wireless data transmission, integration with mobile applications, and cloud-based patient tracking for telemedicine purposes.

VII. References

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