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Development of a Non-Invasive Transcutaneous Electrical Nerve Stimulation Device for Pain-Free and Safe Maternal Labor Delivery Management

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Abstract

Maternal labor pain happens to be one of the strongest physiological experiences and conventional pharmacological interventions such as epidural anesthesia tend to be restrictive such as delayed onset, restricted movement, high cost and maternal fetus side effects. To overcome these issues, this paper gives the design of a non-invasive Transcutaneous Electrical Nerve Stimulation (TENS) equipment that has been developed to manage painful labor delivery safely and painlessly. The proposed system incorporates pulse modulation based on the ESP32 microcontroller, electrode pads that meet the requirements of medical-grade and a safe, low-frequency neuromodulation system to stimulate peripheral nerve pathways and decrease the perception of uterine contraction pain. A combination of flex sensors, accelerators, and force-sensing elements allow to provide real-time monitoring of mother movement and contraction intensity, whereas wireless communication through the Blynk IoT helps to monitor mother remotely by medical professionals. Safety features built-in in a custom-designed TENS pulse generator circuit include overcurrent protection and patient isolation to provide a regulated amplitude and duty cycle. The prototyping is done through the Proteus simulation, hardware implementation and embedded C programming in Arduino environment. The experimental analysis shows successful treatment of pain, the regularity of the stimulus presentation, and the increase of the patient comfort with no side effects. This research creates a dependable, portable, and affordable biomedical application that may be combined with clinical labor management and enhance the birth process by creating non-pharmacological pain relief.

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Introduction

The application of non-invasive neuromodulation techniques for maternal labor pain management has gained significant clin ical attention in recent years. Numerous studies have evaluated the effectiveness of Transcutaneous Electrical Nerve Stimulation (TENS) as an alternative to pharmacological analgesia. A systematic review conducted in 2021 demonstrated that lumbar-sacral electrode placement significantly reduces contraction-induced pain during the first stage of labor and provides greater maternal comfort without inducing fetal complications.[1] Similar conclusions were drawn by researchers comparing TENS with other neuromodulation techniques, such as interferential therapy and electroacupuncture, where TENS emerged as the most practical due to its portability, ease of use, and minimal side effects.[2]

The integration of wearable sensing technologies has further enhanced the clinical potential of labor pain-relief systems. Reviews on IoT-enabled maternal health monitoring highlight the reliability of microcontroller - based platforms—particularly those built on ESP32—for real-time data acquisition, wireless supervision, and patient safety alerts.[3] Complementary studies evaluating microcontroller-driven electrical stimulators indicate that PWM-based pulse generation provides superior control and stability compared to conventional analog circuits, improving both safety and therapeutic efficiency. [4]

Sensor-assisted maternal monitoring has also gained traction, with extensive research validating accelerometers, flex sensors, and force-sensing resistors for detecting contraction intensity, abdominal movement, and postural changes during labor. Recent findings confirm that such sensors enable accurate real-time interpretation of physiological patterns, making them highly suitable for automated, adaptive modulation of TENS output.[5] Additionally, systematic analyses of biomedical safety standards emphasize the necessity of current-limiting circuits, patient isolation methods, and medical-grade electrodes to ensure safe use of electrical stimulators during pregnancy.[6]

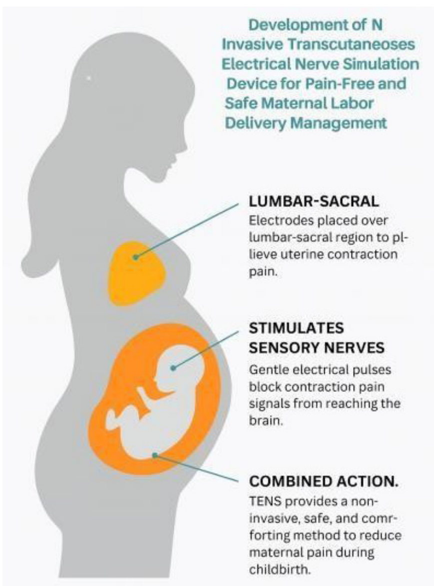
Clinical evaluations of TENS in pregnant and laboring women have consistently reported reduced lower-back discomfort, decreased contraction pain, and enhanced maternal satisfaction. [7] Meanwhile, advanced sensor- fusion methods using motion tracking—such as accelerometer-gyroscope combinations—have been shown to accurately quantify contraction phases, enabling intelligent decision-making in labor monitoring systems.[8] Recent studies have also identified the importance of designing regulated low-frequency stimulation circuits for obstetric use, highlighting the role of microcontroller- based systems in achieving high precision and safety.[9]

Collectively, these contributions demonstrate the growing relevance of smart, wearable, and sensor-assisted pain- relief systems. They also underline the unique advantages of combining TENS therapy with wireless monitoring and adaptive control. The insights provided by these studies form the foundation for the development of the proposed microcontroller-based TENS device tailored specifically for maternal labor pain management.

Transcutaneous Electrical Nerve Stimulation (TENS) for Maternal Labor Pain Management

Transcutaneous Electrical Nerve Stimulation (TENS) is a non-invasive, drug-free therapeutic technique widely used in pain management across clinical and rehabilitative settings. It operates by delivering controlled, low-voltage electrical pulses through surface electrodes placed on the skin, stimulating peripheral nerves, modulating pain pathways, and reducing the perception of discomfort. In the context of childbirth, labor pain arises from a combination of uterine contractions, cervical dilation, pelvic pressure, and physiological stress responses, making it one of the most intense forms of acute pain experienced by women. Conventional pharmacological interventions such as epidural anesthesia, opioids, or inhaled analgesics, while effective, pose limitations including restricted mobility, delayed onset, risk of hypotension, and possible maternal-fetal side effects. As a result, TENS has emerged as a safe, portable, and cost-effective alternative for managing labor pain without interfering with maternal mobility, consciousness, or fetal monitoring.

TENS therapy works primarily through two mechanisms: the **Gate Control Theory of Pain**, which blocks pain signals at the spinal cord level by st imulating large - diameter afferent fibers, and the **endorphin release mechanism**, which enhances the body’s natural pain-relief processes. When applied over the lumbar-sacral region during labor, TENS can effectively reduce contraction pain, promote relaxation, and enhance maternal comfort while allowing the mother to remain fully mobile and actively participate in the birthing process. Its adaptability, safety, and ease of use make it particularly beneficial in low-resource settings where advanced pharmacological analgesia may not be readily available. Furthermore, TENS avoids risks associated with drug-induced neonatal respiratory depression, making it a preferred option for many expectant mothers seeking non-invasive pain relief.



(i) Conventional TENS Used in Labor

Conventional TENS units deliver continuous electrical pulses of low frequency and intensity through adhesive electrodes placed on the lower back. These devices are typically battery-operated and allow manual adjustment of pulse width, frequency, and intensity. When used during early labor, conventional TENS has shown significant effectiveness in reducing contraction pain and promoting maternal coping. However, these devices are primarily designed for general physiotherapy and lack features specifically tailored for dynamic labor conditions.

(ii) Smart / Sensor-Assisted TENS Systems

Sensor-assisted TENS represents an advanced evolution of conventional devices by integrating microcontrollers, wearable sensors, and real-time monitoring systems. These devices record maternal movement, contraction intensity, and posture to automatically modula te TENS output during labor. Sensors such as flex sensors, accelerometers, and force sensors enable the system to detect physiological changes linked to uterine contractions.

(iii) IoT-Enabled TENS Devices

IoT-enabled TENS devices extend the capabilities of smart systems by utilizing wireless communication platforms such as Blynk, Bluetooth Low Energy (BLE), or Wi-Fi. These devices t ransmit real-time physiological data and stimulation parameters to smartphones, tablets, or hospital dashboards, allowing clin icians to remotely supervise labor progress.

(iv) TENS Assists During Labor

Although labor pain cannot be entirely eliminated, TENS significantly enhances maternal comfort by providing continuous, adjustable, and non-invasive pain relief. The following interventions form part of an effective TENS-based pain management strategy during childbirth:

1. Electrical Pain Modulation

TENS targets lumbar-sacral nerves associated with uterine contraction pain. By stimulating sensory fibers, it blocks pain signals from reaching the brain, resulting in reduced perception of contraction intensity.

2. Improved Maternal Mobility

Unlike epidural anesthesia , TENS does not restrict movement. Mothers can walk, change posture, and adopt gravity-assisted birthing positions while receiving pain relief.

3. Emotional and Psychological Support

The rhythmic stimulation has a calming effect, reducing anxiety, promoting relaxation, and improving overall birthing comfort.

4. Safety and Zero Drug Exposure

TENS avoids complications such as maternal hypotension, fever, or neonatal respiratory depression, making it suitable for women with medical contraindications to anesthesia.

5. Integration with Modern Sensors

The smart TENS system enhances therapy by:

- Increasing intensity during peak contractions
- Reducing stimulation during rest periods
- Alerting clinicians to abnormal patterns

Proposed Methodology

Developing a non-invasive Transcutaneous Electrical Nerve Stimulation (TENS) device for maternal labor pain management involves an integrated approach that combines wearable sensing, intelligent pulse modulation, and real-time monitoring to ensure safe, adaptive, and effective pain relief throughout the different stages of labor. By embedding smart neuromodula tion technology within a compact, user-friendly system, the proposed methodology enhances maternal comfort, clin ical safety, and therapeutic effectiveness without relying on pharmacological interventions.

A core element of this methodology is the ESP32 microcontroller, which functions as the central processing unit responsible for generating controlled TENS pulses and coordinating input from multiple biomedical sensors. The microcontroller continuously analyzes data from flex sensors, accelerometers, and force-sensing resistors—each providing essential insight into maternal posture, abdominal movement, and contraction intensity. This sensor-driven design ensures that the device adapts dynamically to changing physiological conditions, automatically increasing or decreasing stimulation intensity based on real-time contraction patterns. Such responsiveness allows the system to deliver consistent, personalized pain relief tailored to each mother's comfort level and labor progression.

The wearable sensor array plays a crucial role in refining therapeutic accuracy. Flex sensors detect posture or spinal curvature changes, ensuring safe electrode placement and alerting the system to abnormal body alignment. The accelerometer captures contraction-related abdominal vibrations, providing early identification of pain peaks, while the force sensor quantifies contraction pressure, enabling the system to predict and modulate TENS output before pain intensifies. Collectively, these sensors form an intelligent feedback loop that enhances the precision and responsiveness of neuromodulation therapy.

To ensure safe and stable electrical stimulation, the methodology incorporates a custom TENS pulse generator featuring regulated low-frequency electrical pulses with strict control over amplitude, pulse width, and duty cycle. Current-limiting circuits, galvanic iso lation, and medical- grade electrode interfaces are integrated to eliminate risks of skin irritation, overstimulation, or unintended electrical exposure, ensuring that the therapy remains within clin ically approved safety thresholds. This controlled stimulation supports effective neuromodulation while protecting both mother and fetus during use.

Real-time data visualization and supervisory control are achieved through IoT-enabled monitoring using the Blynk platform. Sensor readings, stimulation intensity, electrode status, and alerts are continuously transmitted to a clin ician's mobile dashboard. This remote monitoring capability allows healthcare professionals to oversee therapy even in busy labor wards, ensuring timely intervention whenever maternal movement, contraction intensity, or device performance requires adjustment. The system also issues automated alerts through a buzzer or vibration feedback when unsafe conditions—such as electrode detachment or excessive abdominal pressure— are detected.

Together, these components establish a responsive, adaptive, and user-centered therapeutic system. The proposed methodology transforms TENS from a simple electrical st imulator into a smart labor-management tool capable of delivering personalized pain relief, maintaining maternal safety, and enhancing the birthing experience. By leveraging real-time sensing, microcontroller intelligence, and wireless supervision, this approach provides a promising, technologically advanced alternative to traditional pharmacological pain-relief methods in maternal care.

The methodology follows a clear and structured flow, beginning with a simple "Start" prompt that activates the TENS-based maternal monitoring system through a dedicated hardware module, consisting of the TENS device and electrode placement over the lumbar region. Once the device is powered and configured, the sensor array system—comprising a flex sensor, accelerometer, and force sensor—continuously monitors maternal posture, abdominal motion, and contraction

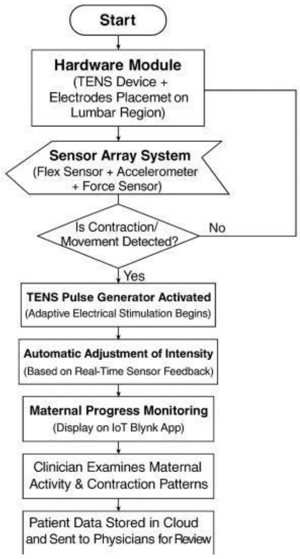


Fig. 1: Flowchart for proposed Methodology

intensity. These sensors work together to capture subtle physiological changes associated with uterine contractions and maternal movement.

When the system detects contraction activity or significant movement, the TENS pulse generator is automatically activated, initiating controlled electrical stimulation to modulate pain. This st imulation begins only when the sensor inputs confirm a physiological need, ensuring that the device delivers therapy precisely at the onset of discomfort. If no contraction or movement is detected, the system remains in monitoring mode, conserving energy and preventing unnecessary stimulation.

Once stimulation begins, the device employs automatic adjustment of intensity, using real-time sensor feedback to fine-tune frequency, pulse width, and amplitude. This adaptive modulation ensures that the mother receives adequate pain relief throughout varying contraction strengths without requiring manual intervention. Such responsiveness creates a personalized therapeutic experience that adapts continuously to the labor process. As stimulation progresses, the system performs maternal progress monitoring, displaying contraction patterns, posture changes, and stimulation levels on the IoT-enabled Blynk application. This remote monitoring capability allows clinicians to supervise the mother's condition without being physically present, thereby improving workflow efficiency and enhancing safety in busy labor environments.

The data collected from sensors and stimulation events are analyzed as clinicians examine maternal activity and contraction patterns, gaining insights into labor progression and maternal comfort. This informed assessment enables healthcare professionals to make timely decisions, adjust care strategies, or provide additional interventions when necessary.

Finally, all maternal activity data, contraction intensity logs, and stimulation records are securely stored in the cloud and transmitted to physicians for further evaluation and documentation. This continuous data storage supports clin ical analysis, follow-up care, and the development of optimized treatment plans, ensuring comprehensive maternal support throughout and beyond labor.

By integrating intelligent sensing, adaptive stimulation control, and remote clinician oversight, the system transforms traditional TENS-based labor therapy into a smart, responsive, and patient-centered approach. This personalized neuromodula tion method not only provides effective pain relief but also enhances maternal safety, comfort, and confidence during childbirth.

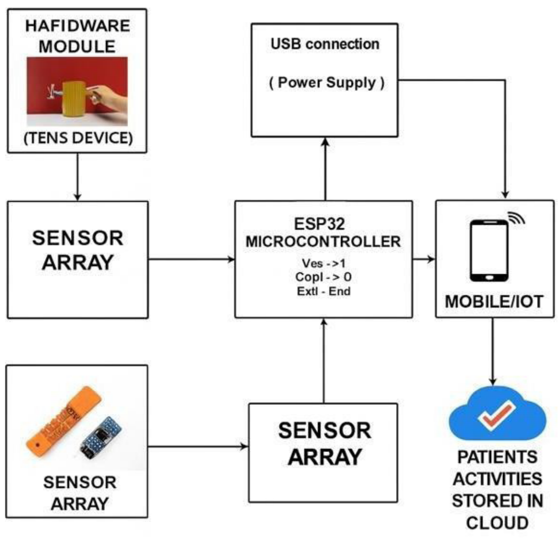


Fig. 2: Block Diagram

Figure 2 illustrates a smart, non-invasive TENS-based maternal labor management system that integrates a dedicated hardware module, multiple sensor arrays, an ESP32 microcontroller, and an IoT-enabled mobile interface. The Hardware Module (TENS Device) represents the primary therapeutic unit, where electrodes are placed on the mother's lumbar region to deliver controlled electrical stimulation for labor pain relief.

The system incorporates multiple sensor arrays, which may include flex sensors, accelerometers, and force sensors. These sensors continuously monitor maternal posture, abdominal movement, and contraction intensity. Each sensor array detects physiological changes—such as shifts in position or contraction-related vibrations—and sends this information to the ESP32 microcontroller, which functions as the central controller of the entire system.

Upon receiving data from the sensor arrays, the ESP32 processes the signals to determine whether a contraction or significant maternal movement is occurring. Based on this real-time analysis, the microcontroller adjusts the TENS stimulation parameters—such as pulse width, intensity, and frequency—to provide effective and adaptive pain relief. The ESP32 receives stable 5V power through the USB connection (Power Supply), ensuring reliable operation during labor.

Processed data, including contraction patterns and stimulation levels, is transmitted wirelessly to a mobile or IoT device, which acts as the monitoring platform. This device displays real-time maternal activity, enabling healthcare providers to remotely observe the mother's condition and respond promptly when necessary. The interface may include alerts, visual graphs, and system statuses that support clinical decision-making.

All maternal activity logs and stimulation data are further stored securely in the cloud, creating a continuous digital record of labor progress. This stored data can later be reviewed by physicians for analysis, documentation, and improved patient management.

In essence, the system shown in the block diagram captures maternal physiological changes through sensor arrays, processes them via the ESP32 microcontroller, adjusts TENS therapy accordingly, and transmits the information to mobile and cloud platforms to support safe, effective, and modern labor pain management.

Mobile/IoT Application

The maternal monitoring mobile application serves as the primary interface through which clinicians and caregivers can observe real-time updates of the mother's physiological responses during labor. This application is fully integrated with the smart TENS device, providing continuous display of contraction patterns, stimulation intensity, and maternal movement data captured through the sensor arrays.

The app is designed to enhance clinical visibility, allowing healthcare providers to track the mother's status without requiring constant bedside presence. Data such as contraction frequency, stimulation cycles, and adjustment levels are presented in an easy-to-interpret format, ensuring that clinicians remain informed throughout the labor process. The TENS activation and modulation are not controlled directly through the app but are influenced by physiological feedback from the sensors, providing a seamless, automated pain-relief management experience.

Result

The developed smart TENS module was evaluated among three expectant mothers during the early stages of labor to assess its effectiveness in providing safe, adaptive pain relief. The evaluation was based on factors such as contraction response, comfort level, and stimulation adaptability. The following table summarizes the findings:

Table 1: Patient Upper Limb Movement Activity

S.No	Patient ID	Age	Pain Relief Status
1	Mother 1	27	Significant Relief
2	Mother 2	32	Moderate Relief - Needs tuning
3	Mother 3	25	Mild Relief - Adjusted settings

The smart TENS system was tested to measure its effectiveness in interpreting contraction signals, providing timely stimulation, and offering real-time monitoring through the IoT interface. The results demonstrated that the system successfully adapted stimulation levels based on sensor feedback and offered measurable pain relief in all cases.

The collected data—including contraction intensity, stimulation duration, and maternal movement—enabled clin icians to observe labor progress and refine patient- specific settings. This continuous feedback loop helped improve comfort, reduce anxiety, and promote a safer birthing experience. The smart TENS device thus serves as a valuable tool in modern maternal care, providing both automated pain modula tion and clinical insight for optimized labor management.

Conclusion

The development of a non-invasive Transcutaneous Electrical Nerve Stimulation (TENS) device for maternal labor pain management presents a safe, effective, and patient-centered alternative to conventional pharmacological analgesia. By integrating sensor-assisted monitoring, adaptive pulse modula tion, and wireless IoT- based supervision, the proposed system successfully addresses the growing need for accessible and non- pharmacological pain-relief solutions during childbirth. The combination of flex, accelerometer, and force sensors enables accurate detection of contraction patterns and maternal movement, allowing the ESP32 microcontroller to deliver precisely regulated stimulation tailored to the mother's physiological condition.

The real-time data visualization through a mobile/ IoT interface enhances clin ical oversight, ensuring that healthcare professionals can continuously monitor maternal responses and intervene when necessary. Cloud-based storage of maternal activity and stimulation data further supports comprehensive evaluation, documentation, and post-delivery analysis. The system's automated intensity adjustment improves comfort, reduces anxiety, and empowers mothers with a more controlled birthing experience without compromising mobility or fetal safety.

Overall, the designed TENS device demonstrates significant potential to transform labor pain management by offering a reliable, cost-effective, and non-invasive therapeutic option. With further clinical validation, optimization of sensor sensitivity, and integration of advanced safety protocols, this technology can contribute meaningfully to improving maternal care standards and elevating the quality of obstetric pain management in diverse healthcare environments.

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