Design and preliminary evaluation of a facial EMG–TENS wearable platform for trigeminal neuralgia therapy

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KEYWORDS

Trigeminal Neuralgia,
EMG,
sEMG,
TENS,
Instrumentation Amplifier,
Gold-coated Electrodes.

ABSTRACT

Trigeminal neuralgia (TN) is a severe facial pain condition characterized by unpredictable, electric shock-like episodes that are hard to assess continuously outside clinical settings. This study presents the design and preliminary validation of a skin-conformal facial electromyography (sEMG) wearable capable of identifying neuromuscular activity associated with TN and delivering transcutaneous electrical nerve stimulation (TENS) for pain relief. The system integrates flexible gold-coated electrodes, a low-noise instrumentation amplifier, and a high-resolution delta-sigma ADC (ADS1115) interfaced with an ESP32 for real-time acquisition, processing, and wireless data transfer. Initial recordings from facial muscle sites demonstrated consistent EMG bursts in the microvolt-to-millivolt range, confirming an adequate signal-to-noise ratio for activity detection. The measurement chain preserved dynamic range without saturation, with residual noise originating mainly from low-frequency drift and mains interference—issues that will be addressed through improved filtering and biasing in future revisions. The platform enables closed-loop operation by triggering TENS based on EMG-derived features to anticipate or suppress TN pain events. Future development involves upgrading to an ADS1299-based, multi-channel front end with dry, conformal electrodes to enhance noise performance, comfort, and scalability. Overall, the proposed system demonstrates feasibility for continuous, home-based TN monitoring and adaptive stimulation, representing a step toward personalized, responsive neuromodulation for facial pain management.

1. Introduction

Trigeminal neuralgia (TN) is a chronic neuropathic disorder causing sudden, unilateral, electric shock-like pain along one or more branches (V1, V2, V3) of the trigeminal nerve (Lambru et al., 2021; Zakrzewska & Linskey, 2014; Kikkeri & Nagalli, 2014). These attacks are short-lived, lasting from fractions of a second to two minutes, but can occur in rapid bursts with pain-free intervals in between. TN severely limits everyday activities such as eating, speaking, and facial care, and contributes to psychological distress, including anxiety, depression, and suicidality in severe cases.

Classical TN usually stems from neurovascular compression of the trigeminal root entry zone, leading to focal demyelination and abnormal ephaptic transmission, most often involving the superior cerebellar artery. Secondary TN can arise from multiple sclerosis, tumors, or vascular malformations affecting the same nerve region. The underlying mechanisms combine peripheral and central factors, including demyelination, ectopic excitation, and central sensitization. Pain episodes are typically triggered by harmless stimuli such as touch, wind, chewing, or shaving, though they can also occur spontaneously. Patients often develop hypersensitive “trigger zones” on the face, complicating daily functioning.

Epidemiologically, TN affects women more frequently and typically manifests between ages 50–60, with an incidence of roughly 10 per 100,000 people annually. Its symptoms — sudden, stabbing facial pain and avoidance behaviors — strongly impact nutrition, social interaction, and quality of life.

This study aims to improve TN management by creating a wearable device that monitors facial

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muscle activity and activates safe TENS therapy in real time. The system seeks to enhance pain control, reduce medication dependency, and record trigger dynamics for improved clinical insight.

2. Methodology

The proposed TN wearable system integrates conformal sEMG sensing, low-noise analog amplification, digital conversion, wireless communication, and a charge-balanced TENS module within a biocompatible, compact design meeting relevant medical safety standards (Lee et al., 2020; Farnsworth et al., 2008; Kim et al., 2011; Imtiaz et al., 2013; Yang et al., 2020; International Organization for Standarization, 2018; International Electrotechnical Commission, 2015; International Organization for Standardization, 2019; Bertozzi et al., 2020).

2.1 Electrode and skin interface

Flexible gold or carbon–based dry electrodes embedded in PDMS/PU layers provide reliable adhesion, reduce motion artifacts, and allow long-duration wear with comfort. Gold-coated PDMS electrodes are favored for their low impedance, corrosion resistance, and ability to conform to facial curvature, ensuring high-quality signal capture during expressions and speech.

2.2 Analog Front-End (AFE)

To detect low-amplitude sEMG signals, the analog front end employs a high-performance instrumentation amplifier featuring high input impedance (≫100 GΩ), CMRR above 100 dB, and low noise. Guarded inputs and half-cell potential biasing preserve signal integrity before filtering and digitization.

A band-pass filter (10–500 Hz) retains essential EMG content while minimizing drift and high-frequency noise. A notch filter removes 50/60 Hz interference typical in indoor settings. A multiple-feedback architecture is used instead of Sallen–Key for improved noise rejection and stage isolation.

2.3 Data conversion and processing

Signal digitization is performed using a 24-bit delta-sigma ADC with programmable gain, providing high-resolution acquisition with minimal quantization error. The ESP32 processor performs lightweight real-time analytics (RMS amplitude, burst metrics, zero-crossing rate, spectral features) and communicates data via BLE/Wi-Fi to a companion mobile application for visualization and clinician-configurable alerts.

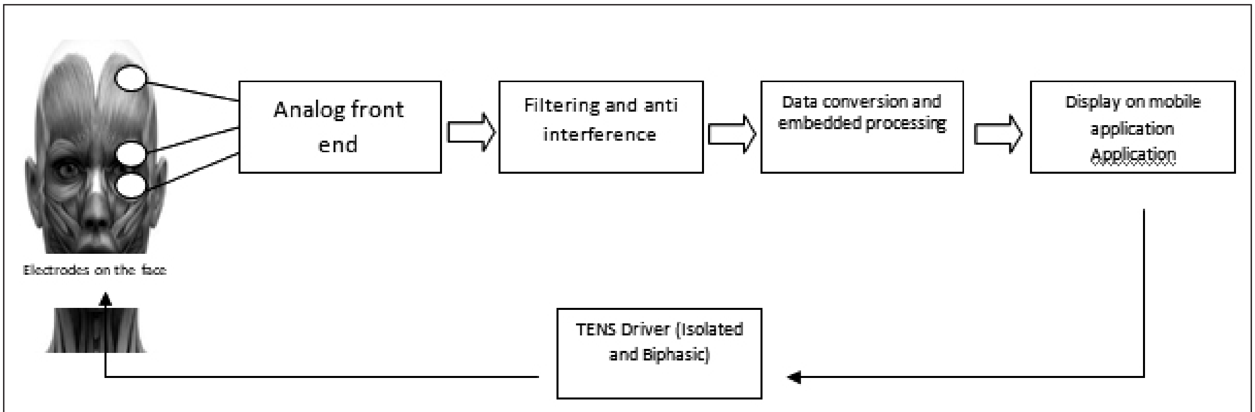
Bluetooth Low Energy (BLE) enables efficient real-time streaming with low energy consumption via intermittent data buffering. A Li-ion battery (250–620 mAh) and power regulation support up to 16 hours of operation, depending on sampling rate and the number of active channels.

2.4 Facial placement and signal validation

Tests with facial sEMG masks demonstrated that localized muscle activations can be reliably recorded and discriminated, validating the usefulness of the system for TN-related zone mapping. Though the system remains noninvasive, its design parameters reflect those of implantable EMG systems to maintain adequate bandwidth (~1 kHz) and low noise.

2.5 TENS stimulation and control

The integrated stimulator provides biphasic, charge-balanced, current-controlled pulses



Block diagram (signal path and actuation) through electrodes near identified trigger regions to minimize skin irritation and ensure electrical safety. Clinical findings suggest that TENS at around 100 Hz for 20-minute sessions can reduce TN pain and drug dependence. The proposed system allows preset safe stimulation parameters (80–120 Hz, 50–250 µs) with session limits, ramp-up and lockout features, ensuring comfort and preventing overstimulation. Stimulation data are logged for later correlation with pain relief outcomes.

2.6 Standards and safety

The device targets Class B medical risk compliance, adhering to relevant standards in quality systems, EMC, biocompatibility, and rechargeable battery safety. Skin-contact materials and adhesives follow ISO-guided biocompatibility practices.

2.7 Design rationale

Dry gold electrodes offer better comfort and lower setup time than wet electrodes, encouraging daily home use. The selected amplifier and filter topology ensure stable, clean sEMG capture with low power consumption. On-device analytics and BLE connectivity balance responsiveness and battery life, while the TENS stage provides clinically safe, adjustable stimulation.

3. Preliminary Signal Acquisition and Characterization

Initial data collection utilized single-use Ag/AgCl electrodes connected to an ADS1115 ADC at high gain, interfaced to an ESP32 via SPI. Calibrated voltage traces revealed facial EMG signals of tens of microvolts to a few millivolts, consistent with standard facial EMG amplitudes. The burst-like waveform profiles exhibited distinguishable activation phases suitable for trigger detection.

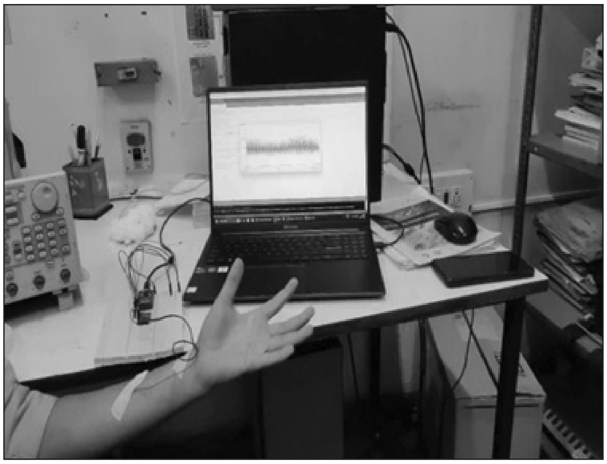


Fig. 1. EMG readings being taken at relaxation.

Fig. 2. EMG readings being taken at flexion.

Cycle 1: Here the electrodes were placed on the forearm region and voltage values were acquired at different times during the trials when the arm was under flexion and relaxation.

Cycle 2: Here single use AgCl electrodes were places on the subjects face. The Initially the electrodes were placed, at the terminal ends of the mascater muscle and reference electrodes was places near the jaw on a hard boney surface. Later the positions were changed to measure forehead muscle movement

4. Results

Cycle 1(fist) was successful and the output was in tandem with the methodological output expected.

The figure 3 shows the resultant graph obtained in cycle 1:

- Region “a” is about 20 seconds long and was used to establish a set of baseline readings.

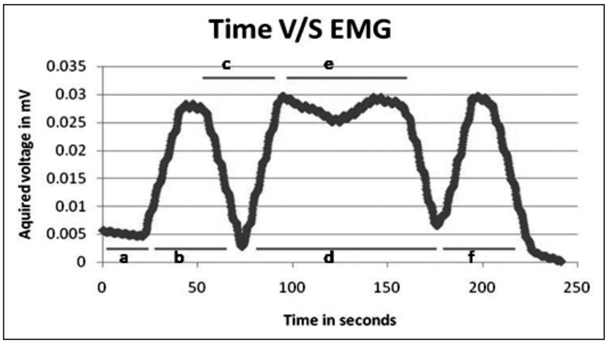


Fig. 3. Resultant graphs of time VS voltage for fist EMG (Cycle 1).

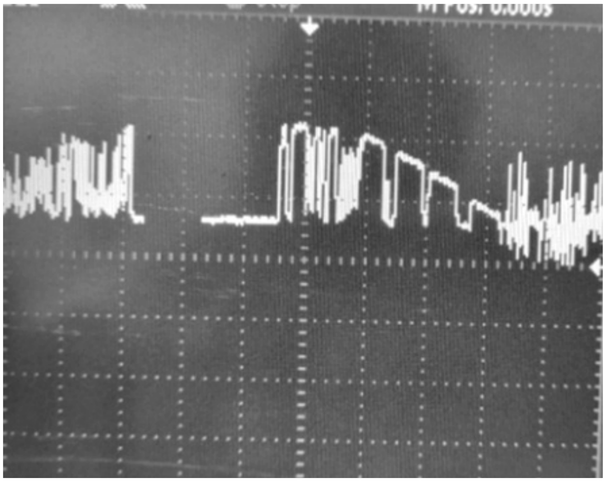


Fig. 4. Output from cycle 2.

- Region "b" is about 25 seconds long, and was acquired at the time of slow flexion and slow extension.
- Region "c" lasts for about 25 seconds, where slow flexion was observed and recorded.
- Region "d" and "e" lasted about 100 seconds, where the subject partially extended the muscle of interest.
- Region "f" lasted about 25 seconds, where the subject for the last time extended his fist.

The facial cycle was not in according to the methodological expectation. There was almost no correlation with the signal that was observed. This can be attributed to the very low magnitude of voltage of the face muscles, insufficient gain at the amplification stage or inaccurate electrode placement. Future versions will adopt an ADS1299 multichannel biopotential ADC to enhance noise performance, synchronous multi-site sampling, and integration. The new configuration will reduce external components, improve noise floor, and support refined trigger detection for responsive closed-loop stimulation.

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