Novel Feedback Stabilized Framework in Transcutaneous Electrical Nerve Stimulation for Clinically Stable Chronic Pain Relief

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Abstract

Transcutaneous electrical nerve stimulation (TENS) is a widely used method of pain management. However, its clinical efficacy is often viewed as controversial due to research lacking consistently reported stimulation parameters. This inconsistency in stimulation is caused by the fact that the skin-electrode interface has unpredictably variable impedances that reduce the accuracy of stimulation intensity. Research in adjacent fields present successful use of active feedback control as a method of stimulation stabilization. This proposal aims to outline the potential to implement a novel feedback control system in TENS stimulation as a method of actively negating inconsistencies in the skin-electrode interface and is hypothesized to maintain a more stable stimulation delivery under variable conditions.

Introduction

Transcutaneous Electrical Nerve Stimulation (TENS) is a method of nerve stimulation that can help regulate chronic pain by targeting type Aβ and Aδ fibers in a non-invasive manner. TENS generally contains stimulation parameters that can be adjusted by the user during a session. Conventionally, TENS is used in the 50 - 100hz range with “just below noxious” intensity to trigger subcutaneous opioid production and provide relief (Sluka & Walsh, 2003). While TENS has been seen to be beneficial to many patients, its clinical efficacy is controversial due to current research failing to report consistent stimulation parameters (Patel et al., 2025). This inconsistency in research makes it difficult to replicate many research findings, causing them to be difficult to clinically validate. Most inconsistencies in TENS stimulation stem from the variance and unpredictability within the skin-electrode interface, being the direct cause for inconsistent activation (Vargas et al., 2015). While direct control of skin impedance is difficult to actively regulate, this proposal aims to evaluate the efficacy of using active feedback current control in TENS and answer the question: To what extent does active feedback control enhance the stability of TENS therapy in variable skin conditions relative to an open loop system?

Literature review

The skin-electrode interface has been shown to be an immensely variable component in electrical stimulation devices. In a research study conducted by Iftime et al. (2025), it was concluded that there were at least 40 independent factors affecting skin impedance during stimulation at any given moment. This introduces many discrepancies in the current traveling through the skin-electrode interface, which has been linked to risk of burns, rashes, and ineffective stimulation (Keller & Kuhn, 2008).

While Patel et al. (2025) state that adaptive controls will be beneficial for electrical therapy, it has yet to be implemented in modern designs. However, it is important to note that active feedback current control has already been implemented and successful in neuro-muscular stimulation devices (Lustenberger et al., 2016). While these devices achieve different objectives than TENS, the same principles can be aligned across domains to ensure constant current delivery under variable conditions and resultingly, a more stable therapy experience. Building on the data from Lustenberger and Patel, the success of feedback-controlled TENS therapy can be hypothesized.

While current research recognizes the restriction of impedance variability, its implications on modern TENS therapy is minimally supported with direct experimentation under variable conditions introducing the need for novel research and development to optimize stability.

Methodology

The aim of this study is to compare the performance of a feedback-controlled TENS stimulator to a traditional open loop system. Both stimulators will be evaluated under multiple variations of simulated skin interfaces to determine if active feedback control improves stimulation accuracy. To accurately replicate the nuanced behavior of human skin, a dynamic impedance model will be used, as skin impedance is known to be variable and non-linear (Vargas et al., 2015).

The study will be conducted using an STM32 microcontroller-based TENS unit with custom loaded firmware capable of switching between both closed (active) and open loop (disabled) control. The circuitry uses synchronized timer interrupt requests to generate a biphasic signal using a dual H-bridge driver and a shunt resistor to allow for precisely timed analog-to-digital conversions (ADC). Using the feedback data from the ADC, the STM32 will then actively adjust the phase width of the stimulation wave without changing its frequency, effectively tuning the duration of fiber activation.

Both stimulators will be placed on identical skin impedance models with an initial target current to be administered through the skin. Stimulators will be evaluated under both fixed and variable impedance conditions. The study will consist of constant load tests and variable load tests. Fixed impedance testing will be used to establish a baseline deviation for both stimulators. Variable load tests will use a potentiometer to create controlled step disturbances that emulate unpredictable changes in skin impedance over time. Each test condition will be repeated multiple time to lessen the impact potential random bias. Furthermore, each run will be conducted over a fixed period of time to sufficiently capture active response.

A multimeter and oscilloscope will be used to measure and log waveform characteristics with respect to time. By using the multimeter and oscilloscope logs, the mean (accuracy), standard (stability) and maximum (worst-case error) deviation of both stimulators will be calculated. Findings will reveal insight on the efficacy of feedback-controlled TENS against open loop therapy.

Conclusion

It is expected that the active feedback control stimulator will result in a much lower deviation when compared to the open-loop system under variable conditions. These findings will allow for future research to be conducted with accurate and consistent stimulation parameters, while also ensuring that future patients receive more effective and safe therapy. Future work may aim to extend experimentation to human trials to evaluate further optimizations to the control algorithm. To recapitulate, this research contributes to the future applications of TENS by allowing for inconsistencies to be mitigated in future therapy.

References

Iftime, A., Scheau, C., Babeș, R.-M., Ionescu, D., Periferakis, A., & Călinescu, O. (2025). Confounding Factors and Their Mitigation in Measurements of Bioelectrical Impedance at the Skin Interface. *Bioengineering*, *12*(9), 926. https://doi.org/10.3390/bioengineering12090926

Keller, T., & Kuhn, A. (2008). Electrodes for transcutaneous (surface) electrical stimulation. *Journal of Automatic Control*, *18*(2), 35–45. https://doi.org/10.2298/jac0802035k

Lustenberger, C., Boyle, M. R., Alagapan, S., Mellin, J. M., Vaughn, B. V., & Fröhlich, F. (2016). Feedback-Controlled Transcranial Alternating Current Stimulation Reveals a Functional Role of Sleep Spindles in Motor Memory Consolidation. *Current biology: CB*, *26*(16), 2127–2136. https://doi.org/10.1016/j.cub.2016.06.044

Patel, P., Green, M., Tram, J., Wang, E., Murphy, M., Abd-Elsayed, A. a, & Chakravarthy, K. (2025). Latest Advancements in Transcutaneous Electrical Nerve Stimulation (TENS) and Electronic Muscle Stimulation (EMS): Revisiting an Established Therapy with New Possibilities. *Journal of Pain Research*, *18*(0), 137–153. https://doi.org/10.2147/JPR.S493162

Sluka, K. A., & Walsh, D. (2003). Transcutaneous electrical nerve stimulation: Basic science mechanisms and clinical effectiveness. *The Journal of Pain, 4*(3), 109–121. https://doi.org/10.1054/jpai.2003.434

Vargas Luna JL, Krenn M, Cortés Ramírez JA, Mayr W (2015) Dynamic Impedance Model of the Skin-Electrode Interface for Transcutaneous Electrical Stimulation. PLoS ONE 10(5): e0125609. https://doi.org/10.1371/journal.pone.0125609