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May 28, 2025

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This research was conducted as part of the ExploraVision 2024 Challenge with results unknown at the time of publication. As a scientific proof of concept towards the advancement of academia rather than a business proposal of the same topic which was worked on in a group setting, there are no conflicts of interest to declare as I am the sole contributor in this regard of literature.

Smart Pain Intervention via Neuromuscular Engineering (SPINE): Novel Integration of EMG Sensing and TENS Stimulation for Adaptive Lower Back Pain Management

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Authors Note

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Abstract

This paper proposes a novel device with a specialized design that transforms lower back pain management through the integration of real-life electromyography (EMG) sensing with transcutaneous electrical nerve stimulation (TENS). In theory, it serves to completely eliminate the need for manual operation by automatically detecting muscle spasms and delivering instant target pain relief. As a hands-free, on-demand solution, its discreet and ergonomic design enables users to manage their pain seamlessly while not inhibiting their daily activities, overcoming the limitations of traditional devices on the market. This device is truly set apart by its innovative integration of proven technologies with adaptability and novel algorithms, overall ensuring precise and effective relief. A breakthrough in wearable health technology, this device has the potential to improve the quality of life for millions and pave the way for future advancements in non-invasive pain management.

Present Technology

Transcutaneous Electrical Nerve Stimulation (TENS) is the most widely used method for managing musculoskeletal pain. It works by delivering low-voltage electric pulses through adhesive electrodes placed on the skin, stimulating sensory nerves to modulate pain perception. This mechanism is based on the gate control theory of pain, which suggests that non-painful stimuli can interfere with the transmission of pain signals to the brain, effectively reducing discomfort (Vijay Kumar Malesu). Additionally, TENS promotes the release of endorphins, the body's natural pain-relieving chemicals, enhancing its effectiveness as a non-pharmacological pain management tool (Mayo Clinic). Its dual-action mechanism makes it an attractive option for individuals seeking drug-free relief from conditions like lower back pain.

Commercial TENS devices, such as the Omron Max Power Relief, AUVON Dual Channel TENS Unit, and PowerDot 2.0, offer varying features tailored to user needs. These devices typically allow users to adjust parameters like intensity, frequency, and duration of stimulation, providing personalized pain relief. Newer models, like the PowerDot 2.0, incorporate wireless connectivity for greater convenience, although manual adjustments are still required (Proto-Electronics). Despite these advancements, TENS remains a practical and accessible solution for pain management, widely adopted in both clinical and home settings. Its simplicity, effectiveness, and ease of use continue to support its popularity in the market.

Electromyography (EMG) is a diagnostic technique that measures the electrical activity produced by skeletal muscles, using electrodes placed on the skin or inserted into muscle tissue to capture signals generated during muscle contraction and relaxation. These signals provide critical insights into muscle and nerve health, aiding in the diagnosis of conditions like

neuropathy, muscular dystrophy, and chronic pain syndromes, as well as monitoring real-time muscle activity for rehabilitation and biofeedback applications (Proto-Electronics). Currently, artificial intelligence (AI) is being explored to enhance EMG signal analysis, with machine learning algorithms capable of processing large datasets to identify subtle variations that may indicate early signs of muscle fatigue, stress, or neurological disorders (Donges). While some advanced models have shown promise in distinguishing between normal and abnormal EMG patterns, such as differentiating muscle activity during simple tasks like sitting versus standing, the integration of AI into EMG analysis remains in its early stages. Challenges such as biological variability between individuals, limited diverse training datasets, and the complexity of interpreting dynamic muscle signals continue to limit the full development of AI-driven, real-time predictive muscle monitoring.

History

In the late 18th century, Luigi Galvani conducted experiments on bioelectricity. Through discovering “animal electricity,” he proved the correlation between electrical signals on nerves and affected muscle groups (Vance). By the early 19th century, doctors like Michael Faraday and Guillaume Duchenne started using both direct and alternating currents to treat neurological disorders (Becerra-Fajardo). They were likewise convinced that controlled electrical stimulation could help restore nerve function and alleviate pain. A vital figure in shaping the current TENS market, Duchenne created early versions of electrodes which, although lacking accuracy, paved the way for modern devices that maintain the original structure and overall functionality (Chircov).

Establishing the foundational basis for TENS, Ronald Melzack and Patrick Wall in the 1960s proposed the Gate Control Theory of pain. This showed that the spinal cord has a neural "gate" that regulates the flow of pain signals to the brain (Mayo Clinic). In short, non-painful stimuli, like electrical impulses, were postulated to effectively "close" this gate and hence block said pain. As previously mentioned, this led to the first modern TENS device in the late 1960s by Dr. C. Norman Shealy. He was a neurosurgeon looking for an alternative to narcotic painkillers for patients suffering from chronic pain (Khan). Shealy's initial prototype was a large device that needed to be applied directly by a clinician. However, despite its size, it showed high promise for pain relief, leading to even further developments. The advancements in electronic component miniaturization by the 1970s allowed for battery-operated and wearable TENS units, increasing the device's accessibility and usage. It was within this period that the FDA first approved these devices, solidifying TENS as a recognized method for pain management (Karvinen). Since the 1980s, companies such as Omron, iReliev, and AUVON have brought TENS units to the consumer market. With high variability and configurations, they have been met with overwhelming support (Proto-Electronics). However, despite these enhancements, the fundamental operation of TENS devices has not changed much over the years.

Future Technology

This device represents the pioneer of the next generation of devices that will be fully autonomous, adaptive, and capable of real-time pain management. Focusing on one of its aspects, current adhesive electrodes often degrade over time, resulting in inconsistent conductivity and requiring frequent replacement. It will overcome these limitations by utilizing biocompatible, flexible electrodes constructed from polydimethylsiloxane (PDMS) embedded with silver nanowires (AgNWs) and graphene-based conductive hydrogels. This ensures superior

electrical conductivity while simultaneously maintaining flexibility and long-term durability. The electrodes will feature self-healing hydrogel technology incorporating polyvinyl alcohol (PVA) and borate crosslinkers, allowing automatic repair of minor damage. The goal is to extend usability and minimize user intervention. Additionally, to enhance comfort, this will integrate microfluidic cooling channels lined with thermoresponsive polymer coatings that dynamically regulate temperature and prevent localized overheating.

In addition, the device will implement deep learning models, bringing us closer to the goal of adaptive and personalized neuromodulation. This includes recurrent neural networks (RNNs) and transformer-based architectures for real-time analysis of EMG signals. Utilizing high-resolution dry capacitive electrodes, the algorithm will continuously monitor neuromuscular activity and detect muscle contractions. However, unlike conventional AI approaches, it will employ neuromorphic computing, leveraging memristor crossbar arrays to perform low-power AI inference directly on the device, increasing accuracy compared to traditional methods. This architecture enables rapid detection and response to muscle spasms while minimizing energy consumption. The closed-loop control system, driven by adaptive Bayesian optimization, will dynamically adjust pulse width, frequency, and amplitude based on real-time feedback. Hence, the concept will ensure optimal pain relief while mitigating the risk of neural adaptation and desensitization.

Within the realm of enhanced efficacy, it will integrate multi-limb neuromodulation through a distributed network of flexible printed circuit boards (FPCBs) embedded with EMG sensor arrays. Although currently applied to lower backs, this would enable the technology to expand to manage pain in areas such as the upper legs and arms. These sensors will be positioned along key muscle groups, including the lumbar, quadriceps, and gastrocnemius regions, enabling

synchronized pain relief. The device will employ microelectromechanical systems (MEMS) actuators to facilitate real-time signal propagation and enhance neuromuscular coordination. This would be particularly beneficial for patients with conditions such as diabetic neuropathy, fibromyalgia, and post-injury rehabilitation. This multi-site approach ensures that pain management is not only localized but also holistic, addressing widespread discomfort with precision.

The positioning of the sensors in the back is crucial to the device's effectiveness. The lumbar region, which controls essential lower body movements and is a frequent source of pain, contains key spinal nerves that connect to the lower limbs and trunk. These nerves, such as the sciatic nerve and the femoral nerve, pass through the lumbar spine and sacral region, making it a critical area for targeting pain and muscle dysfunction. Six key regions in the lower back will be specifically chosen for electrode placement, ensuring maximum coverage. These regions will include: 1) the upper lumbar (L1–L2), 2) the mid-lumbar (L3–L4), 3) the lower lumbar (L5–S1), 4) the sacroiliac joint, 5) the gluteal muscles, and 6) the erector spinae. Each region has distinct neural and muscular characteristics that allow the device to tailor its electrical stimulation to the exact needs of the patient. These target not just the spinal nerves but also the surrounding musculature for effective pain relief and muscle rehabilitation.

The band will be designed to conform to the shape of the lower back, ensuring full coverage while maintaining a sleek, comfortable form. The band will measure approximately 35 cm in length and 10 cm in width, designed to wrap comfortably around the lower back without restricting movement. The electrodes will be spaced 3–7 cm apart along the FPCB network to ensure even distribution of the electrical signals across the targeted regions. Each electrode will be approximately 1 cm in diameter, made from high-conductivity materials such as conductive

hydrogels embedded with silver nanowires, which provide both excellent conductivity and long-term durability. The electrodes will be encased in flexible, biocompatible materials to ensure the device can be worn comfortably for extended periods.

To enhance the user experience and extend the device's lifespan, the electrodes will incorporate self-healing hydrogel technology, which allows minor tears or degradation to automatically repair, minimizing the need for replacement. The MEMS actuators embedded in the band will be compact, measuring around 1–2 cm in diameter, and will facilitate real-time signal propagation through the network of sensor arrays. This will ensure that neuromodulation is synchronized across multiple muscle groups, optimizing pain relief and improving overall neuromuscular coordination. The entire unit will be lightweight, with the main processing unit and energy components integrated into the band to ensure seamless wearability and low-profile aesthetics.

Breakthroughs

One of the key challenges in developing this is the microfabrication of smart electrodes. These technologies must be at a minuscule level and capable of precise, real-time neuromodulation. Current electrode technology is limited by bulkiness, inconsistent conductivity, and a lack of flexibility needed for seamless integration with the body's contours (Chircov and Grumezescu). To achieve the level of precision required, electrodes must be designed with nanoscale conductive patterns embedded within flexible, biocompatible materials. This would allow them to conform to complex anatomical regions, such as the lumbar curvature and leg musculature, without causing discomfort or signal degradation. However, current 3D printing techniques are not yet capable of producing such fine conductive networks. Advancements in

nanomaterial synthesis, such as the development of graphene-infused polymers or liquid metal circuits, are necessary but must be refined to ensure scalability and cost-effectiveness, which currently inhibit the widespread adoption of the technology (Karvinen and Kellomäki).

Another significant barrier to the device's realization is the development of efficient, long-lasting wireless power solutions. Traditional battery systems are bulky, require frequent recharging, and can compromise the sleek, lightweight design necessary for wearable devices. Many people face these issues at work after prolonged sedentary lifestyles and must be able to wear this device while going about their daily lives. To support continuous neuromodulation without interruption, the concept will require advanced energy harvesting methods, such as radiofrequency (RF) energy transfer, inductive coupling, or even bioenergy harvesting from the user's body heat and motion (Khan et al.). While some of these technologies exist in rudimentary forms, they lack the efficiency and miniaturization needed to power high-demand devices. Current wireless charging systems suffer from limited range, energy loss, and potential interference with biological tissues. Overcoming these challenges will require innovations in antenna design, energy conversion efficiency, and thermal management. Additionally, safety protocols must be established to ensure that prolonged exposure to wireless energy fields does not pose any health risks to users (Dawoud et al.).

However, the most pivotal breakthrough is the development of advanced AI algorithms capable of interpreting complex electromyographic (EMG) patterns and accurately predicting pain episodes in real time. Current machine learning models are limited in their ability to process the nuanced, nonlinear biological data required for effective neuromodulation, particularly when it comes to identifying pre-pain physiological states (Chakraborty et al.). The device's success hinges on an AI system that can not only recognize existing pain but also anticipate its onset,

allowing for preemptive modulation to mitigate discomfort before it becomes severe (Hagedorn et al.).

The core challenge lies in the biological variability of EMG signals, which can differ significantly between individuals due to factors such as muscle mass, nerve conduction velocity, and pre-existing medical conditions (Becerra-Fajardo et al.). To address these complexities, the AI must be trained on diverse datasets encompassing a wide range of demographics, pain conditions, and physiological baselines. This requires an unprecedented scale of data collection and analysis, integrating multimodal inputs beyond EMG, such as heart rate variability, skin conductance, and even hormonal markers of stress and inflammation.

A comprehensive investigation will be conducted to evaluate the AI-driven pain prediction capabilities in participants with chronic pain conditions such as diabetic neuropathy, fibromyalgia, and post-injury musculoskeletal pain (Mayo Clinic; Admin). Participants will use these prototypes equipped with flexible printed circuit boards (FPCBs) embedded with EMG sensor arrays placed along the lumbar region, quadriceps, and gastrocnemius muscles, alongside biosensors tracking skin temperature, galvanic skin response, and heart rate. Over several weeks, continuous EMG data and self-reported pain levels will be collected through a mobile app, creating a multimodal dataset for training deep learning models like convolutional neural networks (CNNs) for feature extraction and recurrent neural networks (RNNs) or long short-term memory (LSTM) networks for temporal pattern recognition (Donges). The study will progress through phases: establishing baseline EMG patterns, inducing controlled muscle fatigue to detect early signs of discomfort, and real-world monitoring where the AI will predict pain episodes and adjust neuromodulation parameters autonomously. Effectiveness will be assessed through participant feedback, changes in pain scores, and physiological markers of muscle relaxation,

with key metrics including the AI's prediction sensitivity, timing accuracy, and overall pain reduction. Cross-validation techniques will be used to prevent overfitting and ensure model generalizability. Ultimately, this robust dataset and advanced AI integration aim to position the device as a revolutionary tool in personalized pain management.

Design Process

Throughout numerous iterations of the concept's architecture, we initially explored integrating an onboard pain-relief gel dispenser to provide dual-mode pain management, combining electrical stimulation with topical pharmacological relief. This feature was designed to incorporate a small, refillable cartridge containing analgesic gel within the device. A micro-pump mechanism would dispense controlled amounts of gel through tiny nozzles positioned near the electrodes, ensuring even application to the skin. The gel was intended to enhance conductivity while delivering additional pain relief. However, this feature was ultimately rejected due to several critical drawbacks. Continuous application of analgesic gels can cause skin irritation, allergic reactions, and desensitization over time, diminishing the device's long-term effectiveness. Additionally, the presence of moisture from the gel could interfere with electrode conductivity and adhesion, compromising neuromodulation consistency. The mechanical components required for gel dispensing also introduced unnecessary complexity, increasing the risk of leaks and maintenance issues. In contrast, AI-driven neuromodulation eliminates the need for chemical intervention altogether, offering precise, adaptive pain management without the risks associated with topical treatments. This approach not only enhances long-term efficacy and reduces maintenance but also broadens the device's accessibility for individuals with pre-existing conditions that might be exacerbated by topical agents.

Another design consideration was an onboard vacuum system for electrode cleaning. This feature aimed to maintain optimal electrode performance by removing sweat and debris through miniature vacuum channels integrated within the electrode pads. A small motor-driven pump would create suction, drawing moisture and particulate matter into a filtration unit inside the device. Sensors would trigger automatic cleaning cycles based on detected impedance changes, signaling dirt buildup. Despite its benefits, this feature was ultimately discarded due to significant design complications. The vacuum mechanism increased device bulk and weight, consumed additional power, and potentially generated mechanical noise that could disturb users. Furthermore, the vacuum's moving parts posed long-term reliability concerns, as they would be prone to wear and tear. Instead, the device leverages self-healing hydrogel electrodes that maintain excellent conductivity and adhesion even in the presence of moisture. These advanced materials possess self-repairing properties that ensure durability, eliminating the need for mechanical cleaning systems while enhancing user comfort and longevity.

Consequences

The concept just like all innovations carry both positive and negative consequences, as while its innovative design promises transformative benefits, it also presents certain challenges. One potential drawback is the risk of over-reliance on the device for pain management. Users may become dependent on the device, neglecting other important aspects of health maintenance such as physical therapy, exercise, or addressing the root causes of chronic pain. Additionally, despite its advanced features, it may face technical issues, such as occasional software malfunctions or hardware degradation over time, which could temporarily disrupt its effectiveness. Privacy concerns also arise with the integration of AI-driven data collection, as

continuous monitoring of physiological data may lead to apprehensions about data security, even though robust encryption measures would be in place.

On the positive side, the device represents a revolutionary leap in pain management technology, with far-reaching implications for society. Traditional TENS units have already proven effective for localized pain relief, but it enhances this concept exponentially through personalized, adaptive neuromodulation. This device offers unprecedented convenience, allowing individuals to manage chronic or acute pain seamlessly while going about their daily activities—whether at work, during exercise, or even while sleeping—without being constantly reminded of their condition. Its sleek, wearable design provides discreet support, reducing the stigma often associated with visible medical devices. Moreover, the device's ability to deliver customized pain relief tailored to individual physiological responses ensures more effective treatment, addressing gaps left by one-size-fits-all solutions. Beyond pain management, its technology holds potential for applications in enhancing muscle recovery and supporting conditions like fibromyalgia, diabetic neuropathy, sciatica, lower back pain, carpal tunnel syndrome, and even post-operative rehabilitation. By offering an affordable, scalable solution, this concept has the potential to improve the quality of life for millions globally, making advanced pain management accessible to diverse populations.

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