5-2023

TRANSCUTANEOUS ELECTRICAL STIMULATION DOES NOT DECREASE TORQUE LOSS OVER HIGH INTENSITY REPETITIONS

Ian Koskinen
Northern Michigan University, ikoskine@nmu.edu

Recommended Citation

Koskinen, Ian, "TRANSCUTANEOUS ELECTRICAL STIMULATION DOES NOT DECREASE TORQUE LOSS OVER HIGH INTENSITY REPETITIONS" (2023). *All NMU Master's Theses*. 741.
https://commons.nmu.edu/theses/741

TRANSCUTANEOUS ELECTRICAL STIMULATION DOES NOT DECREASE TORQUE LOSS OVER HIGH INTENSITY REPETITIONS

By

Ian Koskinen

Thesis

Submitted to
Northern Michigan University
In partial fulfillment of the requirements

For the degree of

Masters of Exercise Science

Office of Graduate Studies and Research

May 2023

SIGNATURE APPROVAL FORM

TRANSCUTANEOUS ELECTRICAL STIMULATION DOES NOT DECREASE TORQUE LOSS OVER HIGH INTENSITY REPETITIONS

This thesis by Ian Koskinen is recommended for approval by the student's Thesis Committee and Department Head in the Department of Health and Human Performance and by the Dean of Graduate Studies and Research.

Committee Chair: Dr. Matthew Kilgas Date

First Reader: Dr. Lukus Klawitter Date

Second Reader (if required): Dr. Scott Drum Date

Department Head: Dr. Liz Wuorinen Date

Dr. Lisa Schade Eckert Date
Dean of Graduate Studies and Research

ABSTRACT

TRANSCUTANEOUS ELECTRICAL STIMULATION DOES NOT DECREASE FORCE PRODUCTION LOSS OVER HIGH INTENSITY REPETITIONS

Transcutaneous Electrical Stimulation, TENS, has been used widely as an analgesic and ergogenic aid for many years. Compared to other modalities of electrical stimulation, TENS has been shown to provide some benefits in exercise performance by reducing pain and increasing endurance in low intensity applications, such as time trial cycling or isometric endurance. While TENS has been shown to have a significant effect on exercise induced pain in individuals performing endurance activities, to my knowledge it has not been examined in high intensity contractions. 18 active young adults (age: 23.11 years ± 2.08, resistance training experience: 7.08 years ± 3.79, height: 170.50 cm ± 7.50, weight: 72.38 kg ± 13.91) participated in a randomized, crossover-controlled experiment, with 3 tests involving a (1) no stimulation control, (2) sham and (3) functional electrical intensity at 100µS and 80Hz. Participants performed three sets of six maximal isokinetic contractions of the elbow flexors while being stimulated for the duration of the exercise for each condition. The average torque, average decline in torque per set, and the participant pain ratings were collected. The ANOVA pairwise comparison showed a significant ($p<.05$) reduction in the percent decline in torque, significantly ($p<.05$) lower pain ratings for the control sets, as well as a significantly ($p<.05$) higher average torque for the control sets compared to the sham and TENS sets.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Matthew Kilgas, for his help through this process, as well as my committee, Dr. Lukus Klawitter and Dr. Scott Drum, for their direction. I would also like to thank Alex Schaub for the use of her TENS 7000 unit and several rolls of pre-wrap, and Dr. Megan Nelson for assistance with statistics. Also, thanks to all of my fellow graduate and undergraduate students who volunteered to participate in my research study. This paper utilizes 7th edition APA citation.

Table of Contents

Appendix

List of Figures

Chapter 1: Journal Manuscript

Introduction

Electrical stimulation is a general term used to describe any modality that utilizes electrical current to elicit a response in a muscle or nerve. Electrical stimulation has traditionally been used to reduce pain by stimulating nerves to block the transmission of pain signals, particularly for transcutaneous electrical nerve stimulation (TENS) using a low to moderate intensity (Johnson, 2001; Melzack & Wall, 1996). In more recent studies, the application of electrical stimulation has been used for both athletic performance and mobility rehabilitation by reducing the perceived exercise induced pain (Angius et al., 2015; Astokorki & Mauger, 2017b; Erickson et al., 2017; Gondin et al., 2011; Vanderthommen & Duchateau, 2007). Blocking pain may enable clinical patients to perform rehabilitation exercise longer by reducing the sensations of discomfort or pain caused by exertion.

It has been hypothesized that the pain mitigation effect of TENS utilizes the gate control theory of pain. Melzack and Wall (1996) suggested that the externally applied electricity from the TENS unit acts as a guard, not allowing the signals to excite the first central transmission cells, effectively blocking the nervous signals from reaching the brain. By overloading the one aspect of the pain transmission response, a strong but current will block the further transmission of painful signals downstream of the stimulation (Johnson, 2001; Melzack & Wall, 1996). TENS is generally applied to mitigate chronic pain, but the understanding of how effective TENS can be on acute exercise induced pains requires more research (Binny et al., 2019; Simpson et al., 2014).

Previously, utilizing TENS and performance investigates its effects on low intensity or endurance type activities, reporting an increase in time to exhaustion and reduced perception of pain (Astokorki & Mauger, 2017b; Behm et al., 2019; de-la-Cruz-Torres et al., 2020). It is unclear if similar performance improvements found in endurance activities would be applicable to resistance activities. Only one study was identified that examined the effects of TENS on maximum force production. While examining the effects of TENS on grip strength following a TENS treatment, Dickstein and Kafri (2008) identified a significant increase in maximum finger flexor grip force. This study utilized TENS as a pretreatment, so further research is necessary to assess the efficacy of TENS application during resistance exercise training. Therefore, the purpose of this study is to determine if the application of TENS during a maximum voluntary isokinetic contraction of the elbow flexors would reduce the perceived pain in the elbow flexors, thereby decreasing the decline of torque. It is hypothesized that reduction in pain from the application of TENS will reduce the perceived pain, resulting in an increase in total torque during maximum voluntary isokinetic contractions of the elbow flexors.

Methods

This study was approved by the institutional review board at Northern Michigan University (HS22-1282). A power analysis (G*Power 3.1, Heinrich Heine University, Düsseldorf, Germany) showed a population of 15 participants would sufficiently meet power requirements. Participants were included if they had at least two years of resistance training experience, and excluded if they had any upper body injuries in the past six months, or any form of heart problem or pacemaker, or if they were pregnant. Eighteen eligible adults (age: 23.11 years ± 2.08, resistance training experience: 7.08 years ± 3.79, height: 170.50 cm ± 7.50, weight: 72.38 kg ± 13.91) completed three experimental trials (control, sham, and experimental) over the course of one hour in a random order. For the experimental test, the stimulation intensity was raised until the participant indicated it was noticeable, then slowly increased to the point where it was strong but not painful, and did not produce a muscle twitch, as determined by noticeable muscle spasms by the participant. For the sham stimulation, the intensity was increased until felt by the participant, then stepped down until not noticeable again, the TENS unit remained on at a low but insignificant power level, similar to the sham used by Astokrki and Mauger (2017b). For the control, the TENS was turned up until the participants identified they could feel the electrical pulse, and then the machine would be stepped down and turned off. A portable TENS unit (TENS 7000, Middleburg Heights, Ohio, USA) was used for the experiment and was set at a constant 85Hz and 100μS as determined as an effective pulse frequency to reduce pain (Johnson et al., 1989). TENS electrodes were attached approximately four centimeters above the antecubital fossa, and four centimeters below the anterior deltoid on the long head of the biceps brachii, in accordance with manufacturers recommendations. Due to the lack of body hair on the bicep, the participants were not shaved prior to electrode placement, but the sites were prepared with a gauze pad and cleaned thoroughly with an alcohol wipe, and wrapped with polyurethane foam wrap to prevent accidental movement of the electrodes.

Each trial consisted of three sets of six maximal isokinetic contractions of the elbow flexor of the dominant arm at 90° per second in a Biodex System 4 (Biodex Medical Systems, Shirley, New York, USA) with a 30 second rest in between sets. Participants were asked after every set to rate their pain on a 0-10 numeric scale, where zero was no feeling of pain, and 10 being unbearable (Cook et al., 1997). At the completion of the third set, the participants were released from the Biodex for 15 minutes, and encouraged to get up, and instructed to abstain from consume any calories prior to their next testing session. Data collected included average peak torque, which was the average of the highest torque value recorded during each of the six contractions. The percent decline in work in Joules from the first two repetitions (first third) to the last two repetitions (last third) using the formula $\frac{((first\ third - last\ third)*100)}{\text{first third}}$. Participant pain ratings from 0 – 10 after each set, with 0 representing no pain, and 10 representing severe pain. The sampling rate for the Biodex was consistent at 100 Hz for all participant testing.

Data Analysis

A separate (3 x 3) repeated measures analysis of variance (rANOVA) were used to assess the effect of the intervention (control, sham, and TENS), set (1, 2, and 3), and the condition by set interaction on pain, average peak torque, and work decline. An alpha of ≤ 0.05 was deemed significant. Data is reported as mean ± standard deviation, and partial eta squared (ηp^2) was calculated as a measure of effect sizes with $\eta p^2 \geq 0.01$ indicating small, ≥ 0.059 medium, and ≥ 0.138 large effects, respectively (Cohen, 1988).

Results

Eighteen individuals participated in the study, but one was not valid and their data was removed from the analysis. There was no interaction effect between the sets by intervention for the average peak torque production F(1,16) = 1.007 ($P = .331$, $\eta p^2 = .059$). There was no main effect for sets for average peak torque production F(1,16) = .918 ($P = .352$, $\eta p^2 = .054$), regardless of intervention. The average peak torque produced was not different for each trial. There was a significant main effect of intervention for the average peak torque F(1,16) = 28.931 ($P < .001$, $\eta p^2 = .630$). When examining the average peak torque produced for each intervention, each intervention was significantly different in torque production (control > TENS > sham, all $P < .05$, figure 1).

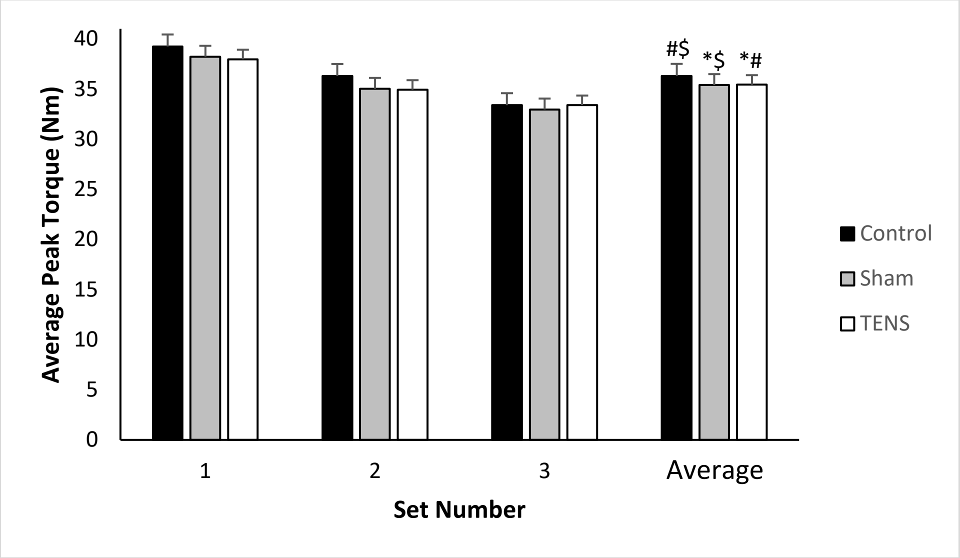


Figure 1. Comparing the average peak torque in Newton meters between control, sham, and TENS. Each presents a significant difference between intervention types. Significant (*P*<.05) difference from control represented with *. Significant (*P*<.05) difference from sham represented with #. Significant (*P*<.05) difference from TENS represented with $.

There was no interaction effect between the sets by intervention for percent decline in work F(1,16) = .002 (P = .964, ηp^2 = .000). There was no main effect for sets for the percent decline in work F(1,16) = 1.709 (P = .210, ηp^2 = .096), regardless of intervention. The average percent decline in work was not different for each set. There was a significant main effect of intervention for the percent decline in work F(1,16) = 28.931 (P < .001, ηp^2 = .644). The percent decline in work produced for each intervention showed there is a significant difference in work by intervention (control > sham > TENS, P <.05, figure 2).

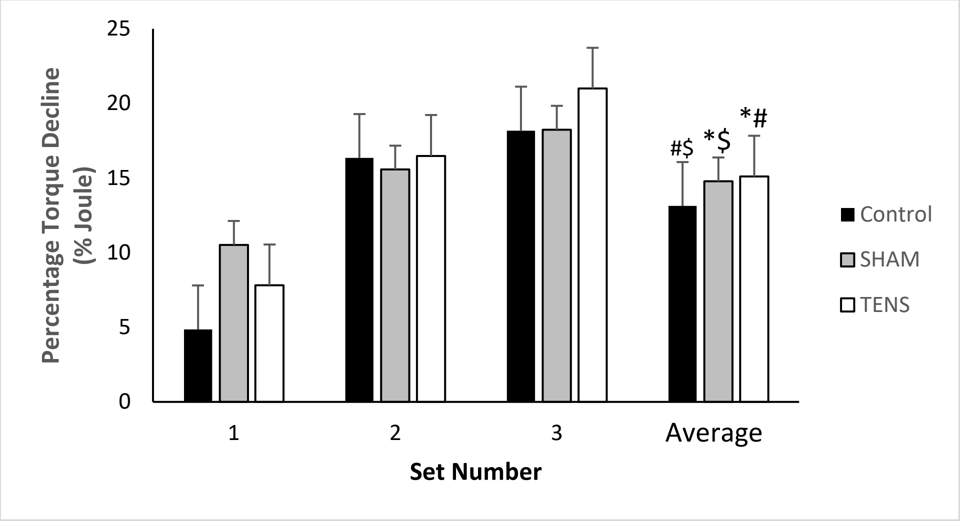


Figure 2. Comparing the percentage of work decline in Joules between the first third and last third of repetitions between control, sham, and TENS. Each presents a significant (p<.05) difference between intervention types. Significant (*P*<.05) difference from control represented with *. Significant (*P*<.05) difference from sham represented with #. Significant (*P*<.05) difference from TENS represented with $.

There was no interaction effect between the sets by intervention for the participant pain ratings F(1,16) = 1.342 (P = .264, $\eta p^2 = .062$). There was no main effect for sets for participant pain ratings F(1,16) = .034 (P = .886, $\eta p^2 = .023$), regardless of intervention. The participant pain ratings were not different for each set. There was a significant main effect of intervention for the participant pain ratings F(1,16) =124.552 ($P < .001$, $\eta p^2 = .809$). Each participant's pain ratings showed a significant difference for each intervention (control < TENS < sham, *P* <.05, figure 3).

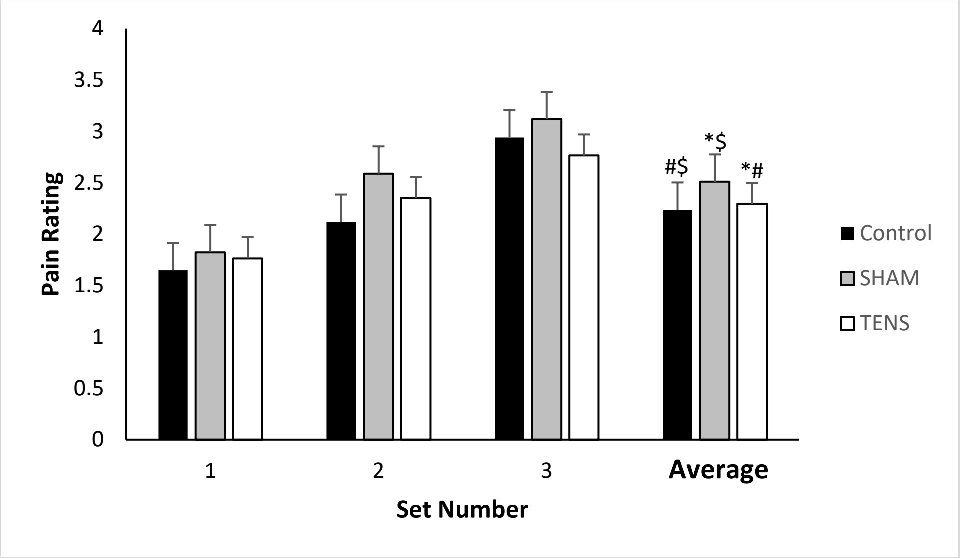


Figure 3. Comparing the pain ratings between each set between control, sham, and TENS. Each presents a significant (p<.05) difference between intervention types. Significant (*P*<.05) difference from control represented with *. Significant (*P*<.05) difference from sham represented with #. Significant (*P*<.05) difference from TENS represented with $.

Discussion

The purpose of this study was to determine the effectiveness of TENS stimulation during maximum voluntary isokinetic contractions to reduce pain, increase the mean peak torque between repetitions and reduce the percent decline in work in an individual performing a maximal isokinetic elbow flexion. The main findings indicate that TENS was less effective than the control on maximal isokinetic elbow flexion torque production. Significant effects were identified between the three intervention groups, showing the control intervention had significantly higher mean peak torque, and significantly lower decline in work compared to both the sham and TENS groups. TENS had a higher average torque, and a lower average pain rating than the sham.

Exercise induced pain is one of the most widely tested performance variables in regards to TENS research, and there are mixed results in support for pain reduction in active muscle during exercise (Astokorki & Mauger, 2017; Menezes et al., 2018). This study was performed on a maximal voluntary isokinetic activity. The majority of the literature supports the use of TENS on low to moderate intensity activity performed to failure. This could be due to the interaction of the TENS on the slow onset muscle discomfort associated with low intensity and aerobic type activities, compared to the acute exertion pain MVCs may have induced in the current protocol. Research examining populations with preexisting chronic pain conditions tended to show the highest positive effect from TENS applications, compared to healthy adults similar to those selected for this research (Ainsworth et al., 2006; Carzoli et al., 2022; Seenan et al., 2016). These healthy adults likely do not have any contraindications to performing maximum intensity exercises, which TENS applications would help treat. This positive effect on pain is consistent with existing research comparing TENS to sham trials on chronic pain, which identified a reduction in pain with the application of TENS compared to the sham (Simpson et al., 2014). The sham setting was utilized with the expectation that the control and sham, which both have no significant electrical intensity, would have similar reported results.

It is surprising that the torque production specifically between the TENS and sham was similar to the control. The sham was included to help blind the participants to the effect of the electrical stimulation and has helped show a significant difference in prior randomized trials (Johnson et al., 1989; Shimoura et al., 2019). Adding a second insignificant electrical intensity was intended to show that any performance outcomes related to TENS applications were not simply due to a placebo effect because participants expect to perform better with the electrical stimulation. Since the TENS unit was still on during the sham intensity, it is possible that the electrical intensity below sensory levels could cause a similar fatiguing mechanism to the full TENS intervention, unrelated to the pain mechanism. A study performed by Park (1999) showed that a 30-minute pre-treatment of high-frequency, low intensity TENS had a decrease in muscle power, similar to the 30-minute pre-treatment of high-frequency, high intensity TENS. Though, their study utilized a pre-treatment protocol versus actual treatment during exercise, the effects could vary with the application of TENS in this study totaling less than three minutes.

The percent decline in work between the three sets for each condition indicated that the control intervention was the lowest, while sham and TENS conditions both had higher decrements. It was hypothesized that the effects of the control and sham interventions would be closer together than either control or sham compared with the TENS trial. The data did not support this assumption. This could be caused by an incorrect selection of TENS intensity. Previous research on the application of neuromuscular electrical stimulation (NMES), which is designed to initiate muscle contraction, showed that an electrical stimulation works to recruit muscle units in a reverse order (Gregory & Bickel, 2005). This demand for fast twitch, fast fatiguing muscle fibers prior to slow twitch, slow fatiguing muscle fibers induced a decline in endurance in lower intensity contractions (Bickel et al., 2011). A study conducted by Gregory and colleagues (2007) identified that frequencies above 50 Hz was great enough to generate a significant muscle contraction, this may suggest the chosen TENS intervention frequency was too high, and similar to an NMES intensity, inadvertently activating muscle fibers rather than simply innervating the nerves. Yet, this does not explain why the control and sham conditions in the current study differed.

Possibly, the 30 second break was not long enough to account for a complete restoration in metabolic energy systems, which could be a limitation to the study. This could have had a confounding effect on each set's force production within the different interventions greater than the influence, or lack thereof, of the TENS intervention. TENS may be effective in endurance type activities, and not maximal activities, because of the readily available energy supply available to the muscles in aerobic exercise. Low intensity, or aerobic, exercise utilizes a continuous energy synthesis in the Krebs cycle and electron transport chain to produce adenosine triphosphate (ATP) for type I muscle fibers. Comparatively, high intensity, or anaerobic, exercise quickly depletes type IIa and IIx muscle fibers of stored ATP, which requires rest to resynthesize the available pool of energy (Hargreaves & Spriet, 2020). While phosphocreatine resynthesis can regenerate ATP quickly, 30 seconds is only a partial replenishment. It can take longer than 120 seconds to return ATP levels to a similar pre-exercise value (Harris et al., 1976). 30 seconds rest was chosen due to the plateauing effect of the phosphagen system when replenishing ATP storage, where research has shown that after a 30 second maximum sprint, a 1.5 minute recovery period recovered approximately 45% of the participant's expended ATP, while a 7 minute recovery only increased it another 20% (Baker et al., 2010). Since the participants would not be maximally exerting themselves more than six seconds per set, 30 seconds rest was deemed long enough for the purpose of this research. Even with adequate rest between sets, any reduction in pain response may not be enough to overcome the loss of energy in the muscle to fully exert themselves in a sustained, high intensity contraction.

While it was hypothesized that the application of TENS would increase muscle peak torque and reduce work decline by reducing the perceived pain, it appears to have had a negative impact on maximum intensity muscle activation. The application of TENS has been hypothesized to reduce function by recruiting and fatiguing the muscle fibers from least efficient type IIa and IIx motor units, to the most efficient type I fibers, which could exacerbate fatigue

(Gregory & Bickel, 2005). An increased demand in fast fatiguing muscle fibers could reduce the function of the muscle more than capability of TENS to mitigating the pain sensation caused by the contractions. Possibly due to these mechanisms, the successful research training programs utilizing TENS with exercise tend to be applied during low intensity training, and more often with diseased populations (Seenan et al., 2016; Son et al., 2016; Vance et al., 2012).

Current literature is often limited in several factors including electrode placement variables, electrical setting variability, and proper placebos. Two significant limitations to increased quality of research involve a difficult to effectively blind participants to the interventions, and high quality controls (Johnson, 2021). Future research into applications of TENS treatments on high intensity resistance training should examine if there is a similar response to nerve stimulation at lower than the 85 Hz selected for this research. Due to the age range of other research of TENS, selecting an older population, or a population that has a muscular disease that contraindicates exercise, may show different results from a young and active population, and should be examined in the future.

Conclusion

While the hypothesis was not supported, this research will add to the body of literature on the application of transcutaneous electrical nerve stimulation on maximum voluntary isokinetic contractions. The current body of literature on the application of TENS as a performance enhancing modality may only be relevant at the lower intensity activities primarily used in the research. While the exact mechanism is unclear, it appears the wider pulse width and higher Hz selected for this experiment had a negative effect on average torque and percent decline in work compared to an unstimulated control. It also appears to have had a negative effect on perceived pain. Electrical stimulation has predominately focused on exercise applications of submaximal and endurance type activities. Future research is warranted into the applications of TENS at varying intensities on muscles performing MVC exercise.

Chapter 2: Literature Review

Introduction

Muscular pain and fatigue commonly result from both submaximal and maximal exercise. Their occurrence may raise a barrier of entry to develop exercise habits or may make continuing exercise difficult. Various forms of analgesics, including electrical stimulation and pharmaceuticals, have been shown to reduce these negative effects (Mauger et al., 2010; Morgan et al., 2018; Paley et al., 2021). Electrical stimulation is a general term used to describe any modality that utilizes electrical current to elicit a response in a muscle or nerve. Transcutaneous electrical nerve stimulation (TENS) is a type of electrical stimulation that relieves pain by stimulating nerves to block the transmission of pain signals (Johnson, 2001; Paley et al., 2021). In recent studies, the application of electrical stimulation has been examined as an ergogenic aid for muscular performance, but the scope of research has been limited to endurance activities. This review aims to highlight the need for research into the effects of TENS on exercise performance by identifying the link between its effect on pain and fatigue in a high intensity exercise.

Pain Development and Exercise

Fatigue is defined as the decline in the ability to produce a given of force over time, and pain is an associated symptom of fatigue (Abulhasan et al., 2016). Maximal resistance exercise requires the use of all muscle types to perform at the highest intensity. Anaerobic exercise creates oxidative stress on the muscle, similar to endurance exercise resulting in muscle pain and fatigue. There are several factors that have been identified as the cause of muscular fatigue. These include the reduction of available energy substrates such as glycogen and adenosine triphosphate (ATP), an accumulation of metabolites including calcium, potassium, sodium, and hydrogen ions, as well as the reduction of electrical excitability of the active muscle. Along with the metabolite buildup, pain may be caused by damage to the sarcomere, or in relation to increased inflammation (Abulhasan et al., 2016; Bloomer & Goldfarb, 2004; J. Kim et al., 2015; Malm, 2001). The continuous firing of these type IIa and IIx fast fatiguing muscle motor units, compared to type I slow fatiguing muscles motor units, results in a lowered force production due to reduced fiber recruitment (Kennedy et al., 2013). Mechanistically, the stimulation of type III and IV motor afferents have been identified as being substantially related to the development of peripheral and central fatigue (Taylor et al., 2016; Taylor & Gandevia, 2008).

Pain Reduction

Approximately 20 percent of Americans suffer from chronic pain, while everyone at some point will suffer from some form of acute pain (Varrassi et al., 2010). These can be severe due to postoperative pain, musculoskeletal injury, or other instances of traumatic injury that is short in duration. Less severe acute injuries include the pain experienced due to muscular damage related to resistance training. While opioids remain the dominant prescription pain killer, others such as acetaminophen, ibuprofen, and other non-steroidal anti-inflammatory drugs (NSAIDs) are also used for daily pain management. NSAIDs are the most widely used drug in athletics, with up to one in four Olympic athletes admitting to using NSAIDs prior to drug testing for the 2000 Olympic games (Cornu et al., 2020). NSAIDs are not banned in sports competition, as they are viewed as a performance enabling, rather than performance enhancing (Warden, 2010). A connection has been examined between the consumption of pharmaceutical painkillers and performance, but there have been conflicting results, showing some increase or no effect on physical (Cook et al., 1997, 2000; Mauger et al., 2010; Morgan et al., 2018, 2019). Another study performed by Garcin and colleagues (2005) examined exertion after acetaminophen use and showed a lowered exertion from a similar exercise intensity compared to non-medicated controls. While the research into the reduction in pain via pharmaceuticals has been well studied, the increases in athletic performances still remain inconclusive and continued investigation can be beneficial (Cornu et al., 2020).

Pain is a natural part of exercise, as athletes perform various types of exercise will experience pain due to mechanical damage to the muscle fibers, and the increasing acidification of the muscle cells (Clarkson & Hubal, 2002; Street et al., 2001). Investigators have shown no major difference between the pain thresholds of aerobic, anaerobic, and non-athletes, there is a difference in pain tolerance across the aforementioned groups related to performance enhancement (Pettersen et al., 2020; Ryan & Kovacic, 1966). As expected, pain tolerance was correlated to success in combat sports, was used as a predictor for success in cycling performance, and was directly related to the competition level amongst competitive swimmers (Astokorki & Mauger, 2017a; F.i et al., 2021; Scott & Gijsbers, 1982). As such, a reduction in pain could give advantages to individuals with a lower pain tolerance looking to perform a fitness regimen similar to athletes who are already capable of withstanding a higher amount of pain across similar exertion levels.

Overview of Transcutaneous Electrical Nerve Stimulation

The main benefits derived from electrical stimulation come from the application of a selected electrical current. This signal can be produced and modulated in the controller and is delivered through electrodes, generally attached to the surface of the skin by use of adhesives or gel pads. There are three major elements that relate to the application of electrical stimulation, the intensity, frequency, and duration. Intensity is the strength of the electrical current in milliamperes, and depending on the particular modality used it will vary from hardly noticeable to strong enough to flex the muscle. The milliamperes are directly related to the amount of current needed to recruit muscle fibers: as more muscle fibers are recruited, the force of the contraction increases (Bickel et al., 2011). The frequency is the number of oscillations the electrical waveform makes per second, which are called hertz (Hz), and as the frequency is increased, the energy usage is increased. The duration refers to the length of the electrical pulsing and is generally measured in microseconds (Johnson, 2001). The pattern of application is also relevant to the chosen modality. Electrical patters can include a continuous even pattern, bursts of activity with segments of rest, and frequency modulation, which increase over time then decrease. The most common form of electrical stimulation is Transcutaneous Electrical Nerve Stimulation (TENS). Reviews of appropriate TENS protocols have identified a median frequency of 85Hz at a sufficiently high intensity for each participant to be the optimum for pain reduction (Bjordal et al., 2003).

Pain Mechanism

Electrical stimulation utilizes the gate control theory of pain as the primary explanation of the effects (Melzack & Wall, 1996). In 1996, Melzack and Wall proposed a new theory for how the body interprets pain signals. In this theory, the pain signals are received and transmitted from the peripheral nervous system through one of three afferent nerve types. These are the A-beta, which is the largest, A-delta which is a moderate size, and C-type fibers being the smallest. Modalities like standard TENS, which use a low intensity and frequency, specifically target the A-beta fibers, which confuse the signaling of the nerve track as it travels from the peripheral to the central nervous system (Johnson, 2001; Melzack & Wall, 1996). This signaling works to close the “gate” located in the substantia gelatinosa, a bundle of closely packed nerve axons that carry afferent input from the dorsal root ganglia and run the length of the spinal cord to the brain.

The use of electricity targets the A-beta fibers and isolates the smaller diameter A-delta and C fibers. As these two varied intensities meet at the substantia gelatinosa, it acts as the guard, not allowing the signals to excite the first central transmission (T) cells, effectively blocking the pain signals. By overloading the one aspect of the pain transmission response, a strong but non-painful current will block the further transmission of pain downstream of the source of pain, this is termed the segmental antinociceptive effect (Johnson, 2001; Melzack & Wall, 1996).

The use of stronger, higher intensity electrical signals work in a slightly different way to help block pain. Acupuncture-like TENS, and other neuromuscular electrical stimulation intervention types, aim to induce the effects of ergoreceptors by targeting the muscle to twitch and release endogenous opioid peptides, which reduce the excitability of the surrounding cells (Froehlich, 1997; Johnson, 2001). While it also produces the same electrical signal that stops activation of the T cells, it also works as an extra-segmental pain reducer, dulling pain in a larger area, making it useful for applications on chronic pain in areas such as the low back (Johnson, 2001).

TENS and Pain

TENS is usually applied to the site of pain to treat chronic pain, but remains effective when applied downstream, in between the pain stimulus and the brain. In musculoskeletal conditions, TENS is most commonly utilized in the treatment of chronic low back pain (Durmus et al., 2010). An extensive review of previous reviews and meta analyses, which includes over 200 TENS treatment studies, showed that while only 69 of the 169 reviews observed a beneficial response, 87 reported inconclusive results due to the low quality of the experimental application (Paley et al., 2021). Of the 169 reviews of randomized clinical trials included, only 13 reported a negative outcome, leading the authors to conclude that there was an stong enough evidence to utilize TENS in clinical pain management (Paley et al., 2021).

While TENS is most often applied to chronic pain, its application into acute pain management, although presenting some mixed results, is mostly supportive of effective pain reduction. A review by Johnson and colleagues looked at 19 studies with a total of 1346 participants and showed a significant reduction in pain in randomized controlled trials (Johnson et al., 2015). A similar review of TENS used on acute pain performed by Simpson et al. illustrated a statistically relevant reduction in pain as well, though it only included 4 studies involving 261 participants (Simpson et al., 2014). Establishing effective and consistent dosage requirements and pad placement for specific applications is a necessity for future reviews, as the inconsistencies make establishing direct comparisons difficult (Lynch & Simpson, 2002; Vance et al., 2014).

TENS and Performance

TENS has been used in a variety of applications to increase performance. Due to the variety of applications of TENS and types of exercise these experiments utilized, the current review will group together similar experimental protocols.

Maximum Voluntary Contractions

There is limited research on the effects of TENS with maximum voluntary contractions. Another study by Son and colleagues (2016) utilized saline infusions to give participants temporary knee pain, and then tested their maximum voluntary contraction (MVC) force with or without TENS applied. Son and colleagues utilized TENS with a 15-minute pretreatment, as well as during the MVC contractions. The authors showed a significant increase in contractile force in the TENS group over the control and placebo, but these tests were utilizing healthy participants that the researchers gave a painful stimulus to the participants, rather than examining the response to natural pain. Another study performed by Dickstein and Kafri (2008) utilized a 15-minute TENS pretreatment, prior to maximal contractions of the finger flexors. EMG activity of the finger flexors increased as a following this pretreatment, resulting in an increased MVC force. Typically, the efficacy of TENS on pain in performance have utilized lower intensity exercise testing, so further research onto the application of TENS during maximum intensity exercise is still warranted.

Time Trials

A two-part study performed by Astokorki and Mauger (2017b) utilized TENS and interferential current (IFC), which is applied like TENS but utilizes a frequency modulation control, to mitigate pain in two different endurance activities, one for the upper body and one for the lower body. The cycling trial utilized a 10-mile distance target, found a statistically significant decrease in pain and decrease in time between both the electrically stimulated compared to the sham stimulation trials.

Low Intensity Contractions

In tests examining low intensity (<30% MVC) contractions, participants who performed time -to-exhaustion tasks saw an increase in duration for the TENS trials over the control trials (Astokorki & Mauger, 2017b; Behm et al., 2019). A study performed by de-la-Cruz-Torres and colleagues (2020) on ballerinas utilized TENS on the flexor hallicus longus of the lower leg which showed an increase in a bodyweight heel raise time to exhaustion trial, identified as a decrease in fatigue from the individual heel raises. In a study by Behm and colleagues (2019) examining the effects of TENS on the maximum voluntary isometric contraction of the quadriceps, the TENS-treated leg had a significantly longer time until failure than the non-treated leg. While the TENS had little effect on the maximum voluntary isometric contraction, TENS did prove to be effective in the 30% MVC fatigue protocol.

Gaps in Research

There are a limited number of studies examining the effects of TENS on dynamic high intensity anaerobic exercises in healthy individuals. A study performed by Menezes and colleagues (2018) examined the effects of TENS on participants subjected to delayed onset muscle soreness showed that there was an increase in total repetitions at the cost of an increase of ratings of fatigue. This could be due to the use of a high frequency and motor activating intensity, rather at the sensory intensity.

Current evidence displays mixed effects of TENS on pain perception during exercise (Dickstein & Kafri, 2008; Hibbert et al., 2017). These studies may show conflicting results due to the timing of application, as TENS works best when utilized during pain stimulus, compared to applications in preparation for exercise (Sluka et al., 2013). Other factors include the use of low-intensity electrical stimulation and failure to increase as adaptations form (Sluka et al., 2013). While it has been shown that pharmaceutical pain killers are capable of increasing performance outcomes (Holgado et al., 2018; Mauger et al., 2010) there are some studies that show no statistically significant change (Cornu et al., 2020; Lundberg & Howatson, 2018). Pain reduction studies often mainly focus on performance in endurance type activities (Astokorki & Mauger, 2017b; Behm et al., 2019; de-la-Cruz-Torres et al., 2020). These studies have predominately looked at cycling, or low intensity resistance training. There is a limited amount of research into voluntary force production, rather than forced muscle innervation from neuromuscular electrical stimulation. Most of the research into the application of electrical stimulation on strength utilize a strong electrical signal that helps augment the muscle contraction (Bickel et al., 2011; Donnelly et al., 2021; Erickson et al., 2017; Gondin et al., 2011; R. Holcomb, 2006). Most of these studies also only targeted the quadricep and biceps femoris muscles (Abulhasan et al., 2016; G. K. Fitzgerald et al., 2003; K.-M. Kim et al., 2010; Taradaj et al., 2013).

The multi-decade review of TENS applications has shown several problems in identifying the efficacy of treatments. This can be due to several factors, including inclusion of research that does not meet the minimum requirements for effective response, and the challenge of excluding the placebo effect (Johnson, 2021). There has been a lack of randomized, crossover, and placebo-controlled study on the efficacy of TENS as a pain-mitigating or performance-enhancing modality (Johnson, 2021). The small number of tests performed that utilize these controls have shown a significant improvement while utilizing TENS (Astokorki & Mauger, 2017b).

The individual aspects of the application of electrical stimulation have been presented as a means to increase muscular endurance, rather than to decrease muscular fatigue, in a high resistance activity. While the research into electrical stimulation and its uses has been going on for many years, the application as an ergogenic aid is limited. When looking into performance fatigue, there are two parts: a loss of contractile function and a loss of muscle activation (Enoka & Duchateau, 2016). TENS could act as a blocker to the afferent signals utilized by the central nervous system to control muscle activation, therefore reducing perceived pain and fatigue. There has been a limited amount of research into the connection between exercise, pain, and fatigue. Identifying the connection may serve to improve health outcomes by increasing the duration of individual bouts of exercise and adherence to fitness programs (Mauger & Hopker, 2012).

Conclusion

While chronic pain may affect up to 20% of the population, acute muscle pain or discomfort will affect all active individuals as part of the natural, biological response to fatigue and muscle use (Varrassi et al., 2010). It is known that individuals with a higher pain tolerance perform better than those with lower pain tolerance (Astokorki & Mauger, 2017a). Performing at a higher level helps promote a higher pain tolerance (Scott & Gijsbers, 1982). Researchers have identified that both pharmaceuticals and TENS can be used to help improve the performance of individuals in endurance and low intensity exercise by reducing the perceived pain (Astokorki & Mauger, 2017b; Morgan et al., 2018). Being able to promote pain reduction in individuals performing high intensity exercise could aid them in increasing performance gains as they are able to continue to push harder, or stay active longer, than in a normal setting.

References

Abulhasan, J. F., Rumble, Y. L. D., Morgan, E. R., Slatter, W. H., & Grey, M. J. (2016). Peripheral Electrical and Magnetic Stimulation to Augment Resistance Training. *Journal of Functional Morphology and Kinesiology*, *1*(3), 328–342. https://doi.org/10.3390/jfmk1030328

Angius, L., Hopker, J. G., Marcora, S. M., & Mauger, A. R. (2015). The effect of transcranial direct current stimulation of the motor cortex on exercise-induced pain. *European Journal of Applied Physiology*, *115*(11), 2311–2319. https://doi.org/10.1007/s00421-015-3212-y

Astokorki, A. H. Y., & Mauger, A. R. (2017a). Tolerance of exercise-induced pain at a fixed rating of perceived exertion predicts time trial cycling performance. *Scandinavian Journal of Medicine & Science in Sports*, *27*(3), 309–317. https://doi.org/10.1111/sms.12659

Astokorki, A. H. Y., & Mauger, A. R. (2017b). Transcutaneous electrical nerve stimulation reduces exercise-induced perceived pain and improves endurance exercise performance. *European Journal of Applied Physiology*, *117*(3), 483–492. https://doi.org/10.1007/s00421-016-3532-6

Behm, D. G., Colwell, E. M., Power, G. M. J., Ahmadi, H., Behm, A. S. M., Bishop, A., Murph, C., Pike, J., McAssey, B., Fraser, K., Kearley, S., & Ryan, M. (2019). Transcutaneous electrical nerve stimulation improves fatigue performance of the treated and contralateral knee extensors. *European Journal of Applied Physiology*, *119*(11), 2745–2755. https://doi.org/10.1007/s00421-019-04253-z

Bickel, C. S., Gregory, C. M., & Dean, J. C. (2011). Motor unit recruitment during neuromuscular electrical stimulation: A critical appraisal. *European Journal of Applied Physiology*, *111*(10), 2399. https://doi.org/10.1007/s00421-011-2128-4

Binny, J., Wong, N. L. J., Garga, S., Lin, C.-W. C., Maher, C. G., McLachlan, A. J., Traeger, A. C., Machado, G. C., & Shaheed, C. A. (2019). Transcutaneous electric nerve stimulation (TENS) for acute low back pain: Systematic review. *Scandinavian Journal of Pain*, *19*(2), 225–233. https://doi.org/10.1515/sjpain-2018-0124

Bjordal, J. M., Johnson, M. I., & Ljunggreen, A. E. (2003). Transcutaneous electrical nerve stimulation (TENS) can reduce postoperative analgesic consumption. A meta-analysis with assessment of optimal treatment parameters for postoperative pain. *European Journal of Pain*, *7*(2), 181–188. https://doi.org/10.1016/S1090-3801(02)00098-8

Bloomer, R. J., & Goldfarb, A. H. (2004). Anaerobic Exercise and Oxidative Stress: A Review. *Canadian Journal of Applied Physiology*, *29*(3), 245–263. https://doi.org/10.1139/h04-017

Cook, D. B., O'Connor, P. J., Eubanks, S. A., Smith, J. C., & Lee, M. (1997). Naturally occurring muscle pain during exercise: Assessment and experimental evidence. *Medicine and Science in Sports and Exercise*, *29*(8), 999–1012. https://doi.org/10.1097/00005768-199708000-00004

Cook, D. B., O'Connor, P. J., & Ray, C. A. (2000). Muscle pain perception and sympathetic nerve activity to exercise during opioid modulation. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *279*(5), R1565–R1573. https://doi.org/10.1152/ajpregu.2000.279.5.R1565

Cornu, C., Grange, C., Regalin, A., Munier, J., Ounissi, S., Reynaud, N., Kassai-Koupai, B., Sallet, P., & Nony, P. (2020). Effect of Non-Steroidal Anti-Inflammatory Drugs on Sport Performance Indices in Healthy People: A Meta-Analysis of Randomized Controlled Trials. *Sports Medicine - Open*, *6*(1), 20. https://doi.org/10.1186/s40798-020-00247-w

de-la-Cruz-Torres, B., Barrera-García-Martín, I., & Romero-Morales, C. (2020). Comparative Effects of One-Shot Electrical Stimulation on Performance of the Flexor Hallucis Longus Muscle in Professional Dancers: Percutaneous Versus Transcutaneous? *Neuromodulation: Technology at the Neural Interface*, *23*(6), 865–870. https://doi.org/10.1111/ner.13040

Dickstein, R., & Kafri, M. (2008). Effects of antecedent TENS on EMG activity of the finger flexor muscles and on grip force. *Somatosensory & Motor Research*, *25*(2), 139–146. https://doi.org/10.1080/08990220802131416

Donnelly, C., Stegmüller, J., Blazevich, A. J., Crettaz von Roten, F., Kayser, B., Neyroud, D., & Place, N. (2021). Modulation of torque evoked by wide-pulse, high-frequency neuromuscular electrical stimulation and the potential implications for rehabilitation and training. *Scientific Reports*, *11*(1), 6399. https://doi.org/10.1038/s41598-021-85645-0

Durmus, D., Durmaz, Y., & Canturk, F. (2010). Effects of therapeutic ultrasound and electrical stimulation program on pain, trunk muscle strength, disability, walking performance, quality of life, and depression in patients with low back pain: A randomized-controlled trial. *Rheumatology International*, *30*(7), 901–910. https://doi.org/10.1007/s00296-009-1072-7

Enoka, R. M., & Duchateau, J. (2016). Translating Fatigue to Human Performance. *Medicine and Science in Sports and Exercise*, *48*(11), 2228–2238. https://doi.org/10.1249/MSS.0000000000000929

Erickson, M. L., Ryan, T. E., Backus, D., & McCully, K. K. (2017). Endurance neuromuscular electrical stimulation training improves skeletal muscle oxidative capacity in individuals with motor-complete spinal cord injury. *Muscle & Nerve*, *55*(5), 669–675. https://doi.org/10.1002/mus.25393

F.i, S., A.a, P., M.o, D., & V.a, M. (2021). PAIN TOLERANCE VERSUS COMPETITIVE SUCCESS IN YOUTH KICKBOXING. *Theory and Practice of Physical Culture*, *4*, 39–41.

Fitzgerald, G. K., Piva, S. R., & Irrgang, J. J. (2003). A Modified Neuromuscular Electrical Stimulation Protocol for Quadriceps Strength Training Following Anterior Cruciate Ligament Reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *33*(9), 492–501. https://doi.org/10.2519/jospt.2003.33.9.492

Fitzgerald, P. B., Fountain, S., & Daskalakis, Z. J. (2006). A comprehensive review of the effects of rTMS on motor cortical excitability and inhibition. *Clinical Neurophysiology*, *117*(12), 2584–2596. https://doi.org/10.1016/j.clinph.2006.06.712

Froehlich, J. C. (1997). Opioid Peptides. *Alcohol Health and Research World*, *21*(2), 132–136.

Gandevia, S. C., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: Evidence for suboptimal output from the motor cortex. *The Journal of Physiology*, *490*(2), 529–536. https://doi.org/10.1113/jphysiol.1996.sp021164

Garcin, M., Mille-Hamard, L., Billat, V., Humbert, L., & Lhermitte, M. (2005). Influence of Acetaminophen Consumption on Perceived Exertion at the Lactate Concentration Threshold. *Perceptual and Motor Skills*, *101*(3), 675–683. https://doi.org/10.2466/pms.101.3.675-683

Golaszewski, S. M., Bergmann, J., Christova, M., Kunz, A. B., Kronbichler, M., Rafolt, D., Gallasch, E., Staffen, W., Trinka, E., & Nardone, R. (2012). Modulation of motor cortex excitability by different levels of whole-hand afferent electrical stimulation. *Clinical Neurophysiology*, *123*(1), 193–199. https://doi.org/10.1016/j.clinph.2011.06.010

Gondin, J., Cozzone, P. J., & Bendahan, D. (2011). Is high-frequency neuromuscular electrical stimulation a suitable tool for muscle performance improvement in both healthy humans and athletes? *European Journal of Applied Physiology*, *111*(10), 2473. https://doi.org/10.1007/s00421-011-2101-2

Hibbert, A. W., Billaut, F., Varley, M. C., & Polman, R. C. J. (2017). No Influence of Transcutaneous Electrical Nerve Stimulation on Exercise-Induced Pain and 5-Km Cycling Time-Trial Performance. *Frontiers in Physiology*, *8*. https://www.frontiersin.org/articles/10.3389/fphys.2017.00026

Holgado, D., Hopker, J., Sanabria, D., & Zabala, M. (2018). Analgesics and Sport Performance: Beyond the Pain-Modulating Effects. *PM&R*, *10*(1), 72–82. https://doi.org/10.1016/j.pmrj.2017.07.068

Johnson, M. I. (2001). Transcutaneous Electrical Nerve Stimulation (TENS) and TENS-like devices: Do they provide pain relief? *Pain Reviews*, *8*(3–4), 121–158. https://doi.org/10.1191/0968130201pr182ra

Johnson, M. I. (2021). Resolving Long-Standing Uncertainty about the Clinical Efficacy of Transcutaneous Electrical Nerve Stimulation (TENS) to Relieve Pain: A Comprehensive Review of Factors Influencing Outcome. *Medicina*, *57*(4), 378. https://doi.org/10.3390/medicina57040378

Johnson, M. I., Ashton, C. H., Bousfield, D. R., & Thompson, J. W. (1989). Analgesic effects of different frequencies of transcutaneous electrical nerve stimulation on cold-induced pain in normal subjects. *Pain*, *39*(2), 231–236. https://doi.org/10.1016/0304-3959(89)90010-9

Johnson, M. I., Paley, C. A., Howe, T. E., & Sluka, K. A. (2015). Transcutaneous electrical nerve stimulation for acute pain. *Cochrane Database of Systematic Reviews*, *6*. https://doi.org/10.1002/14651858.CD006142.pub3

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2013). Firing of antagonist small-diameter muscle afferents reduces voluntary activation and torque of elbow flexors. *The Journal of Physiology*, *591*(14), 3591–3604. https://doi.org/10.1113/jphysiol.2012.248559

Kim, J., Lee, J., Kim, S., Yoon, D., Kim, J., & Sung, D. J. (2015). Role of creatine supplementation in exercise-induced muscle damage: A mini review. *Journal of Exercise Rehabilitation*, *11*(5), 244–250. https://doi.org/10.12965/jer.150237

Kim, K.-M., Croy, T., Hertel, J., & Saliba, S. (2010). Effects of Neuromuscular Electrical Stimulation After Anterior Cruciate Ligament Reconstruction on Quadriceps Strength, Function, and Patient-Oriented Outcomes: A Systematic Review. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(7), 383–391. https://doi.org/10.2519/jospt.2010.3184

Lundberg, T. R., & Howatson, G. (2018). Analgesic and anti-inflammatory drugs in sports: Implications for exercise performance and training adaptations. *Scandinavian Journal of Medicine & Science in Sports*, *28*(11), 2252–2262. https://doi.org/10.1111/sms.13275

Lynch, L., & Simpson, K. H. (2002). Transcutaneous electrical nerve stimulation and acute pain. *BJA CEPD Reviews*, *2*(2), 49–52. https://doi.org/10.1093/bjacepd/2.2.49

Malm, C. (2001). Exercise-induced muscle damage and inflammation: Fact or fiction? *Acta Physiologica Scandinavica*, *171*(3), 233–239. https://doi.org/10.1046/j.1365-201x.2001.00825.x

Mauger, A. R., & Hopker, J. (2012). The Pain of Exercise – Insights in to The Role of Pain on Exercise Regulation and Performance. *Journal of Sports Medicine & Doping Studies, 2*(4), Article 4. https://dx.doi.org/10.4172/2161-0673.1000e115

Mauger, A. R., Jones, A. M., & Williams, C. A. (2010). Influence of acetaminophen on performance during time trial cycling. *Journal of Applied Physiology*, *108*(1), 98–104. https://doi.org/10.1152/japplphysiol.00761.2009

Melzack, R., & Wall, P. D. (1996). Pain mechanisms: A new theory: A gate control system modulates sensory input from the skin before it evokes pain perception and response. *Pain Forum*, *5*(1), 3–11. https://doi.org/10.1016/S1082-3174(96)80062-6

Menezes, M. A., Pereira, T. A. B., Tavares, L. M., Leite, B. T. Q., Neto, A. G. R., Chaves, L. M. S., Lima, L. V., Da Silva-Grigolleto, M. E., & DeSantana, J. M. (2018). Immediate effects of transcutaneous electrical nerve stimulation (TENS) administered during resistance exercise on pain intensity and physical performance of healthy subjects: A randomized clinical trial. *European Journal of Applied Physiology*, *118*(9), 1941–1958. https://doi.org/10.1007/s00421-018-3919-7

Morgan, P. T., Bowtell, J. L., Vanhatalo, A., Jones, A. M., & Bailey, S. J. (2018). Acute acetaminophen ingestion improves performance and muscle activation during maximal intermittent knee extensor exercise. *European Journal of Applied Physiology*, *118*(3), 595–605. https://doi.org/10.1007/s00421-017-3794-7

Morgan, P. T., Vanhatalo, A., Bowtell, J. L., Jones, A. M., & Bailey, S. J. (2019). Acute ibuprofen ingestion does not attenuate fatigue during maximal intermittent knee extensor or all-out cycling exercise. *Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquee, Nutrition Et Metabolisme*, *44*(2), 208–215. https://doi.org/10.1139/apnm-2018-0432

Paley, C. A., Wittkopf, P. G., Jones, G., & Johnson, M. I. (2021). Does TENS Reduce the Intensity of Acute and Chronic Pain? A Comprehensive Appraisal of the Characteristics and Outcomes of 169 Reviews and 49 Meta-Analyses. *Medicina*, *57*(10), 1060. https://doi.org/10.3390/medicina57101060

Pettersen, S. D., Aslaksen, P. M., & Pettersen, S. A. (2020). Pain Processing in Elite and High-Level Athletes Compared to Non-athletes. *Frontiers in Psychology*, *11*. https://www.frontiersin.org/articles/10.3389/fpsyg.2020.01908

R. Holcomb, W. (2006). Effect of Training with Neuromuscular Electrical Stimulation on Elbow Flexion Strength. *Journal of Sports Science & Medicine*, *5*(2), 276–281.

Rainville, J., Hartigan, C., Martinez, E., Limke, J., Jouve, C., & Finno, M. (2004). Exercise as a treatment for chronic low back pain. *The Spine Journal*, *4*(1), 106–115. https://doi.org/10.1016/S1529-9430(03)00174-8

Ryan, E. D., & Kovacic, C. R. (1966). Pain Tolerance and Athletic Participation. *Perceptual and Motor Skills*, *22*(2), 383–390. https://doi.org/10.2466/pms.1966.22.2.383

Scott, V., & Gijsbers, K. (1982). Pain perception in competitive swimmers. *British Medical Journal (Clinical Research Ed.)*, *284*(6309), 117.

Seenan, C., McSwiggan, S., Roche, P. A., Tan, C.-W., Mercer, T., & Belch, J. J. F. (2016). Transcutaneous Electrical Nerve Stimulation Improves Walking Performance in Patients With Intermittent Claudication. *Journal of Cardiovascular Nursing*, *31*(4), 323–330. https://doi.org/10.1097/JCN.0000000000000258

Simpson, P. M., Fouche, P. F., Thomas, R. E., & Bendall, J. C. (2014). Transcutaneous electrical nerve stimulation for relieving acute pain in the prehospital setting: A systematic review and meta-analysis of randomized-controlled trials. *European Journal of Emergency Medicine*, *21*(1), 10–17. https://doi.org/10.1097/MEJ.0b013e328363c9c1

Sluka, K. A., Bjordal, J. M., Marchand, S., & Rakel, B. A. (2013). What Makes Transcutaneous Electrical Nerve Stimulation Work? Making Sense of the Mixed Results in the Clinical Literature. *Physical Therapy*, *93*(10), 1397–1402. https://doi.org/10.2522/ptj.20120281

Sluka, K. A., Law, L. F., & Bement, M. H. (2018). Exercise-induced pain and analgesia? Underlying mechanisms and clinical translation. *Pain*, *159*(Suppl 1), S91–S97. https://doi.org/10.1097/j.pain.0000000000001235

Son, S. J., Kim, H., Seeley, M. K., Feland, J. B., & Hopkins, J. T. (2016). Effects of transcutaneous electrical nerve stimulation on quadriceps function in individuals with experimental knee pain. *Scandinavian Journal of Medicine & Science in Sports*, *26*(9), 1080–1090. https://doi.org/10.1111/sms.12539

Taradaj, J., Halski, T., Kucharzewski, M., Walewicz, K., Smykla, A., Ozon, M., Slupska, L., Dymarek, R., Ptaszkowski, K., Rajfur, J., & Pasternok, M. (2013). The Effect of NeuroMuscular Electrical Stimulation on Quadriceps Strength and Knee Function in Professional Soccer Players: Return to Sport after ACL Reconstruction. *BioMed Research International*, *2013*, e802534. https://doi.org/10.1155/2013/802534

Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural Contributions to Muscle Fatigue: From the Brain to the Muscle and Back Again. *Medicine and Science in Sports and Exercise*, *48*(11), 2294–2306. https://doi.org/10.1249/MSS.0000000000000923

Taylor, J. L., Butler, J. E., Allen, G. M., & Gandevia, S. C. (1996). Changes in motor cortical excitability during human muscle fatigue. *The Journal of Physiology*, *490*(2), 519–528. https://doi.org/10.1113/jphysiol.1996.sp021163

Taylor, J. L., & Gandevia, S. C. (2008). A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *Journal of Applied Physiology*, *104*(2), 542–550. https://doi.org/10.1152/japplphysiol.01053.2007

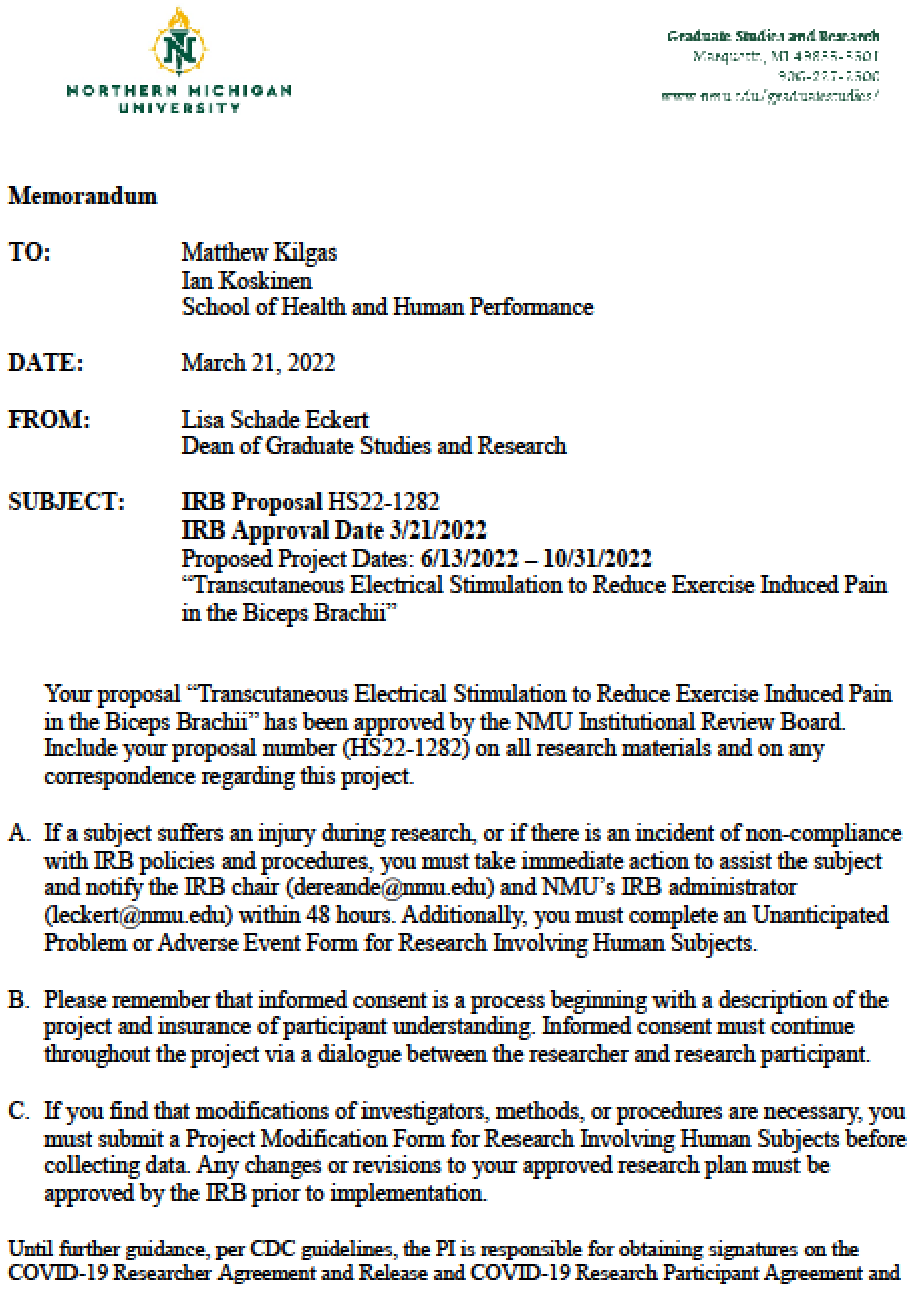
Vance, C. G. T., Dailey, D. L., Rakel, B. A., & Sluka, K. A. (2014). Using TENS for pain control: The state of the evidence. *Pain Management*, *4*(3), 197–209. https://doi.org/10.2217/pmt.14.13

Vanderthommen, M., & Duchateau, J. (2007). Electrical Stimulation as a Modality to Improve Performance of the Neuromuscular System. *Exercise and Sport Sciences Reviews*, *35*(4), 180–185. https://doi.org/10.1097/jes.0b013e318156e785

Varrassi, G., Müller-Schwefe, G., Pergolizzi, J., Orónska, A., Morlion, B., Mavrocordatos, P., Margarit, C., Mangas, C., Jaksch, W., Huygen, F., Collett, B., Berti, M., Aldington, D., & Ahlbeck, K. (2010). Pharmacological treatment of chronic pain – the need for CHANGE. *Current Medical Research and Opinion*, *26*(5), 1231–1245. https://doi.org/10.1185/03007991003689175

Warden, S. J. (2010). Prophylactic Use of NSAIDs by Athletes: A Risk/Benefit Assessment. *The Physician and Sportsmedicine*, *38*(1), 132–138. https://doi.org/10.3810/psm.2010.04.1770

Appendix



NORTHERN MICHIGAN
UNIVERSITY

Graduate Studies and Research
Marquette, MI 49855-5301
906-227-2300
www.nmu.edu/graduatestudies/

Memorandum

TO: Matthew Kilgas
Ian Koskinen
School of Health and Human Performance

DATE: March 21, 2022

FROM: Lisa Schade Eckert
Dean of Graduate Studies and Research

SUBJECT: **IRB Proposal** HS22-1282
IRB Approval Date 3/21/2022
Proposed Project Dates: **6/13/2022 – 10/31/2022**
"Transcutaneous Electrical Stimulation to Reduce Exercise Induced Pain in the Biceps Brachii"

Your proposal "Transcutaneous Electrical Stimulation to Reduce Exercise Induced Pain in the Biceps Brachii" has been approved by the NMU Institutional Review Board. Include your proposal number (HS22-1282) on all research materials and on any correspondence regarding this project.

A. If a subject suffers an injury during research, or if there is an incident of non-compliance with IRB policies and procedures, you must take immediate action to assist the subject and notify the IRB chair (dereande@nmu.edu) and NMU's IRB administrator (leckert@nmu.edu) within 48 hours. Additionally, you must complete an Unanticipated Problem or Adverse Event Form for Research Involving Human Subjects.

B. Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding. Informed consent must continue throughout the project via a dialogue between the researcher and research participant.

C. If you find that modifications of investigators, methods, or procedures are necessary, you must submit a Project Modification Form for Research Involving Human Subjects before collecting data. Any changes or revisions to your approved research plan must be approved by the IRB prior to implementation.

Until further guidance, per CDC guidelines, the PI is responsible for obtaining signatures on the COVID-19 Researcher Agreement and Release and COVID-19 Research Participant Agreement and