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ORIGINAL SCIENTIFIC PAPER

Effect of Pulsed Electromagnetic Field Therapy on Recovery from Fatiguing Exercise: A Randomized Controlled Trial in Recreational Athletes

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Abstract

This study investigates the potential benefits of Pulsed Electromagnetic Field (PEMF) therapy for recovery following a fatiguing exercise protocol in recreational athletes. Despite growing interest in PEMF therapy for athletic recovery, few studies have evaluated its effects across a wide range of performance and recovery measures, particularly among recreationally active individuals. This study is the first-ever investigation to examine the effects of PEMF therapy on recovery from fatiguing exercise across multiple performance outcomes, including maximal strength, power, vertical jump height, and muscle soreness, in a sample of recreationally active college-aged individuals. Thirty participants (mean age: 23.7 ± 3.7 years; 19 males, 11 females) were randomly assigned to one of three recovery conditions: PEMF therapy (n=10), placebo (n=10), or control (n=10). The fatigue protocol used in this study was the Yo-Yo Intermittent Recovery Test Level 1 (YYIRT1), designed to induce neuromuscular fatigue. Recovery was assessed through quantitative measures of performance (peak power, peak cadence, vertical jump, and isometric strength) and qualitative measures of muscle soreness. No statistically significant differences were observed between the recovery groups in terms of performance outcomes. However, PEMF therapy did show trends toward improved recovery, particularly in peak power at 24, 48, and 72 hours post-exercise, and was the only group to show consistent reductions in muscle soreness. These findings underscore the need for further research in this area and suggest that PEMF therapy may offer marginal recovery benefits, particularly for perceived recovery and power restoration. This study addresses a crucial gap in the scientific literature by providing empirical evidence on the efficacy of PEMF therapy for recreational athletes, suggesting potential applications in non-elite athletic populations, though further research is required to confirm its mechanisms and long-term effects.

Keywords: PEMF · Electromagnetic Field · Medico-technology · Electro Therapy Trial · Elecrotherapy

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Introduction

Athletes employ a variety of strategies to optimize their performance, which typically include strength and conditioning programs, sport-specific skills training, and nutrition. Additionally, athletes may incorporate novel recovery modalities to enhance physical preparation and recovery, offering potential advantages. Recovery plays a crucial role in the athlete's preparation, defined as the restoration of homeostasis within various physiological systems after the metabolic, thermoregulatory, and inflammatory challenges imposed by exercise (Hausswirth & Le Meur, 2011). The goal of optimal recovery is to mitigate the fatigue or damage resulting from intense exercise, enabling the individual to either meet or exceed performance standards in specific activities (Bishop et al., 2008). Recovery strategies are commonly encouraged, as they facilitate physiological adaptations from training and enhance preparedness for subsequent training sessions or competitions.

Various recovery approaches have been advocated to accelerate the recovery process, such as massage (Zainuddin et al., 2005), compression (Hanson et al., 2013), and hot and cold water immersion (Ingram et al., 2009). A more recent, innovative method gaining attention for enhancing athletic performance is pulsed electromagnetic field (PEMF) therapy. In recent years, multiple companies have promoted the use of PEMF therapy (Almagia International, n.d.; Longoria & Gielen, n.d.; Pawluk, 2020). Lockie (2020) reviewed PEMF therapy specifically within the context of strength and conditioning. PEMF therapy utilizes a device that emits low-frequency electromagnetic currents across a broad range of frequencies, which may increase cell membrane permeability and stimulate various intracellular functions (Abdelhalim et al., 2019). One of PEMF's primary advantages is its non-invasive nature, requiring no electrode placement or any other invasive device (Chalidis et al., 2011; Hug & Röösli, 2012; Longoria & Gielen, n.d.). Numerous studies have acknowledged PEMF therapy as safe (Lisi et al., 2019; Wu et al., 2018), with most devices emitting frequencies lower than those of common electronic devices. For instance, a commercial PEMF device operates within the frequency range of 3-11,875 hertz (Hz) (HAELO, n.d.), significantly lower than those for television broadcasts (54-700 MHz), cellphones
(1.9-2.2 GHz), or diagnostic radiation such as magnetic resonance imaging (5-50 exahertz) (National Cancer Institute, n.d.). The frequency range of PEMF devices positions them in the non-ionizing radiation segment of the electromagnetic spectrum, which is not known to directly damage DNA or cells (National Cancer Institute, n.d.). Moreover, a systematic review across 11 studies on different PEMF applications (e.g., osteoarthritis, fibromyalgia, pain perception, heart rate variability) indicated no adverse treatment effects (Hug & Röösli, 2012). Therefore, PEMF therapy is considered to pose minimal risk to users.

While most PEMF research has focused on clinical applications (Hug & Röösli, 2012), there is emerging interest in its potential benefits for athletes. PEMF therapy has shown promise in accelerating injury healing (Almagia International, n.d.), with some scientific support for this claim. For example, PEMF has been employed to stimulate bone healing by mimicking mechanical loading effects (Hannouche et al., 2001; Victoria et al., 2009). When bones undergo mechanical stress, strain gradients create pressure gradients in the interstitial fluid, which drives fluid through the bone's canaliculae, exposing osteocyte membranes to shear stress and streaming electrical potentials (Duncan & Turner, 1995; Hannouche et al., 2001). These streaming potentials can contribute to mechanotransduction, where biophysical forces are converted into cellular responses (Duncan & Turner, 1995). An external electrical field can replicate these effects at fracture sites (Hannouche et al., 2001). PEMF therapy can also promote angiogenesis (formation of new blood vessels) and vasodilation (widening of blood vessels to increase blood flow) (Strauch et al., 2009). Strauch et al. (2009) suggested that PEMF aids in the treatment and management of post-surgical wounds, edema, and pain. However, research on PEMF therapy for athletic populations remains limited, highlighting the need for further investigation in this area.

Manufacturers have advocated for PEMF therapy as a means to enhance recovery from intense exercise (Longoria & Gielen, n.d.). informal reports suggest that PEMF may improve recovery by enhancing blood circulation, muscle oxygen uptake, and the removal of exercise-induced waste products (Pawluk, 2020; Schall & Ishee, 2008). Similar recovery modalities, such as sports massage, also promote blood circulation, aiding the inflammatory response post-exercise (Zainuddin et al., 2005). Intermittent pneumatic compression devices have been shown to assist with blood circulation, thereby facilitating the reabsorption of interstitial tissue swelling and promoting tissue healing (Chleboun et al., 1995; Hanson et al., 2013). For instance, Hanson et al. (2013) found those 20 minutes of intermittent pneumatic compression reduced blood lactate levels

in collegiate female athletes following a Wingate test compared to passive or active recovery. Therefore, if PEMF therapy can influence blood circulation, it may offer similar recovery benefits to those observed with massage therapy (Zainuddin et al., 2005) and intermittent pneumatic compression (Hanson et al., 2013). A logical next step in PEMF research would be to examine whether it can accelerate recovery from high-intensity activities, such as those requiring maximal strength and power.

Despite informal reports (Almagia International, n.d.; Pawluk, 2020; Schall & Ishee, 2008), there is a scarcity of research on PEMF therapy and recovery from exercise (Tamulevicius et al., 2021). If PEMF therapy proves effective for recovering physical performance following intense exercise, it offers potential benefits. As noted, PEMF therapy is non-invasive (Chalidis et al., 2011; Hug & Röösli, 2012; Longoria & Gielen, n.d.), which could be particularly advantageous for athletes. Given the design of the PEMF devices (e.g., cords, coils, and mats used while sitting or lying down) (Longoria & Gielen, n.d.; PEMF-Devices.com, n.d.), athletes could easily incorporate it into their training regimens if evidence supports its efficacy. However, Hannouche et al. (2001) emphasized that the underlying mechanisms of treatments like PEMF therapy remain insufficiently understood. Further research is required to determine whether PEMF therapy can enhance recovery from training and competition. Thus, this study aimed to assess whether PEMF therapy could improve recovery from fatiguing exercise. Recreationally trained college-aged men and women participated in this RCT study, utilizing a specific PEMF device (Longoria & Gielen, n.d.), which was compared to placebo and control conditions. Recovery interventions were implemented immediately after the fatigue protocol, as well as at 24, 48, and 72 hours post-fatigue (Magrini et al., 2018). The hypothesis was that PEMF therapy would accelerate recovery, as indicated by both qualitative measures of muscle soreness and quantitative assessments of maximal strength and power.

Method

Participants

Thirty recreationally active, college-aged participants (mean age: 23.7 ± 3.7 years; 19 males, 11 females) were involved in this study. The eligibility criteria required participants to be recreationally active, having engaged in aerobic or resistance exercise at a moderate-to-vigorous intensity for at least one hour, three times per week, over the past year. Additionally, participants had to be free from lower extremity injuries in the preceding six months and not have any other disabilities that could hinder their participation in the study. Participants were also required to complete a Physical Activity Readiness Questionnaire (PAR-Q) prior to participation. The sample size and group composition were consistent with other research investigating exercise recovery protocols (Ascensão et al., 2011; Jajtner et al., 2015). Prior to participation, all subjects provided written informed consent, which outlined the potential risks and benefits of participation, as well as a general overview of the study. The institutional review board approved the study (HSR-18-19-586), and the study adhered to the ethical guidelines set forth by the Declaration of Helsinki (World Medical Association, 1997).

Blinding and Randomization

Participants were randomly assigned to one of three recovery conditions: PEMF therapy, placebo, or control. The randomization process was conducted using block randomization to ensure an even distribution of participants across groups, accounting for variables such as sex and baseline fitness levels. Participants were blinded to their group allocation, meaning they were unaware of whether they were receiving the PEMF treatment, a placebo, or no external device in the control condition.

Assessors who conducted the performance and soreness assessments were also blinded to group allocation, ensuring that the evaluation of recovery outcomes was not influenced by knowledge of the treatment group. This was done to reduce potential biases in the measurement of the quantitative and qualitative recovery outcomes.

Control and Placebo Conditions

While the placebo group used a non-operational device during the recovery protocol, the control group did not receive any external treatment (i.e., they remained seated without any device). It is important to note that the control condition may not be fully equivalent to the placebo condition in terms of expectancy effects. Participants in the control group may have experienced psychological or cognitive factors due to their awareness that they were not receiving a treatment. In contrast, participants in the placebo group were unaware that the device was not activated, which could have influenced their expectations and perceived recovery. This difference could potentially confound the results, and therefore, the control

condition may not have provided a completely neutral comparison to the placebo treatment. This is a limitation of the study, and future research should consider addressing this by incorporating a more fully matched placebo condition.

Protocols

A RCT design was employed for this study, a methodology previously utilized in research investigating recovery protocols (Ascensão et al., 2011; Hanson et al., 2013; Jajtner et al., 2015). Participants were randomly assigned to one of three recovery conditions: PEMF therapy (subjects underwent 22 minutes and 32 seconds of PEMF therapy while holding a designated device); placebo (subjects sat for the same duration with a non-operational device, unbeknownst to them); and control (subjects remained seated for 22 minutes and 32 seconds with no external device). Due to the variety of variables examined, the researchers were unable to control all factors to ensure group balance. Consequently, block randomization was implemented, with each group consisting of 10 subjects (Suresh, 2011). Participants were randomly allocated to each group until the target group size was reached. Fatigue was induced using a 3-stage Yo-Yo fatigue protocol (Gathercole et al., 2015). Quantitative recovery measures were obtained through a 6-second peak power test on a cycle ergometer, vertical jump (VJ) performance to assess lower-body power, and isometric strength using a leg/back dynamometer. Recovery was also monitored qualitatively with a visual analogue scale (VAS) and Likert scale to rate muscle soreness. Recovery interventions were administered immediately following the fatigue protocol (0 hours), and at 24 hours, 48 hours, and 72 hours post-fatigue. Quantitative assessments were conducted at baseline (before the fatigue protocol), immediately after the 0-hour recovery intervention, and again at 24, 48, and 72 hours. Qualitative assessments of muscle soreness were recorded before and after each recovery intervention.

Prior to study participation, subjects were instructed to refrain from strenuous exercise during the 24-hour period leading up to each laboratory visit. Upon arrival for the first visit, participants completed the necessary documentation (informed consent, PAR-Q). Height was measured barefoot using a portable stadiometer (Detecto, Webb City, MO, USA), and body mass was recorded using electronic digital scales (Ohaus, Parsippany, NJ, USA). The structure of the testing protocol is outlined in Figure 1.

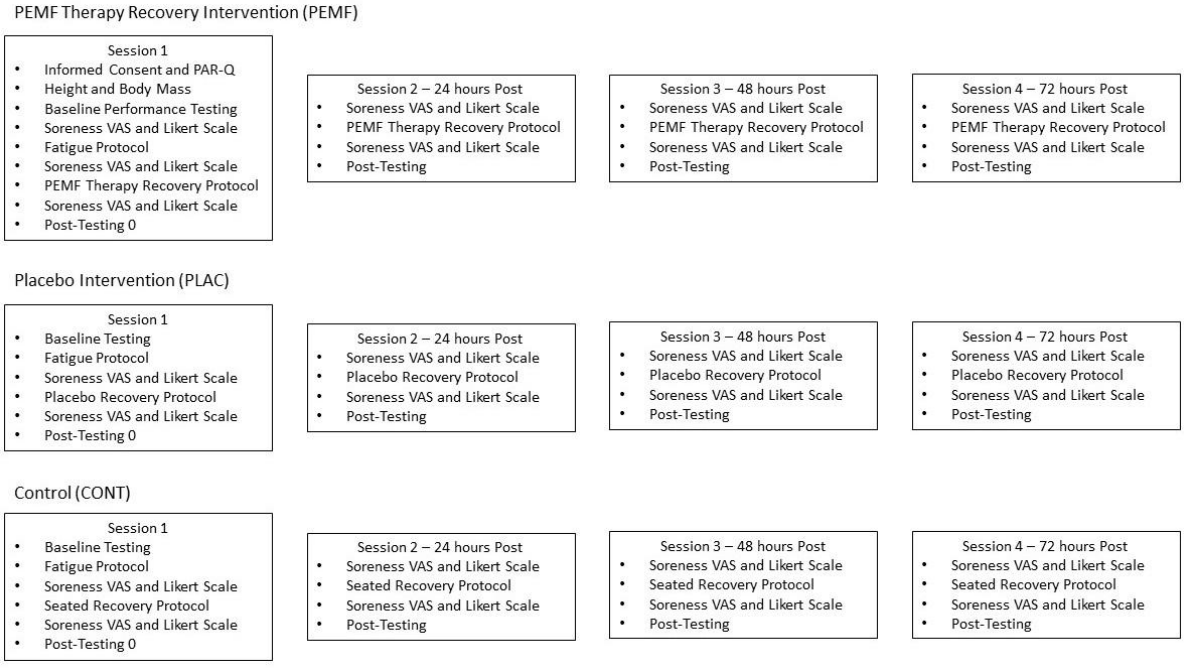

Figure 1. Structure for the study testing protocols for each of the recovery intervention groups (PEMF, PLAC, and CONT)

As noted, participants were randomly allocated to one of three recovery groups via block randomization (Suresh, 2011): PEMF therapy recovery intervention (PEMF), placebo recovery intervention (PLAC), and control condition (CONT). Before each testing session, all participants performed the same dynamic warm-up, which consisted of 5 minutes of cycling at a power output of 100-120 watts on a cycle ergometer (Wattbike Pro, Nottingham, UK), followed by three

maximal standing-start accelerations lasting approximately 2 seconds (Mendez-Villanueva et al., 2012). This was followed by 10 minutes of full-body dynamic stretching, including walking lunges, straight leg kicks, hip openers, side lunges with groin stretches, quadruped calf stretches, and leg swings. Performance testing was conducted prior to the fatigue protocol using procedures adapted from the literature (Magrini et al., 2018). Post-fatigue testing occurred at 0 hours (immediately after the recovery protocol), and at 24, 48, and 72 hours post-fatiguing exercise and recovery protocol. The testing battery was completed in the specified order, with approximately 2 minutes of rest between each test. Muscle soreness was assessed qualitatively before and after each subject's respective recovery protocol. Participants were instructed to maintain consistent dietary habits during the four days they attended the laboratory, refrain from engaging in intense lower-body exercise, and avoid using any supplementation (e.g., whey protein) or undergoing other recovery interventions (e.g., massage) that could influence recovery from the fatiguing exercise (Chleboun et al., 1995). Session 1 lasted approximately 90-120 minutes, while Sessions 2-4 were each approximately 40-50 minutes in duration.

Study Design and Randomization

The study utilized a randomized controlled trial (RCT) design, where participants were randomly assigned to one of three recovery conditions: PEMF therapy, placebo, or control. To ensure an even allocation of participants into each group, block randomization was employed. This approach ensures that each group receives an equal number of participants, reducing the risk of group imbalances that could arise through simple randomization. Block randomization was specifically chosen to control for potential confounders such as age, sex, and baseline fitness levels, guaranteeing that the groups would be equally distributed across these variables, which is essential for minimizing bias and maximizing the validity of the comparisons between groups.

Recovery Intervention and Treatment Duration

The PEMF treatment duration of 22:32 minutes was based on manufacturer recommendations for the HAELO Symphony One device. The manufacturer's guidelines suggest this time frame as optimal for the "Recovery" setting, which is specifically designed to enhance muscle recovery following fatiguing exercise. This treatment duration was chosen to ensure consistency with the device's intended therapeutic use and to align with previously recommended PEMF durations used in clinical settings for recovery and pain management. Research in related fields has shown that 20-30 minutes of PEMF exposure is effective in promoting recovery, with no adverse effects noted.

6-second (s) Peak Power Test

Following the dynamic warm-up, the initial performance test was the 6-second peak power sprint, conducted on a factory-calibrated cycle ergometer (Wattbike Pro, Nottingham, UK). This equipment is widely utilized for testing and training purposes within athletic populations (Grainger & Neville, n.d.; Herbert et al., 2015; Wehbe et al., 2015). The cycle ergometer used in this study employed both air-braked and magnetically-braked resistance systems. The air-braked resistance was controlled by a lever that regulated airflow through the flywheel, with 10 adjustable levels, while the magnetically-braked resistance was adjusted via a turn dial, offering 7 resistance levels. The configuration for each participant on the cycle ergometer was adapted from established protocols in the literature (Herbert et al., 2015). Saddle height was set to allow near full knee extension (approximately 170°) when the foot was at the bottom of the pedal stroke. The fore and aft positioning of the saddle was adjusted to ensure the knee tip was aligned with the pedal's center when the feet were horizontal. Handlebar height was matched to the saddle height, and the fore and aft position of the handlebars was modified so that the arms formed approximately a 90° angle with the torso. Foot straps secured the feet to the pedals. This setup was consistently recorded to ensure the same configuration was used for each 6-second sprint test across all testing sessions.

The procedures for the 6-second sprint test were based on established protocols from the literature (Herbert et al., 2015; Wehbe et al., 2015), with two trials performed (Wehbe et al., 2015). The resistance for each participant's sprint was determined in accordance with the guidelines provided by the cycle ergometer manufacturer (Wattbike UK, n.d.). The sprint was initiated from a stationary seated position, and participants were instructed to remain seated throughout the test. The test began with a 5-second countdown followed by a clear verbal command to start, and participants received strong verbal encouragement during the 6-second sprint. The test concluded with another firm verbal command. Participants were instructed to reach peak power as quickly as possible. After the first trial, in accordance with Wehbe et al. (2015), a 60-second active recovery phase was performed, where participants pedaled at a self-selected cadence with both the air-braked and magnetically-braked

resistance adjusted to Level 1. Following the active recovery, a second 6-second maximal sprint was performed, maintaining the same starting position and resistance settings. Peak power (PP) and peak cadence (PC) were recorded for both sprints, and the best sprint was used for analysis.

Vertical Jump (VJ)

The vertical jump (VJ) test was utilized to assess recovery from fatigue, as both eccentric capacity and the stretch-shortening cycle are critical factors in jump performance (Magrini et al., 2018). A jump mat (Probotics Inc., Alabama, USA) was used to measure jump height, following established protocols (Magrini et al., 2018). To assess VJ height, the participant began on the jump mat. In accordance with Magrini et al. (2018), five consecutive countermovement vertical jumps were performed, with a 10-second rest interval between each jump. There were no restrictions on the depth of the countermovement, but participants were instructed to jump as high and explosively as possible. Jump height was determined using the software associated with the jump mat, and the results were converted from inches to centimeters. The average of the five trials was then calculated.

Isometric Leg/back Dynamometer Strength Test

Following completion of the jumps, subjects completed the isometric strength test using a leg/back dynamometer (Fabrication Enterprises, Inc., New York, USA) (Magrini et al., 2018). The dynamometer measurement provided a metric of leg/back isometric maximal strength (LBD). Subjects were positioned so that their arms were extended and both hands were on the handle positioned at the mid-thigh (knee flexion angle of approximately 110°) (Magrini et al., 2018). From here, and while maintaining proper spinal alignment and their feet flat on the base, recruits pulled the handle upward as hard as possible by attempting to extend the hips and knees. Subjects completed three trials with 60-s rest between attempts (Magrini et al., 2018). Measurements were taken to the nearest kilogram, with the best trial at each time point used for analysis.

Qualitative Measures of Muscle Soreness

Qualitative assessments of muscle soreness were recorded at multiple time points (Figure 1), including:

Immediately following the fatigue protocol and prior to the recovery protocol;

Immediately following the recovery protocol (0 hours);

Before and after the recovery protocol at 24 hours;

Before and after the recovery protocol at 48 hours; and

Before and after the recovery protocol at 72 hours.

Two distinct scales were employed to measure soreness. The first was a visual analogue scale (VAS), which consisted of a 100-mm (10-cm) line with endpoints labeled "No Soreness" and "Extremely Sore" (Figure 2) (Delextrat et al., 2013).

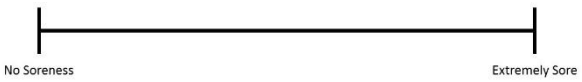

Figure 2. Visual analogue scale for muscle soreness (not to scale)

Participants indicated the point on the line that most accurately reflected their perceived level of soreness, and the distance from the leftmost endpoint was measured to the nearest 1 mm (Delextrat et al., 2013). The second method was a Likert scale, as shown in Table 1 (Gibson et al., 2006), where participants selected the box that best represented their level of soreness at the time of the test.

Table 1. Modified Likert scale used in muscle soreness assessment

Please check the sentence below that best describes your level of muscle soreness.	
( ) 0	A complete absence of soreness
( ) 1	A light soreness in the muscle/s felt only when touched/a vague ache
( ) 2	A moderate soreness felt only when touched/a slight persistent pain
( ) 3	A light muscle soreness when walking up and down stairs
( ) 4	A light muscle soreness when walking on a flat surface
( ) 5	A moderate muscle soreness, stiffness, or weakness when walking
( ) 6	A severe muscle soreness, stiffness, or weakness that limits my ability to move

Fatigue Protocol

After completing the warm-up and baseline assessment during the first testing session, participants proceeded with the fatigue protocol, which was adapted from Gathercole et al. (2015). A 3-stage Yo-Yo fatiguing protocol (Figure 3) was performed indoors on a basketball court to induce neuromuscular fatigue. Initially, the Yo-Yo Intermittent Recovery Test 1 (YYIRT1) was conducted twice consecutively. The YYIRT1 consists of repeated 2 x 20 m sprints at progressively increasing speeds, which were controlled by audio beeps emitted from an iPad handheld device (Apple Inc., Cupertino, California) connected via Bluetooth to a portable speaker (JBL FLIP 5, Los Angeles, CA) placed adjacent to the running lane, marked by specific markers. Between each sprint, participants had a 10-second rest period, during which they were required to move to a cone placed 5 meters away before returning to the starting line. As outlined by Gathercole et al. (2015), the YYIRT1 includes four runs at speeds of 10-13 kilometers per hour ($km \cdot hr^{-1}$) and seven runs at speeds of 13.5-14 $km \cdot hr^{-1}$. The protocol then continues with 0.5 $km \cdot hr^{-1}$ speed increments after every eight runs until exhaustion.

Following the completion of the YYIRT1 twice, participants moved on to the Yo-Yo Intermittent Endurance Test Level 1 (YYIET1). The YYIET1 also consists of 2 x 20 m sprints at progressively increasing speeds but with shorter recovery intervals of 5 seconds between each shuttle. During these recovery periods, participants were required to move to a cone placed 2.5 meters away from the starting line before returning. The same iPad (Apple Inc., Cupertino, California) and Bluetooth portable speaker (JBL FLIP 5, Los Angeles, CA) were used for the YYIET1. The initial speed for the YYIET1 was 8 $km \cdot hr^{-1}$, increasing by 1 $km \cdot hr^{-1}$ after each of the first two stages (Castagna et al., 2006). The protocol then continued with 0.5 $km \cdot hr^{-1}$ speed increments after each stage until failure (Castagna et al., 2006).

This study utilized the Level 1 versions of the YYIRT and YYIET tests, which differed from the Level 2 versions used in the original protocol by Gathercole et al. (2015). However, similar to Gathercole et al. (2015), the primary aim of the 3-stage Yo-Yo fatiguing protocol was to induce fatigue rather than measure physiological capacity. During the final stages of the protocol, participants were encouraged to continue performing each Yo-Yo test, regardless of whether they completed the shuttle runs within the designated time. Thus, participants voluntarily terminated the exercise only when they determined they could no longer continue. Between each Yo-Yo test and following the final test, participants completed 5 minutes of active recovery (i.e., walking without sitting) and were allowed to drink water as needed (Gathercole et al., 2015). After completing the fatigue protocol, participants proceeded with their assigned recovery intervention and subsequent post-testing.

Recovery Procedures

Following the completion of the fatigue protocol and active cooldown, participants were seated and began their designated recovery protocol. The timing for the initiation of the recovery protocol was adapted from previous studies that utilized recovery interventions (Hanson et al., 2013; Robertson et al., 2004) and adhered to the manufacturer's recommendations. For the PEMF group, participants used a PEMF device (HAELO, Encino, CA, USA), which included a Symphony One unit and magnetic coil (Longoria & Gielen, n.d.). The unit's dimensions were 0.26 m x 0.20 m x 0.08 m, with a mass of approximately 2.5 kg (HAELO, n.d.). The device operated within a frequency range of 3-11,875 Hz and had a coil resistance of 1.01 Ohm (HAELO, n.d.). The researcher controlled the device through an app (HAELO, Encino, CA, USA) via Bluetooth. The frequency set labeled 'Recover' was selected, as recommended by the manufacturer. The exact electromagnetic frequency emitted by the coil during this setting was not disclosed to the researchers for proprietary reasons. However, the manufacturer described the frequency set as promoting "deep recovery of muscles, bones, ligaments, and fascia after strenuous exercise or competition that typically results in soreness, stiffness, and pain. It supports rapid recovery for regular and consistent routines" (Longoria & Gielen, n.d.). While seated, participants held the PEMF device against their chest, as per the manufacturer's instructions. The duration of the frequency set was 22 minutes and 32 seconds. Based on a meta-analysis of PEMF literature, Wu et al. (2018) recommended exposure durations of ≤30 minutes for enhanced efficacy in pain relief and functional recovery. While this meta-analysis focused on osteoarthritis (Wu et al., 2018), the suggested time frame is relevant to the current study, particularly in terms of muscle soreness recovery and pain relief.

For the placebo (PLAC) group, participants held the device to their chest for 22 minutes and 32 seconds during the recovery protocol, but the device was not activated, and participants were unaware that it was not turned on. In the control condition, participants

remained seated in a chair without an external device for the same duration of 22 minutes and 32 seconds, matching the length of the PEMF therapy protocol. Recovery interventions were also conducted at 24 hours, 48 hours, and 72 hours following the fatiguing exercise. This protocol was adapted from previous research involving intermittent pneumatic compression applied for several days post-fatigue (Chleboun et al., 1995). Additionally, manufacturer guidelines recommended multiple applications of the 'Recover' frequency set, which was incorporated into the study.

Statistical Analysis

Statistical analyses were performed using the Statistics Package for Social Sciences (SPSS) Version 29.0 (IBM Corporation, New York, USA). Data normality was assessed using the Shapiro-Wilk test and visual inspection of stem-and-leaf plots. In cases where a variable was not normally distributed, extreme outliers (defined as data points more than 3 box lengths away from the box in the plot) were addressed through a Winsorization procedure (Lien & Balakrishnan, 2005). Descriptive statistics (mean ± standard deviation [SD]) were computed for each variable. A one-way analysis of variance (ANOVA) was conducted to compare age, height, and body mass across groups. For the recovery protocol analyses, sex was included as a covariate in all repeated measures analysis of covariance (ANCOVA) calculations, with statistical significance set at $p < 0.05$. If a significant interaction between groups was observed in any part of the analysis, a Bonferroni adjustment was applied for post hoc comparisons. For the quantitative outcomes (PP, PC, VJ, and LBD), a 3 (PEMF, PLAC, CONT) x 5 (baseline, 0 hours, 24 hours, 48 hours, 72 hours) repeated measures ANCOVA was conducted to assess differences between the recovery interventions. Change scores, calculated as the difference between the post-test at each time point and baseline values (Cocke et al., 2016), were analyzed using a 3 (PEMF, PLAC, CONT) x 4 (0-baseline, 24-baseline, 48-baseline, 72-baseline) repeated measures ANCOVA.

For the qualitative measures (VAS and Likert scale), data normality was again evaluated using the Shapiro-Wilk test and visual inspection of stem-and-leaf plots. As noted, the majority of the qualitative data did not follow a normal distribution. Ordinal scale data, such as that obtained from the VAS and Likert scales, can often exhibit non-normal distributions (Jamieson, 2004). Nevertheless, Norman (2010) suggested that parametric statistics may still be applicable to ordinal data derived from Likert scales. Additionally, ANCOVAs are known to be robust to violations of normality (Olejnik & Algina, 1984). Therefore, parametric statistics were applied in the analysis of the qualitative data. Paired samples t-tests were initially used to determine if there were significant changes in perceived recovery before and after each session's intervention. Effect sizes (d) were calculated for pre- and post-recovery intervention values within each session, where the difference between the means was divided by the pooled standard deviation (Cohen, 1988). A d value of less than 0.2 indicated a trivial effect; 0.2 to 0.6 signified a small effect; 0.6 to 1.2 represented a moderate effect; 1.2 to 2.0 denoted a large effect; 2.0 to 4.0 indicated a very large effect; and 4.0 or greater was considered an extremely large effect (Hopkins, 2004).

Subsequently, a 3 (PEMF, PLAC, CONT) x 8 (baseline, 0 hours, 24 hours pre, 24 hours post, 48 hours pre, 48 hours post, 72 hours pre, 72 hours post) repeated measures ANCOVA was used to analyze changes in perceived recovery across the interventions. Finally, change scores within each session were calculated for the qualitative measures to determine if any intervention resulted in a greater magnitude of change in perceived recovery. A 3 (PEMF, PLAC, CONT) x 4 (0 hours-baseline, 24 hours post-pre, 48 hours post-pre, 72 hours post-pre) repeated measures ANCOVA was employed for this analysis.

Results

All data for peak power (PP), peak cadence (PC), vertical jump (VJ), and leg/back dynamometer (LBD) were normally distributed ($p = 0.117$-0.779). However, change scores at 24 hours relative to baseline, as well as PC48-baseline, LBD48-baseline, and PC72-baseline, did not follow a normal distribution ($p \leq 0.011$). After addressing the extreme outliers, all change score variables became normally distributed ($p = 0.052$-0.846). No significant differences in age, height, or body mass were observed across the groups (Table 2), although the control (CONT) group contained a higher proportion of women compared to the other two groups due to random allocation.

Table 2. Descriptive (mean ± SD) data for age, height, and body mass for college aged men and women allocated to the pulsed electromagnetic therapy (PEMF), placebo (PLAC), or control (CONT) recovery conditions groups

	PEMF (7 men, 3 women)	PLAC (7 men, 3 women)	CONT (4 men, 6 women)
Age (years)	23.10 ± 3.54	25.20 ± 4.54	22.70 ± 3.34
Height (m)	1.65 ± 0.10	1.70 ± 0.05	1.71 ± 0.12
Body Mass (kg)	70.70 ± 12.34	77.29 ± 13.44	74.93 ± 17.62

For PP, the main effect of time was significant ($F_{(4,23)} = 7.169$, $p < 0.001$, $\eta p^2 = 0.555$). The time by group ANCOVA ($F_{(8,48)} = 1.007$, $p = 0.443$, $\eta p^2 = 0.144$) and main effect between groups ($F_{(2,26)} = 0.699$, $p = 0.506$, $\eta p^2 = 0.051$) were not significant. Across all groups, PP0 was significantly lower than PP at all other times ($p \leq 0.003$). Baseline PP was significantly lower than PP48 ($p = 0.007$) and PP72 ($p = 0.010$). For the PP change scores, the main effect of time was significant ($F_{(3,24)} = 7.374$, $p < 0.001$, $\eta p^2 = 0.512$). Across the groups, PP0-baseline difference was significantly ($p < 0.001$) lower than PP differences compared to baseline at 24, 48, and 72 hours. The time by group ANCOVA ($F_{(6,50)} = 0.909$, $p = 0.496$, $\eta p^2 = 0.098$) and main effect between groups ($F_{(2,26)} = 1.407$, $p = 0.263$, $\eta p^2 = 0.098$) were not significant. Although it was not significant, the PEMF group had a magnitude of change that was 11-385% greater at 24 hours, 16-109% greater at 48 hours, and 31-190% greater at 72 hours.

Demographic Characteristics

The participants' demographic characteristics are as follows:

- Age: 23.7 ± 3.7 years
- Height: 1.68 ± 0.09 m
- Body Mass: 73.16 ± 14.18 kg

These values are consistent with typical recreationally active populations, and the sample included both male (n=19) and female (n=11) participants. Table 2 provides a breakdown of the demographic characteristics of participants in each recovery condition group. Descriptive statistics for the quantitative measures are provided in Table 3, and the change scores for PP, PC, VJ, and LBD are illustrated in Figure 3.

Table 3. Descriptive (mean ± SD) data for peak power (PP), peak cadence (PC), vertical jump (VJ), and leg/back dynamometer (LBD) strength recorded at baseline, and immediately after (0 hours), 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women who received pulsed electromagnetic therapy (PEMF), a placebo (PLAC), or control (CONT) recovery conditions

	PEMF ($n = 10$)	PLAC ($n = 10$)	CONT ($n = 10$)	All ($N = 30$)
PP Baseline (watts)	927.25 ± 296.28	910.70 ± 244.00	887.75 ± 345.80	908.57 ± 288.28*
PP0 (watts)	884.85 ± 285.55	871.40 ± 213.37	831.05 ± 301.12	862.43 ± 260.99
PP24 (watts)	1005.45 ± 311.03	959.90 ± 248.97	899.05 ± 310.21	954.80 ± 284.76*
PP48 (watts)	996.10 ± 304.28	943.60 ± 217.64	947.00 ± 331.86	962.23 ± 279.66*§
PP72 (watts)	997.25 ± 309.12	964.10 ± 204.66	911.90 ± 277.73	957.75 ± 260.52*§
PC Baseline (revolutions)	148.10 ± 16.86	141.00 ± 15.79	136.80 ± 12.68	141.97 ± 15.43
PC0 (revolutions)	148.55 ± 17.06	139.10 ± 14.88	135.15 ± 10.56	140.93 ± 15.04
PC24 (revolutions)	152.85 ± 19.93	145.15 ± 17.65	139.40 ± 11.02	145.80 ± 17.00*
PC48 (revolutions)	152.25 ± 16.83	147.75 ± 17.96	141.55 ± 10.58	147.18 ± 15.58*§
PC 72 (revolutions)	151.45 ± 16.33	142.14 ± 20.49	140.15 ± 9.85	144.58 ± 16.38
VJ Baseline (cm)	47.22 ± 12.40	38.16 ± 7.73	38.84 ± 9.78	40.74 ± 10.86
VJ0 (cm)	45.42 ± 11.91	37.34 ± 7.28	36.04 ± 9.37	39.60 ± 10.27
VJ24 (cm)	50.25 ± 12.10	39.54 ± 6.51	35.81 ± 9.93	41.87 ± 11.31
VJ48 (cm)	46.20 ± 11.19	40.48 ± 7.45	37.70 ± 10.50	41.46 ± 10.16
VJ72 (cm)	46.74 ± 12.33	40.94 ± 7.66	37.29 ± 8.96	41.66 ± 10.29
LBD Baseline (kg)	125.07 ± 30.96	136.99 ± 38.45	120.52 ± 30.67	127.53 ± 33.14
LBD0 (kg)	122.48 ± 36.76	137.98 ± 38.99	123.69 ± 28.38	128.05 ± 34.53
LBD24 (kg)	144.07 ± 57.88	145.58 ± 36.79	130.13 ± 34.81	139.93 ± 43.42
LBD48 (kg)	137.63 ± 50.30	138.96 ± 34.81	133.31 ± 37.94	136.63 ± 40.17
LBD72 (kg)	135.24 ± 39.60	150.79 ± 43.62	134.69 ± 36.43	140.24 ± 39.33

* Significantly different from 0 hours; § Significantly different from baseline

For PC, the main effect of time was significant ($F_{(4,23)}$ = 4.355, p = 0.009, ηp^2 = 0.431). The time by group ANCOVA ($F_{(8,48)}$ = 0.569 p = 0.798, ηp^2 = 0.087) and main effect between groups ($F_{(2,26)}$ = 1.189, p = 0.321, ηp^2 = 0.084) were not significant. Across the groups, PC0 was significantly lower than PC24 (p = 0.002) and PC48 (p < 0.001). Baseline PC was significantly lower than PP48 (p = 0.002). With regards to the change scores, there was a significant main effect for time ($F_{(3,24)}$ 5.356, p = 0.006, ηp^2 = 0.401). The difference compared to baseline at 0 hours was significantly (p < 0.001) lower than at 24, 48, and 72 hours across all groups The time by group ANOVA ($F_{(6,50)}$ = 0.932, p = 0.481, ηp^2 = 0.101) and main effect between groups ($F_{(2,26)}$ = 0.376, p = 0.690, ηp^2 = 0.028) were not significant.

For the VJ, the main effect of time ($F_{(4,23)}$ = 0.854, p = 0.506, ηp^2 = 0.129), time by group ANCOVA ($F_{(8,48)}$ = 1.218, p = 0.309, ηp^2 = 0.169), and main effect between groups ($F_{(2,26)}$ = 3.381, p = 0.050, ηp^2 = 0.206) were not significant. Regarding the change scores, the main effect of time ($F_{(3,24)}$ = 1.144, p = 0.352, ηp^2 = 0.125), time by group ANCOVA ($F_{(6,50)}$ = 1.797, p = 0.119, ηp^2 = 0.177), and main effect between groups ($F_{(2,26)}$ = 1.075, p = 0.356, ηp^2 = 0.076) were not significant.

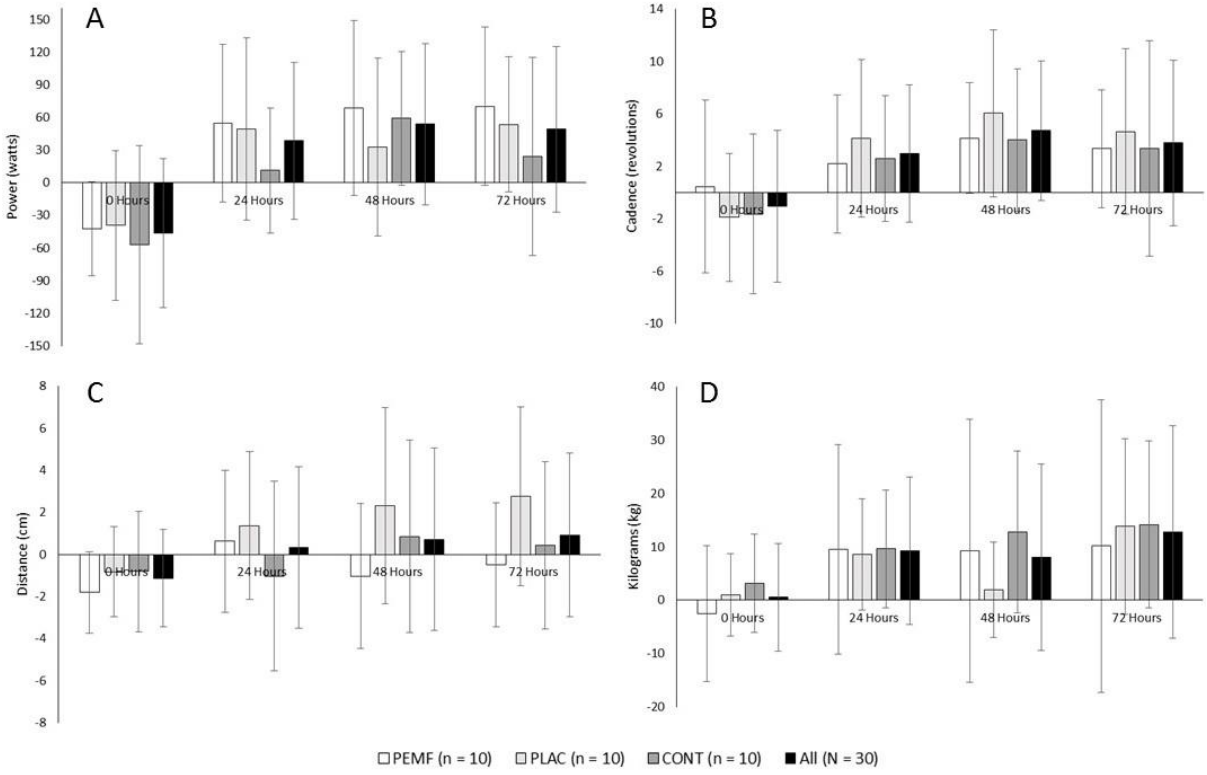

Figure 3. Descriptive (mean ± SD) data for change scores relative to baseline for peak power (A), peak cadence (B), vertical jump (C), and leg/back dynamometer strength (D) recorded at 0 hours, 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women who received pulsed electromagnetic therapy (PEMF), a placebo (PLAC), or control (CONT) recovery conditions

Regarding the LBD, the main effect of time ($F_{(4,23)}$ = 1.085, p = 0.387, ηp^2 = 0.159), time by group ANCOVA ($F_{(8,48)}$ = 0.939, p = 0.494, ηp^2 = 0.135), and main effect between groups ($F_{(2,26)}$ = 0.622, p = 0.545, ηp^2 = 0.046) were not significant. That same was true for the LBD change scores. The main effect of time ($F_{(3,24)}$ = 1.332, p = 0.287, ηp^2 = 0.143), time by group ANCOVA ($F_{(6,50)}$ = 1.119, p = 0.365, ηp^2 = 0.118), and main effect between groups ($F_{(2,26)}$ = 0.400, p = 0.674, ηp^2 = 0.030) were not significant. Although not significant, it was notable that the PEMF group did have the highest magnitude for their change scores at 24 hours post-fatiguing activity, with a difference of 21-54% compared to the PLAC and CONT groups.

Only two out of the twelve visual analogue scale (VAS) variables were normally distributed (0-baseline, p = 0.108; VAS Pre at 48 hours, p = 0.624); all other variables deviated from normality (p ≤ 0.037). Additionally, all Likert scale variables were not normally distributed (p ≤ 0.043). However, as previously mentioned, parametric

statistical methods were applied to analyze the qualitative data (Norman, 2010; Olejnik & Algina, 1984), and the results are presented as mean ± standard deviation (SD).Comparisons between pre- and post-recovery session scores for the VAS and Likert scales are shown in Table 4. Few significant differences were observed between pre- and post-recovery intervention scores across the groups. Notably, a significant decrease with a moderate effect was observed in the Likert scale score for the PEMF group 72 hours after the fatiguing protocol, suggesting a positive impact of the intervention on recovery. A significant decrease was also noted in the Likert scale score for the control (CONT) group 24 hours after the fatiguing protocol, with a moderate effect. It is important to highlight that, for the PEMF group, although the effects were generally small, the post-intervention VAS or Likert scale scores at 24, 48, and 72 hours were consistently lower than the pre-intervention scores. This was not the case for the placebo (PLAC) and CONT groups.

Table 4. Descriptive (mean ± SD) data for pre- and post-recovery intervention for the visual analogue scale (VAS) and Likert scale immediately after (0 hours), 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college-aged men and women who received pulsed electromagnetic therapy (PEMF), a placebo (PLAC), or control (CONT) recovery conditions

	PEMF (n = 10)				PLAC (n = 10)				CONT (n = 10)			
	Pre	Post	p	d	Pre	Post	p	d	Pre	Post	p	d
VAS												
Baseline-0	2.65 ± 1.44	3.28 ± 2.00	0.366	0.301	1.80 ± 1.97	1.78 ± 1.63	0.930	0.029	2.78 ± 1.99	2.85 ± 1.67	0.873	0.052
24 Hours	2.93 ± 1.66	2.90 ± 1.40	0.954	0.019	2.23 ± 1.81	1.88 ± 1.40	0.343	0.316	1.44 ± 0.52	1.43 ± 0.61	0.969	0.013
48 Hours	2.23 ± 1.60	1.88 ± 1.22	0.105	0.569	1.95 ± 1.30	1.75 ± 1.16	0.280	0.363	1.65 ± 1.29	1.35 ± 1.29	0.394	0.283
72 Hours	2.73 ± 2.41	2.46 ± 2.50	0.128	0.531	1.10 ± 1.37	1.00 ± 0.85	0.779	0.091	2.05 ± 0.60	1.95 ± 0.64	0.555	0.194
Likert												
Baseline-0	2.50 ± 1.65	2.40 ± 1.84	0.832	0.069	1.70 ± 1.77	2.00 ± 1.15	0.496	0.224	1.30 ± 1.16	1.49 ± 1.63	0.604	0.170
24 Hours	2.30 ± 1.06	1.90 ± 0.88	0.223	0.414	2.30 ± 1.70	1.90 ± 1.37	0.343	0.316	2.00 ± 1.25	1.30 ± 0.68*	0.025	0.850
48 Hours	1.90 ± 1.20	1.79 ± 1.34	0.343	0.316	1.90 ± 1.37	2.00 ± 1.25	0.832	0.069	1.60 ± 1.35	1.60 ± 0.97	1.000	0.000
72 Hours	2.00 ± 1.63	1.50 ± 1.65*	0.015	0.949	1.40 ± 1.17	1.40 ± 1.17	1.000	0.000	1.20 ± 0.42	1.60 ± 0.84	0.223	0.414

* Significantly ($p < 0.05$) different from the session pre-recovery protocol value

When comparing the qualitative measures across the groups for all the time points, there was a general trend for the qualitative measures to all decrease over time. Nonetheless, the main effect of time ($F_{(7,20)}$ = 0.667, p = 0.697, ηp^2 = 0.189), time by group ANCOVA ($F_{(14,42)}$ = 0.983, p = 0.486, ηp^2 = 0.247), and main effect between groups ($F_{(2,26)}$ = 2.271, p = 0.123, ηp^2 = 0.149) were not significant for the VAS (Figure 4A). This was also the case for the Likert scale data (Figure 4B).

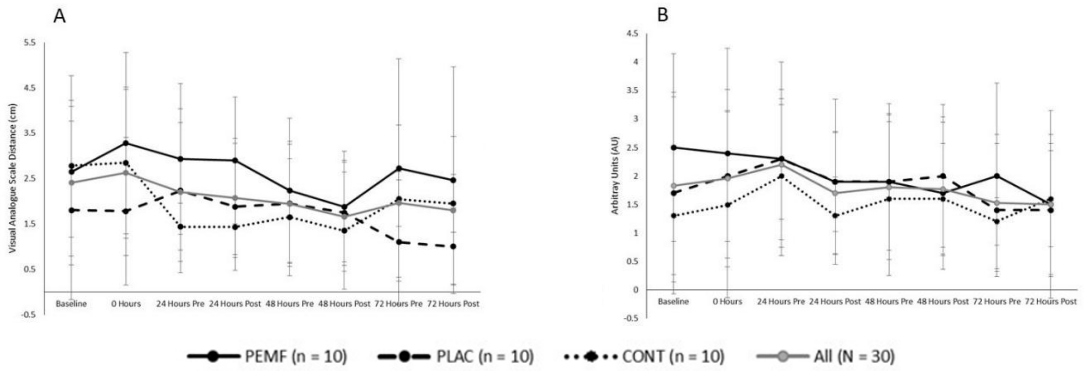

Figure 4. Descriptive (mean ± SD) data for visual analogue scale (VAS; A) and Likert scale (B) values recorded at baseline, immediately after the first recovery protocol (0 hours), and pre- and post-recovery protocol 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women who received pulsed electromagnetic therapy (PEMF), a placebo (PLAC), or control (CONT) recovery conditions

The main effect of time ($F_{(7,20)}$ = 1.704, p = 0.165, ηp^2 = 0.374), time by group ANCOVA ($F_{(14,42)}$ = 0.939, p = 0.528, ηp^2 = 0.238), and main effect between groups ($F_{(2,26)}$ = 1.052, p = 0.364, ηp^2 = 0.075) were not significant. Change score data relative to the baseline for the VAS and Likert scale is shown in Figure 5. A negative value indicates less fatigue and soreness and better recovery. For the VAS change scores in each testing day (Figure 5A), the main effect of time ($F_{(3,24)}$ = 0.121, p = 0.947, ηp^2 = 0.015), time by group ANCOVA ($F_{(6,50)}$ = 0.373, p = 0.893, ηp^2 = 0.034), and main effect between groups ($F_{(2,26)}$ = 0.167, p = 0.847, ηp^2 = 0.013) were not significant. This was also the case for the Likert scale (Figure 5B); the main effect of time ($F_{(3,24)}$ = 2.810, p = 0.061, ηp^2 = 0.260), time by group ANCOVA ($F_{(6,50)}$ = 1.273, p = 0.286, ηp^2 = 0.133), and main effect between groups ($F_{(2,26)}$ = 1.209, p = 0.315, ηp^2 = 0.085) were not significant. Although not significant, what was notable was that the PEMF had VAS and Likert scale scores that indicated recovery at 24, 48, and 72 hours, with 165-225% differences for both scales at 72 hours post-fatiguing protocol.

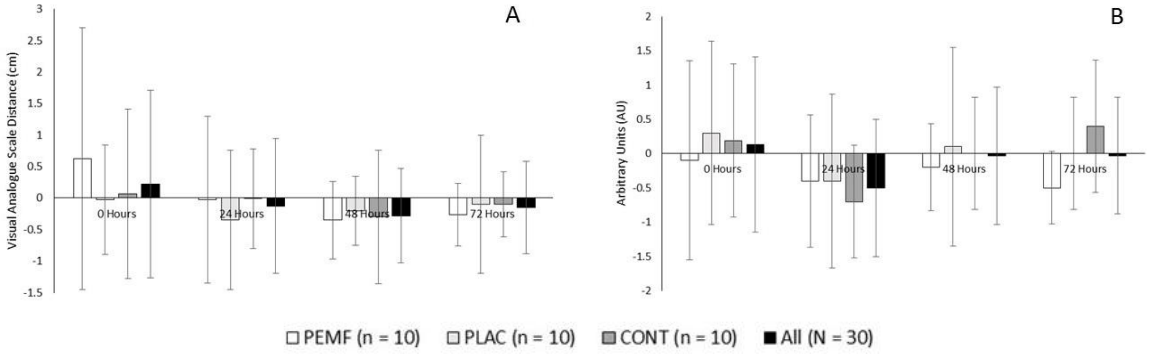

Figure 5. Descriptive (mean ± SD) data for change scores within each session for visual analogue scale (VAS; A) and Likert scale (B) values recorded at 0 hours, 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women who received pulsed electromagnetic therapy (PEMF), a placebo (PLAC), or control (CONT) recovery conditions

Discussion

The objective of this study was to determine whether the use of PEMF therapy following a fatiguing exercise protocol would lead to improved recovery compared to a placebo and control group. It was hypothesized that PEMF therapy would enhance recovery from fatiguing exercise, as indicated by quantitative measures of maximal strength and power (6-s cycling test PP and PC, VJ height, and LBD) and qualitative measures of muscle soreness (VAS and Likert scale scores). However, the results generally did not support these hypotheses, as no significant differences were found between the treatments. Despite this, the PEMF group demonstrated larger, non-significant improvements in PP from the 6-s cycling sprint test at 24, 48, and 72 hours. Additionally, although not statistically significant, the qualitative measures (VAS and Likert scale) indicated recovery post-intervention at each time point, with a significant decrease in Likert scale scores from pre- to post-intervention at 72 hours. While the current results did not reach statistical significance, these modest changes in performance and perceived recovery could be crucial for more effective training and competition success, especially given the small margins that often determine victory in athletic performance (Hall et al., 2012).

As mentioned, the study found no significant differences between recovery protocols. Previous research has also shown non-significant effects from various recovery interventions, such as massage (Robertson et al., 2004), stretching (Torres et al., 2013), and pneumatic compression (Overmayer & Driller, 2018), and there has been skepticism regarding the benefits of PEMF therapy in clinical settings (Wade, 2013). However, for PP measured during the 6-s cycling sprint test, the PEMF group exhibited larger change scores compared to the placebo (PLAC) and control (CONT) groups, with improvements ranging from 11-385% at 24 hours, 16-109% at 48 hours, and 31-190% at 72 hours. As recovery is defined as the restoration of homeostasis in physiological systems following exercise-induced challenges (Hausswirth & Le Meur, 2011), these results may suggest that the PEMF group experienced a more substantial positive change in PP compared to baseline after the intervention. Although not measured in this study,

there are several physiological mechanisms associated with PEMF therapy that may aid recovery. For example, PEMF therapy has been shown to stimulate angiogenesis (formation of new blood vessels) and vasodilation (widening of blood vessels), both of which contribute to recovery (Strauch et al., 2009). Furthermore, PEMF therapy can enhance the structural integrity of the extracellular matrix of bone and cartilage, supporting repair and altering homeostatic balance (Peng et al., 2021). Prior research has suggested that PEMF therapy could positively influence ventilatory threshold in endurance runners after six sessions (Tamulevicius et al., 2021). The findings from this study imply that PP could be positively affected by PEMF therapy over the 72 hours following fatiguing exercise.

Although the results were not statistically significant, the relatively large percentage differences in change scores should not be overlooked. Peak power in this study is calculated using the formula: force x (distance/time) (Grainger & Neville, n.d.). Force and movement speed are critical factors for athletes across various sports, and any intervention that facilitates a faster restoration of these variables, especially between training sessions and competitions, would be valuable. Sir Dave Brailsford's marginal gains theory posits that small improvements in multiple areas can cumulatively lead to greater success for athletes (Hall et al., 2012). Minor performance improvements, resulting from faster recovery, could be crucial for athletes competing in events where victory margins are measured in fractions of a second. Adequate recovery restores both physiological and psychological functions, enabling athletes to perform or train at the required level (Halson, 2013). It is conceivable that PEMF therapy could be incorporated into an athlete's recovery routine to contribute to the performance improvements necessary for success.

However, there were no significant differences observed between the groups for peak cadence (PC) from the cycling test, vertical jump (VJ), or LBD at any time points, nor for the change scores. One potential factor influencing the VJ and LBD results, particularly considering the non-significant changes in PP from baseline to 72 hours, may be the rate of force development, which was not considered in these measures. For instance, a fatigued individual may adjust their VJ technique to achieve the same jump height (e.g., spending more time in the eccentric phase to generate force, thus slowing the rate of force development while maintaining jump height) (McMahon et al., 2018). The same may apply to the LBD, where the time to achieve maximal force output is not recorded (Magrini et al., 2018). This represents a limitation of the current study, as a force plate was not available to measure VJ and LBD. Future PEMF therapy research should incorporate a force plate to assess VJ and a maximal isometric pull following a fatiguing protocol. Although the absolute measures of jump height and maximal strength did not differ across recovery conditions, variables such as contraction time during the VJ (McMahon et al., 2018) and the rate of force development during a maximal pull (Haff et al., 2015) may produce different results.

For the qualitative measures, no significant differences were found between the groups for the VAS and Likert scale scores. However, a significant decrease in Likert scale scores from pre- to post-intervention was observed for the CONT group at 24 hours and for the PEMF group at 72 hours. Notably, although not significant, the PEMF group was the only group to show decreases in both VAS and Likert scale scores from pre- to post-recovery intervention at all-time points. This suggests that there was some perceived reduction in muscle soreness following the PEMF intervention. Delayed onset muscle soreness (DOMS) typically peaks between 24 and 72 hours after intense exercise (Cheung et al., 2003). While DOMS is a complex phenomenon (Cheung et al., 2003; Connolly et al., 2003), it can significantly impair an athlete's ability to train. Connolly et al. (2003) noted that strength loss generally peaks immediately after exercise or within the first 48 hours, while pain and tenderness peak between 24 and 72 hours post-exercise. While time and rest generally mitigate DOMS (as evidenced by the significant result in the CONT group), PEMF therapy could potentially expedite the recovery process for some individuals. Supporting this theory, PEMF therapy has been employed in the treatment of low back pain (Alzayed & Alsaadi, 2019; Elshiwi et al., 2019; Lisi et al., 2019). Alzayed and Alsaadi (2019) found that 39 PEMF sessions over 13 weeks reduced pain on a VAS and decreased disability in individuals with chronic low back pain, though changes were similar to those seen in subjects undergoing exercise therapy. A PEMF treatment protocol involving twice-daily 30-minute sessions for six weeks, followed by 2-3 weekly sessions for the next six weeks, led to reduced pain on a VAS and improved low back function (Lisi et al., 2019). Similarly, Elshiwi et al. (2019) reported a significant reduction in pain intensity and improved low back function and range of motion after 12 PEMF sessions over four weeks. Although low back pain and muscle soreness are distinct conditions, these studies offer a foundation for understanding why the PEMF

group in the current study may have reported lower VAS and Likert scale scores following recovery treatment. Despite the non-significant results, the data suggests that PEMF therapy may be valuable in reducing perceived muscle soreness.

There were large standard deviations observed for many of the quantitative and qualitative measures across the three groups, indicating variability in individual responses to the recovery interventions. Lockie (2020) noted similar variations in individual responses to PEMF therapy in clinical applications, such as in the treatment of bone fractures. This suggests that some individuals may be high or low responders to PEMF therapy, as well as to placebo or control conditions. Understanding individual responses to recovery interventions is an essential skill for strength and conditioning coaches. Anecdotally, some adverse reactions to PEMF therapy include fatigue, changes in sleep patterns, pain, loss of energy, prickly sensations in the skin, dizziness, and heart palpitations (Pawluk, 2020). However, no adverse reactions were reported by any participants in the PEMF group in this study. While the frequencies used in PEMF therapy are unlikely to have negative health effects (Wade, 2013), Lockie (2020) recommended that any negative experiences with PEMF therapy should be documented, and coaches should monitor these responses when implementing this protocol with athletes. Positive responses should also be recorded. The results of this study suggest that PEMF therapy may be beneficial for certain individuals in the 72 hours following fatiguing exercise, and for these individuals, it could be a valuable addition to their recovery protocols.

The objective of this study was to determine whether PEMF therapy could improve recovery from fatiguing exercise, as indicated by both quantitative and qualitative measures. Although the results did not support the primary hypothesis that PEMF therapy would lead to significant improvements in recovery outcomes, there were trends suggesting that PEMF therapy had a marginal effect on recovery, particularly for power restoration and muscle soreness. The link to the "marginal gains" theory, which posits that small improvements across various domains can lead to greater overall performance, is an interesting perspective. However, it is important to acknowledge that applying this theory in the current context is somewhat speculative. While small, non-significant improvements in performance outcomes, particularly in peak power (PP), might have cumulative benefits over time, the marginal gains theory should be interpreted cautiously in this study due to the absence of significant statistical findings. Despite the lack of significant differences in vertical jump (VJ) height and leg/back dynamometer (LBD) strength, there were notable improvements in PP. This discrepancy could stem from different physiological underpinnings involved in each measure. VJ and LBD are more complex and may be influenced by factors such as rate of force development and jump technique, which were not specifically measured in this study. A fatigued individual might compensate for muscle fatigue by altering their technique, which could help maintain jump height without improving the underlying strength or power capacity. For example, in the VJ test, participants may have spent more time in the eccentric phase of the jump, allowing them to maintain height while not improving the explosive power typically associated with the test. Similarly, for LBD, the rate at which maximal force is developed might have been altered by fatigue, affecting the measurement of maximal strength even though power output improved. This highlights a limitation of the current study's methodology: while VJ and LBD are valuable measures of recovery, they do not account for the rate of force development or changes in neuromuscular coordination that may occur with fatigue. Future studies may benefit from incorporating more specific measures of force production, such as using a force plate for VJ or including time-based measures for maximal strength development during LBD testing. This would allow for a more comprehensive understanding of how recovery interventions like PEMF therapy impact both the strength and speed components of muscle performance.

There are several limitations in this study that warrant discussion. This research aimed to isolate a single recovery modality, specifically PEMF therapy. However, in practical settings, athletes are more likely to utilize multiple recovery interventions (e.g., nutrition, hydration, massage, compression) to facilitate recovery from training and competition (Barnett, 2006; Halson, 2013). Therefore, future studies should explore whether the combination of PEMF therapy with other recovery modalities can accelerate the recovery process for athletes. Furthermore, the potential mechanisms through which PEMF therapy may exert its effects were not examined in this study. Given the limited research on PEMF therapy and its influence on athletic performance (Tamulevicius et al., 2021), the initial focus for research in this area should be to determine whether PEMF therapy has a measurable effect on key performance variables such as force and power. Subsequent studies could investigate changes in neuromuscular function or inflammatory

markers in response to PEMF therapy. This study analyzed a single PEMF therapy session with duration of 22 minutes and 32 seconds over three days, but it is possible that a dose-response relationship exists between PEMF therapy and recovery, which warrants further investigation. Additionally, the intensity of the PEMF device used in this study may not have been sufficient to induce more significant recovery benefits following intensive exercise. Only a running-based fatigue protocol was employed to induce fatigue (Gathercole et al., 2015), and other fatigue protocols (e.g., cycling, resistance exercise) might produce different outcomes. As previously noted, the vertical jump (VJ) and leg/back dynamometer (LBD) measurements did not account for the time or rate of force development (Haff et al., 2015; McMahon et al., 2018), which may have provided additional insights and potentially different results. For the purposes of sample size optimization, the sexes were combined within each group. Moreover, due to the random allocation of participants, the distribution of male and female participants was unequal across groups. Future studies should assess whether there are sex-based differences in recovery from fatiguing exercise when using PEMF therapy. Additionally, the training history of subjects within each group may have varied, potentially influencing the results observed. The participants in this study were recreationally active men and women, and it is possible that professional or elite athletes may respond differently to PEMF therapy compared to the subjects in this study.

Conclusion

Athletes constantly seek methods that may enhance their performance and recovery. PEMF therapy could provide a beneficial recovery aid for some individuals following strenuous exercise. While the evidence is not definitive, the findings from this study suggest that PEMF therapy may be a valuable addition to an athlete's recovery regimen, potentially leading to faster recovery of peak power (PP) and an improved perception of recovery between 24 and 72 hours post-exercise. As noted, PEMF devices are designed to be non-invasive, allowing them to be used concurrently with other activities (e.g., athletes can use the device while performing tasks such as working on a computer, watching film, receiving a massage, or eating). Although further research is required to explore the mechanisms by which PEMF therapy influences recovery after intense exercise, the current results indicate that PEMF devices could be incorporated into an athlete's recovery protocol, particularly within the first 72 hours following strenuous physical activity.

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