Scientific-Expert Journal of Anthropological Aspects of Sports, Physical Education and Recreation

Submitted: 03/05/2025
Accepted: 25/12/2025
Online first: 29/12/2026
UDK: to be registered

Original article

The Effects of Pulsed Electromagnetic Field (PEMF) Therapy on Recovery from Strenuous Exercise

[1]Robert G. Lockie, [2,3]J. Jay Dawes, and [2,3]Kristine J. Sanchez

[1]Department of Kinesiology, California State University, Fullerton, Fullerton, CA, USA
[2]Department of Health and Human Performance, Oklahoma State University, Stillwater, OK, USA.
[3]Tactical Fitness and Nutrition Lab, Oklahoma State University, Stillwater, OK, USA.

*Correspondence: rlockie@fullerton.edu

Abstract

This study investigated whether pulsed electromagnetic field (PEMF) therapy enhanced recovery after fatiguing exercise. Thirty recreationally-trained participants were randomly allocated to PEMF (22:32 min:s of PEMF therapy), PLAC (placebo; held device that was not on), or CONT (control) groups. Fatigue was induced by a Yo-Yo running protocol. Recovery interventions were provided after the fatigue protocol (0 hours), and at 24, 48, and 72 hours. Recovery was measured quantitatively by a cycle ergometer peak power (PP) and cadence test, vertical jump, and leg/back dynamometer. These were measured at baseline, and after the interventions from 0-72 hours. Qualitative recovery was measured by visual analogue and Likert scales pre and post intervention. A 3 (group) x 5 (time) repeated measures ANCOVA, with sex as a covariate, derived between-group differences. Change scores relative to baseline were calculated, and analyzed by a 3x4 (0-baseline, 24-baseline, 48-baseline, 72-baseline) repeated measures ANCOVA. Paired samples t-tests compared the qualitative measures pre and post recovery intervention. A 3x8 and 3x4 repeated measures ANCOVA calculated differences in perceived recovery and change scores. There were no significant time by group ANCOVAs for any variable. The PEMF group did have 11-385% greater PP change scores at each time point. There was a significant decrease (p=0.015; d=0.949) in the PEMF group Likert scale score at 72 hours with the qualitative data indicating recovery for this group. Large standard deviations suggested variation in individual responses. Although significant differences were lacking, PEMF therapy may be beneficial for recovery from fatiguing exercise among some individuals.

Keywords: electromagnetic fields, fatigue, Likert scale, muscle soreness, peak power

Citation: Lockie, R.G. et al. (XXXX). The Effects of Pulsed Electromagnetic Field (PEMF) Therapy on Recovery from Strenuous Exercise. *SportLogia*. *XX*(X), X-X. doi: registering

Introduction

Athletes use many different approaches to optimize their performance. Strength and conditioning programs, sport-specific skills training, and nutrition are all typically part of an athlete's preparation for competition. Athletes may also adopt other, more novel modalities that could contribute to their physical preparation and recovery to provide an additional advantage. Indeed, recovery from intensive exercise and competition is an essential part of an athlete's preparation. Recovery can be defined as the return to homeostasis of various physiological systems following the metabolic, thermoregulatory, and inflammatory challenges incurred by exercise (Hausswirth & Le Meur, 2011). Optimal recovery is intended to negate the fatigue or damage incurred during intensive exercise, such that the individual may meet or exceed performance in a particular activity (Bishop et al., 2008). Athletes are typically encouraged to utilize strategies that will optimize recovery, as this could assist with physiological adaptations from training, while also allowing the athlete to be more physically prepared for their subsequent training sessions or competition.

Numerous approaches have been advocated to expedite the recovery process, such as stretching, massage, compression, hot and cold water immersion, and electromyostimulation (Barnett, 2006). One example of a more novel approach to enhancing athletic performance is pulsed electromagnetic field (PEMF) therapy. In recent years, several different companies have promoted the use of PEMF therapy (Longoria & Gielen, 2021; Pawluk, 2007). Lockie (2020) provided a review of PEMF therapy specific to strength and conditioning. Pulsed electromagnetic field therapy involves using a device that emits slow frequency electromagnetic currents with an extended range of frequencies that may increase cell membrane permeability and stimulation of many intracellular functions (Abdelhalim et al., 2019). One of the perceived benefits of PEMF therapy is that it is non-invasive and requires no electrode placement, or placement of any other type of invasive device (Hug & Röösli, 2012; Longoria & Gielen, 2021). PEMF therapy has been acknowledged as a safe process (Lisi et al., 2019; Wu et al., 2018), and most PEMF devices will emit a frequency much lower than many other everyday electronic devices. As an example, one commercial PEMF therapy device has a frequency range of 3-11875 hertz (Hz) (HAELO, 2021). This frequency is much lower than that for a television broadcast (54-700 megahertz), cellphone (1.9-2.2 gigahertz), or diagnostic radiation such as magnetic resonance imaging (5-50 exahertz) (National Cancer Institute, 2019). The frequency range for PEMF therapy devices would position them in the non-ionizing radiation part of the electromagnetic spectrum, and frequencies in in this range are not known to directly damage deoxyribonucleic acid (DNA) or cells (National Cancer Institute, 2019). Furthermore, a systematic review of the literature indicated that there were no adverse treatment affects reported across 11 studies that analyzed different PEMF treatments via different clinical applications (e.g., osteoarthritis, fibromyalgia, pain perception, heart rate variability) (Hug & Röösli, 2012). Accordingly, PEMF therapy should provide no more than minimal risk to the user.

Most research utilizing PEMF therapy has focused on clinical applications (Hug & Röösli, 2012). As an example, PEMF therapy has been used to stimulate bone healing as it can stimulate the bone in a similar manner to mechanical loading (Hannouche et al., 2001). As detailed by Hannouche et al. (2001), when a bone is subjected to mechanical stress, strain gradients are created, resulting in pressure gradients in the interstitial fluid. This drives fluid through the canaliculae in the bone from regions of high to low pressure, exposing the osteocyte membranes to flow-related shear stress and streaming electrical potentials (Duncan & Turner, 1995; Hannouche et al., 2001). These streaming potentials could contribute to mechanotransduction, which is the conversion of a biophysical force into a cellular response (Duncan & Turner, 1995). In order to replicate these effects, an exogenous electrical field can be administered at the fracture site (Hannouche et al., 2001). Angiogenesis (creation of new blood vessels controlled by signals from chemicals in the body) and vasodilation (phenomenon in which the blood vessels widen, thus increasing blood flow) can also occur with the use of PEMF therapy (Strauch et al., 2009). Strauch et al. (2009) also suggested that PEMF therapy facilitated the treatment and management of post-surgical wounds, edema, and

pain. Research investigating PEMF therapy for athletic populations is lacking, which highlights why work in this area is needed.

Relative to athletic performance, one of the strategies that manufacturers have advocated for PEMF therapy has been to facilitate recovery from intensive exercise (Longoria & Gielen, 2021). The anecdotal recommendations for PEMF therapy in the optimization of recovery from intensive activity have been linked to factors such as improved blood circulation, muscle oxygen uptake, and removal of waste products resulting from exercise (Pawluk, 2007). Other modalities used to enhance recovery also could affect blood circulation. For example, sports massage during the recovery process may stimulate blood circulation that assists with ameliorating the inflammatory response after exercise (Zainuddin et al., 2005). Intermittent pneumatic compression devices are said to assist with blood circulation, which should encourage reabsorption of interstitial tissue swelling to promote healing to injured tissue (Chleboun et al., 1995; Hanson et al., 2013). To provide an example, Hanson et al. (2013) found that 20 minutes of intermittent pneumatic compression in collegiate female athletes led to lower blood lactate levels following a Wingate test (30-second [s] maximal cycling test against a set load) compared to passive or active recoveries. Thus, if PEMF therapy could influence blood circulation, it could be surmised that it may encourage similar positive effects on recovery from exercise as those seen for massage therapy (Zainuddin et al., 2005) and intermittent pneumatic compression (Hanson et al., 2013). A starting point for investigating PEMF therapy would be to ascertain whether performance in high-intensity activities (e.g., actions requiring maximal strength and power) are recovered quicker following bouts with this modality.

There is a lack of research regarding PEMF therapy and recovery from exercise (Tamulevicius et al., 2021). If PEMF therapy is effective in recovering physical performance from high-intensity exercise, there are advantages to this modality. As noted, PEMF therapy has been designed to be non-invasive to the individual (Hug & Röösli, 2012; Longoria & Gielen, 2021), which could be especially useful for athletes. Given the product design (i.e., cords, coils, and mats that can be used when the athlete is sitting or lying down in a training facility or residence) (Longoria & Gielen, 2021), it could be easily utilized by the athlete if evidence suggests it was effective. Nonetheless, Hannouche et al. (2001) has noted that the underlying effects of treatments such as PEMF therapy are not well understood. Therefore, this study investigated whether PEMF therapy could enhance recovery from fatiguing exercise. Recreationally trained college-aged men and women were recruited for this cross-sectional analysis. A specific PEMF therapy device was used in this study (Longoria & Gielen, 2021), and compared to a placebo and a control condition. The recovery interventions were implemented immediately after the fatigue protocol, and 24 hours, 48 hours, and 72 hours post-fatigue protocol (Magrini et al., 2018). It was hypothesized that PEMF therapy would enhance recovery (i.e., a faster return to baseline) from fatiguing exercise as demonstrated by qualitative measures of muscle soreness, and quantitative measures of maximal strength and power.

Methods

Design

A cross-sectional study was used, which has been adopted in other research investigating recovery protocols (Ascensão et al., 2011; Hanson et al., 2013). Participants were randomly allocated to one of three recovery conditions: PEMF therapy (participants sat and received 22:32 minutes:s [min:s] of PEMF therapy while holding a specific device); placebo (participants sat for 22:32 min:s with a device that that was not on, but they were unaware that this was the case); and control (participants were seated for 22:32 min:s with no external device). Due to the variety of variables analyzed in this study, the researchers could not control all variables to ensure all groups were balanced. Rather, block randomization was used (i.e., each group was required to have 10 participants) (Suresh, 2011), and participants were randomly allocated to each group until the capacity of 10 was reached. Fatigue was induced by a 3-stage Yo-Yo fatiguing protocol (Gathercole et al., 2015). Quantitative measures of recovery were provided by a 6-s peak power test on a cycle ergometer;

vertical jump (VJ) performance as a measure lower-body power; and isometric strength as measured by a leg/back dynamometer. Recovery was monitored qualitatively by a visual analogue scale (VAS) and Likert scale to rate muscle soreness. The recovery interventions were provided immediately after the fatigue protocol (0 hours), and 24 hours, 48 hours, and 72 hours post-fatigue protocol. The quantitative measures were taken at baseline (prior to the fatigue protocol), immediately after the 0-hour recovery intervention, and after the recovery interventions at 24 hours, 48 hours, and 72 hours. The qualitative measures were taken prior to and after the recovery intervention on each testing occasion.

Participants

Thirty recreationally-active, college-aged participants (age: 23.70 ± 3.66 years; height: 1.68 ± 0.09 m; body mass: 73.16 ± 14.18 kg), which included 19 men (age: 23.79 ± 3.49 years; height: 1.71 ± 0.09 m; body mass: 79.36 ± 12.68 kg) and 14 women (age: 23.57 ± 4.01 years; height: 1.65 ± 0.10 m; body mass: 64.75 ± 11.83 kg), completed this study. Participants were recruited from the student population at the university via information sessions and word-of-mouth on campus. Inclusion criteria for participants included whether they were recreationally active, having trained in either aerobic or resistance exercise for a minimum of 1 hour at moderate-vigorous intensity 3 times a week for the past year. Participants also were required to free of lower-extremity injury within the past 6 months and not have any other disabilities that influenced study participation. The sample and resulting group sizes were similar to previous research investigating exercise recovery protocols (Ascensão et al., 2011). Participants received and signed a written informed consent detailing the risks and benefits of participation, as well as an overview of the study. They then read and completed a physical activity readiness questionnaire (PAR-Q) prior to their study participation. The institutional review board approved the study (HSR-18-19-586).

Measurements and Procedures

Prior to study participation, participants were instructed not to exercise heavily in the 24 hours before attending the laboratory for all visits. On arrival at the laboratory for the first visit, participants completed the required paperwork (informed consent, PAR-Q). Following this, height was measured barefoot using a portable stadiometer (Detecto, Webb City, MO, USA). Body mass was recorded by electronic digital scales (Ohaus, Parsippany, NJ, USA). The structure of the testing protocol is shown in Figure 1. As stated, participants were randomly allocated into one of three groups via block randomization (Suresh, 2011); PEMF therapy recovery intervention (PEMF); placebo recovery intervention (PLAC); and the control condition (CONT).

Participants completed the same dynamic warm-up prior to each testing session. This warm-up was comprised of cycling for 5 minutes at a power of 100-120 Watts on a cycle ergometer (Wattbike Pro, Nottingham, UK), followed by three bouts of maximal standing-start accelerations for approximately 2 s. Participants then completed approximately 10 minutes of full-body dynamic stretching. The dynamic stretches involved walking lunges, straight leg kicks, hip openers, side lunge with groin stretch, quadruped calf stretch, and leg swings. Performance pre-testing was conducted prior to the fatigue protocol, following procedures adapted from Magrini et al. (2018). Post-testing of these performance measures occurred at 0 hours (immediately after the recovery protocol), 24 hours, 48 hours, and 72 hours post-fatiguing exercise and the recovery protocol. The testing battery was completed in the order presented, with approximately 2 minutes recovery between each test. The qualitative muscle soreness measures were recorded prior to and after the specific recovery protocol completed by each participant. Participants were instructed to not make significant changes in their diet during the four days they were required to be in the laboratory, refrain from intensive lower-body exercise during their study participation, nor take any type of supplementation (e.g., whey protein) or complete any type of other intervention (e.g., massage) that could facilitate their recovery from the fatiguing exercise (Chleboun et al., 1995). Session 1 had a duration of approximately 90-120 minutes. Sessions 2-4 each lasted approximately 40-50 minutes.

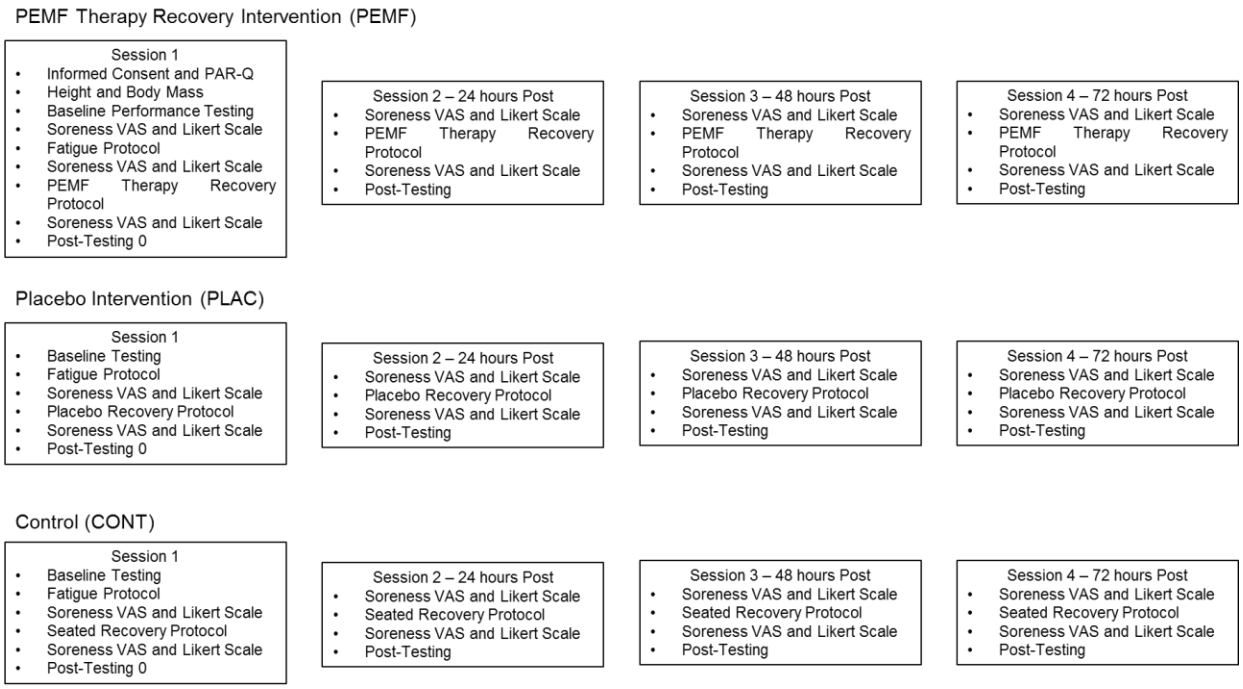

Figure 1. Structure for the study testing protocols for each of the recovery intervention groups (PEMF, PLAC, and CONT).

6-second (s) Peak Power Test

After the dynamic warm-up, the first performance test was the 6-s peak power sprint test performed on a factory-calibrated cycle ergometer (Wattbike Pro, Nottingham, UK). The cycle ergometer used in this study operated with air-braked and magnetically braked systems. A lever regulated the air flow through the flywheel to control air-braked resistance (Levels 1-10), and a turn dial adjusted the magnetically-braked resistance (Levels 1-7). Saddle height was determined relative to each participant such that their knee reached almost full extension (approximately 170°) when the foot was in the bottom position. The fore and aft position of the saddle were aligned so the tip of the knee dropped over the center of the pedal when feet were horizontal. Handlebar height was adjusted to level with the saddle height and handlebar fore and aft position was adjusted so there was an approximate 90° angle between the arms and torso. The feet were secured to the pedals via foot straps. The set-up for each participant was noted such that the same set-up was used for each 6-s sprint test on each testing occasion, with 2 trials performed. The resistance for the 6-s sprint for each participant was based on manufacturer guidelines.

The sprint was initiated from a stationary, seated position, and participants were required to remain seated throughout the test. The test was initiated following a 5 s countdown followed by a firm verbal command, and participants received strong verbal encouragement throughout the 6 s. Test completion was also indicated with a firm verbal command. Participants were instructed to attempt to reach their peak power as quickly as possible. After the first trial, a 60-s active recovery "easy spin" at a self-selected cadence was performed with air-braked and magnetically-braked resistance returned to Level 1 as needed. Following the active recovery, an additional 6-s maximal sprint was performed using the same start position and resistance setting. Peak power (PP) and peak cadence (PC) were recorded for both sprints, with the best sprint used for analysis.

Vertical Jump (VJ)

The VJ was also used to track recovery from fatigue, as eccentric capacity and the stretch-shortening cycle are essential components to jump performance (Magrini et al., 2018). A jump mat (Probotics Inc, Alabama, USA) was utilized to measure jump height and followed established protocols (Magrini et al., 2018). To measure VJ height, the participant initially started on the jump mat. Five successive VJs with

countermovement were performed, with 10 s rest allowed between efforts. No restrictions were placed on the depth of the countermovement, but participants were instructed to jump as high and as explosively as possible. VJ height was calculated via the software for the jump mat. VJ height was converted from inches to centimeters then averaged across the five trials.

Isometric Leg/back Dynamometer Strength Test

Following completion of the jumps, participants 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). Participants 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°). 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. Participants completed three trials with 60-s rest between attempts. Measurements were taken to the nearest kilogram, with the best trial at each time point used for analysis.

Isometric Leg/back Dynamometer Strength Test

Qualitative measures of muscle soreness were taken at several time points (Figure 1):

- Immediately after the fatigue protocol and before the recovery protocol;
- Immediately after the recovery protocol (0 hours);
- Prior to and after the recovery protocol at 24 hours;
- Prior to and after the recovery protocol at 48 hours; and,
- Prior to and after the recovery protocol at 72 hours.

Two different scales were used. Firstly, a visual analogue scale (VAS) was used, in which a 100-mm (10-cm) line which was anchored at the extremes by “No Soreness” and “Extremely Sore” (Figure 2) (Delextrat et al., 2013). Participants marked the location on the line that best corresponded to their perceived level of soreness, and the distance from the left access was measured to the nearest 1 mm (Delextrat et al., 2013). The second pain/soreness measure was a Likert scale shown in Table 1 (Gibson et al., 2006). Participants checked the corresponding box to their soreness at the time of the respective test.

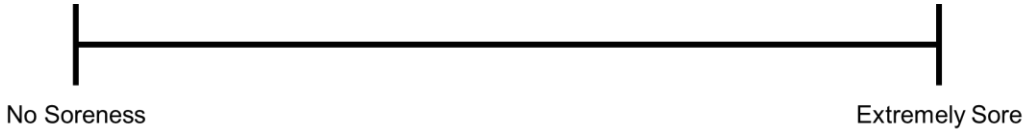

Figure 2. Visual analogue scale for muscle soreness (not to scale) (Delextrat et al., 2013).

Table 1. Modified Likert scale used in muscle soreness assessment (Gibson et al., 2006).

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 inly 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

Following the warm-up and baseline assessment in testing session 1, participants completed the fatigue protocol, which was adapted from Gathercole et al. (2015). A 3-stage Yo-Yo fatiguing protocol (Figure 3) was completed indoors on a basketball court to elicit neuromuscular fatigue. Firstly, Yo-Yo Intermittent Recovery Test 1 (YYIRT1) was performed twice consecutively. Briefly, the YYIRT1 involved repeated 2 x 20 m runs at a progressively increased speed, which was controlled by audio beeps from an iPad handheld device (Apple Inc., Cupertino, California) connected via Bluetooth to a portable speaker (JBL FLIP 5, Los Angeles, CA) located immediately adjacent to the running lane indicated by markers. Between each running bout, the participant had a 10-s rest period in which they were required to move to a cone 5 m away before returning to the start line. The YYIRT1 has four running bouts at 10-13 kilometers per hour ($km \cdot hr^{-1}$), and another seven runs at 13.5-14 $km \cdot hr^{-1}$. Following this, the YYIRT1 continues with stepwise 0.5 $km \cdot hr^{-1}$ speed increments after every eight running bouts until exhaustion. After completing the YYIRT1 twice, participants then completed the Yo-Yo Intermittent Endurance Test Level 1 (YYIET1). This test also featured 2 x 20 m runs at a progressively increased speed but had shorter recovery times of 5 s between shuttles. During this recovery time, participants had to move to a cone 2.5 m away before returning to the start line. The same iPad (Apple Inc., Cupertino, California) and Bluetooth portable speaker (JBL FLIP 5, Los Angeles, CA) were used for the YYIET1. The YYIET1 started at a speed of 8 $km \cdot hr^{-1}$, which then increased by 1 $km \cdot hr^{-1}$ after the first stage, and 1 $km \cdot hr^{-1}$ after the second stage. The test continued with stepwise 0.5 $km \cdot hr^{-1}$ speed increments after every stage until failure.

This study used the Level 1 versions of the YYIRT and YYIET test, which differed from Gathercole et al. (2015) who used the Level 2 versions for each test. However, similar to Gathercole et al. (2015), the purpose of the 3-stage Yo-Yo fatiguing protocol was to elicit fatigue and not measure physiological capacity. In the final stages, participants were encouraged to continue performing each Yo-Yo test regardless of whether shuttle runs were made within the time. Thus, participants volitionally terminated the exercise only once they self-determined they could not continue. In between each of the Yo-Yo tests and after the last one, participants completed 5 minutes of active recovery (i.e., walking without sitting down), and consumed water as required (Gathercole et al., 2015). Following the fatigue protocol, participants completed their recovery intervention and post-testing.

Recovery Procedures

After completion of the fatigue protocol and active cooldown, participants were seated and completed their respective recovery protocol. The timing of when the participants initiated their recovery protocol was adapted from other literature that utilized recovery interventions (Hanson et al., 2013; Robertson et al., 2004), and also followed manufacturer recommendations. For the PEMF group, they utilized a PEMF device (HAELO, Encino, CA, USA) that consisted of a Symphony One unit and magnetic coil (Longoria & Gielen, 2021). The size of the unit was 0.26 m x 0.20 m x 0.08 m, with a mass of approximately 2.5 kg (HAELO, 2021). The device had a frequency range of 3-11875 Hz and a coil rating of 1.01 Ohm (HAELO, 2021). The researcher used an app (HAELO, Encino, CA, USA) to drive the device from their phone, which paired via Bluetooth to the device. A frequency set called 'Recover' was utilized, which was recommended by the manufacturer. The exact electromagnetic frequency emitted by the coil during this set was not provided to the researchers for proprietary reasons. Nonetheless, this frequency set was described by the manufacturer thusly: "Deep recovery of muscles, bones, ligaments, and fascia after strenuous workout or competition that typically produces soreness, stiffness, and pain. Supports a quick recovery for regular and consistent routines" (Longoria & Gielen, 2021). Participants held the PEMF device to their chest (as per manufacturer guidelines) while they were seated, and the frequency set had a duration of 22:32 min:s. Following a meta-analysis of the PEMF literature, Wu et al. (2018) recommended exposure durations of ≤30 min for better efficacy in pain relief and recovery of function. Although this meta-analysis by Wu et al. (2018) focused on osteoarthritis, this

recommended time frame has application for the current study (especially relative to recovery of pain and muscle soreness).

For the PLAC group, participants held the device to their chest for 22:32 min:s in their recovery protocol, but the device was not turned on and participants were not informed that the device was not on. For the control condition, participants were seated in a chair with no external device for 22:32 min:s, which was the duration of the PEMF therapy protocol. The recovery protocols were also applied at 24 hours, 48 hours, and 72 hours after the fatiguing exercise. This was adapted from previous research that applied intermittent pneumatic compression for several days after a fatiguing exercise intervention (Chleboun et al., 1995). Manufacturer guidelines also encouraged multiple applications of the 'Recover' frequency set, so this was incorporated into the study.

Statistical Analyses

Statistical analyses were processed using the Statistics Package for Social Sciences (SPSS) Version 29.0 (IBM Corporation, New York, USA). Normality of the data was evaluated by the Shapiro-Wilk test and visual analysis of stem-and-leaf plots. If a variable was not normally distributed, extreme outliers (variables identified as being 3 box lengths outside of the box in the plot) were treated via a Winsorization process (Lien & Balakrishnan, 2005). Descriptive statistics (mean ± standard deviation [SD]) were calculated for each variable. A one-way analysis of variance was used to compare age, height, and body mass of the groups. For the analyses of the recovery protocols, Sex was used as a covariate for all repeated measures analysis of covariance (ANCOVA) calculations, with significance set *a priori* at $p < 0.05$. If a significant interaction between the groups was found for any part of the statistical analysis, a Bonferroni adjustment was applied for post hoc comparisons. For the quantitative measures (PP, PC, VJ, and LBD), a 3 (PEMF, PLAC, CONT) x 5 (baseline, 0 hours, 24 hours, 48 hours, 72 hours) repeated measures ANCOVA derived any differences between the recovery interventions. Change scores were also calculated as the difference between the post-test at the different time points relative to baseline data. The change scores were analyzed by 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), normality of the data was also evaluated by the Shapiro-Wilk test and visual analysis of stem-and-leaf plots. As will be detailed, the majority of the qualitative data was not normally distributed. There can be a tendency for scale data, such as for the VAS and Likert scales, to not have normal distribution (Jamieson, 2004). However, Norman (2010) has argued that parametric statistics can be used on ordinal data derived from Likert scales. Furthermore, ANCOVAs can be robust to data normality violations (Olejnik & Algina, 1984). Thus, parametric statistics were still used in the qualitative data analysis. Paired samples t-tests were firstly used to ascertain whether there were significant changes in perceived recovery prior to and after each session's intervention. Effect sizes (*d*) were calculated for the pre- and post-recovery intervention values within each session, where the difference between the means was divided by the pooled SD. A *d* less than 0.2 considered a trivial effect; 0.2 to 0.6 a small effect; 0.6 to 1.2 a moderate effect; 1.2 to 2.0 a large effect; 2.0 to 4.0 a very large effect; and 4.0 and greater an extremely large effect (Hopkins, 2004).

Following this, a 3 (PEMF, PLAC, and 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 calculate changes in perceived recovery across the interventions. Lastly, change scores were calculated within each session for the qualitative measures to ascertain whether a greater magnitude of change for perceived recovery was present for any intervention. A 3 (PEMF, PLAC, and CONT) x 4 (0 hours-baseline, 24 hours post-pre, 48 hours post-pre, 72 hours post-pre) repeated measures ANCOVA was adopted for this part of the analysis.

Results

All PP, PC, VJ, and LBD data were normally distributed (p = 0.117-0.779). The change scores at 24 hours relative to baseline, PC48-baseline, LBD48-baseline, and PC72-baseline were not normally distributed ($p \leq$ 0.011). Once the extreme outliers were treated, all change score variables were normally distributed (p = 0.052-0.846). There were no significant differences in age, height, and body mass between the groups (Table 2), despite the CONT group having more women than the other two groups due to random allocation. Descriptive data for the quantitative measures are displayed in Table 3, while the change scores for PP, PC, VJ, and LBD are shown in Figure 3.

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

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 PP, the main effect of time was significant ($F_{(4,23)}$ = 7.169, p < 0.001, ηp^2 = 0.555). The time by group ANCOVA ($F_{(8,48)}$ = 1.007, p = 0.443, ηp^2 = 0.144) and main effect between groups ($F_{(2,26)}$ = 0.699, p = 0.506, ηp^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, ηp^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, ηp^2 = 0.098) and main effect between groups ($F_{(2,26)}$ = 1.407, p = 0.263, ηp^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.

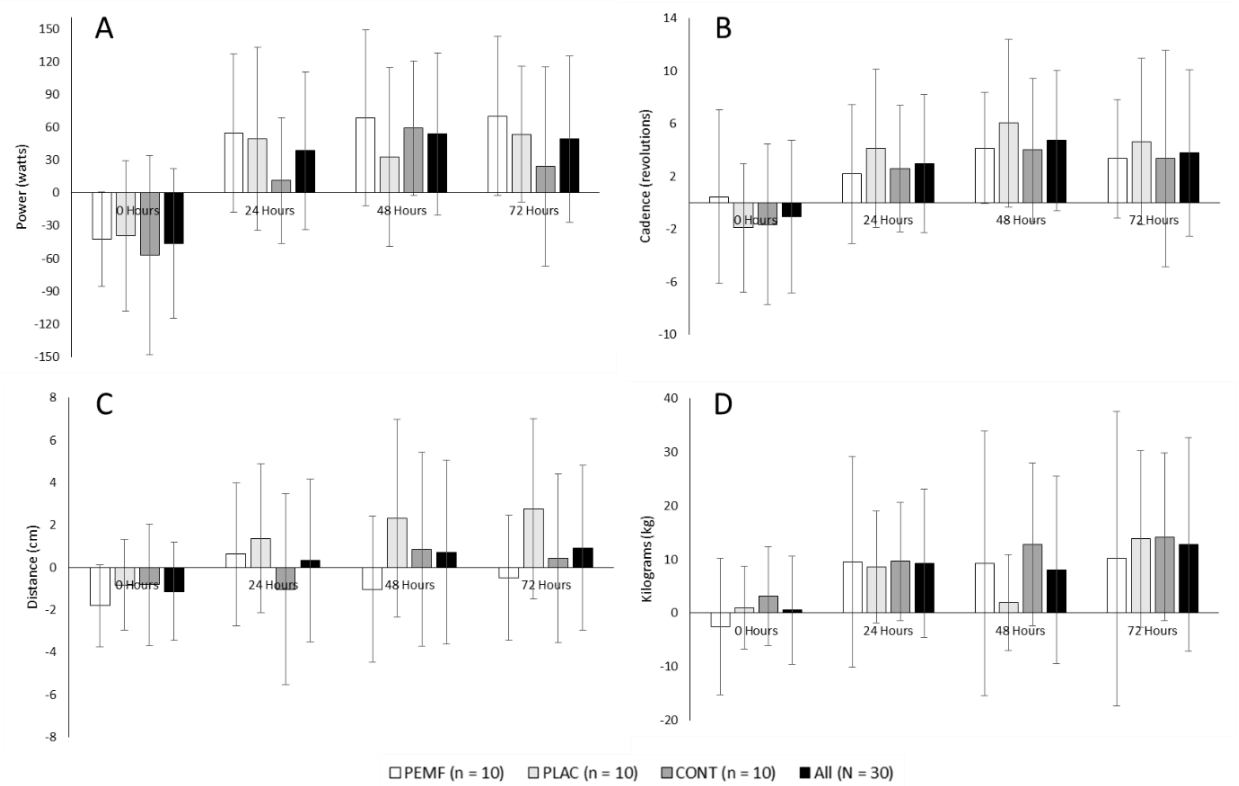

Figure 3. Descriptive (mean ± SD) data for change scores relative to baseline for peak power (A), peak cadence (B), vertical jump (C), and leg/back dynamometer strength (D) recorded at 0 hours, 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women who received pulsed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

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.

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 of 12 VAS variables were normally distributed (0-baseline p = 0.108; VAS Pre at 48 Hours p = 0.624); all other variables were not normally distributed ($p \leq 0.037$). All Likert scale variables were not normally distributed ($p \leq 0.043$). However, as previously stated parametric statistics were still used for qualitative data analysis (Norman, 2010; Olejnik & Algina, 1984), and data was presented as mean ± SD. The pre- and post-recovery session comparisons for the VAS and Likert scales is shown in Table 4. There were few significant results for any of the groups when comparing pre and post recovery intervention data. There was a significant decrease, with a moderate effect, in the Likert scale score for the PEMF group 72 hours after the fatiguing protocol, which suggested a positive effect of the intervention on recovery. There was also a significant decrease in the Likert scale score 24 hours after the fatiguing protocol for the CONT group, which had a moderate effect. What is worth noting is that for the PEMF groups, even though the effects were typically small, post VAS or Likert scale score was always lower than the pre value for the 24, 48, and 72 hour measures. This cannot be said for the 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). 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.

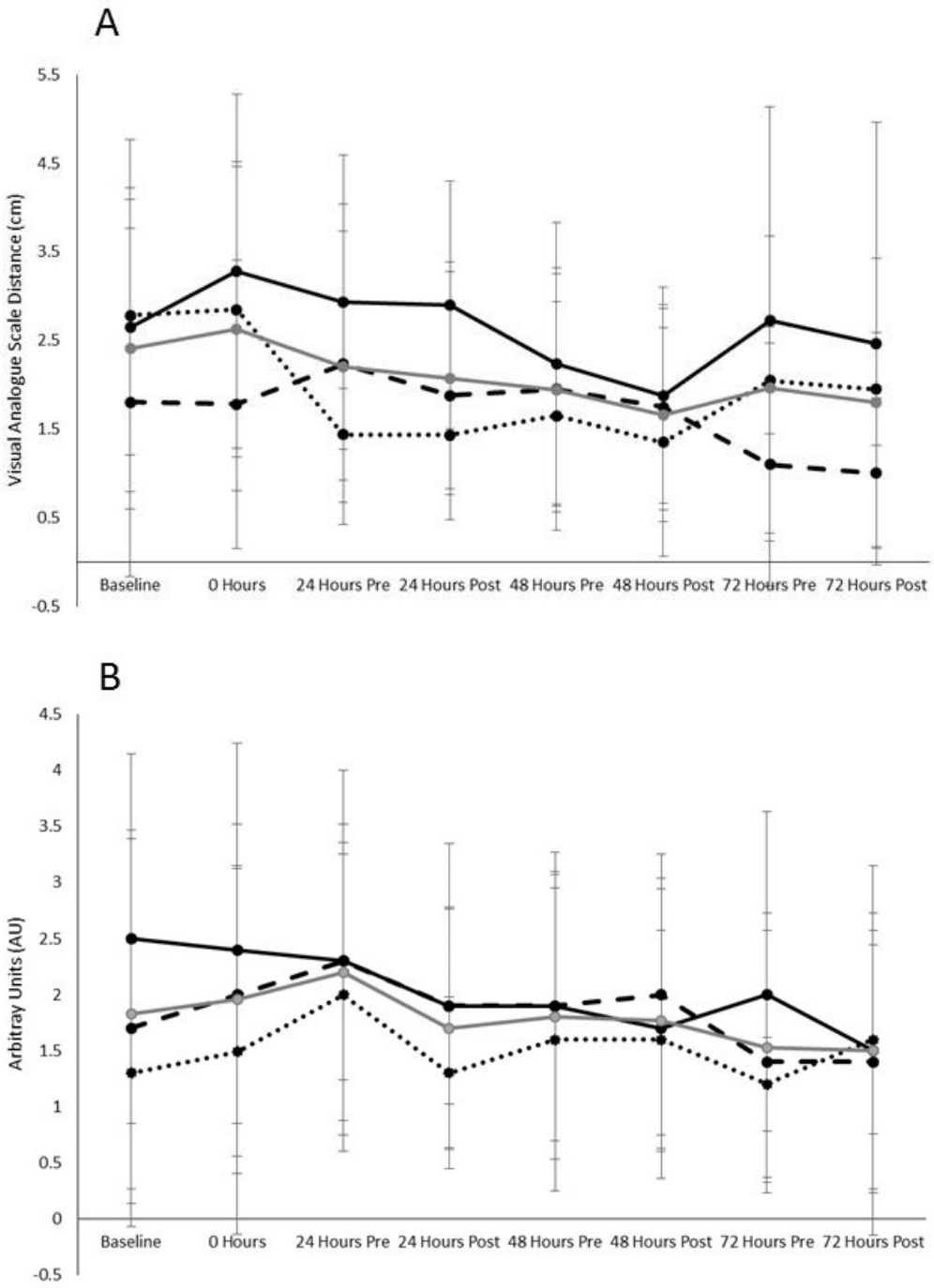

Figure 4. Descriptive (mean ± SD) data for visual analogue scale (VAS; A) and Likert scale (B) values recorded at baseline, immediately after the first recovery protocol (0 hours), and pre- and post-recovery protocol 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women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

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.

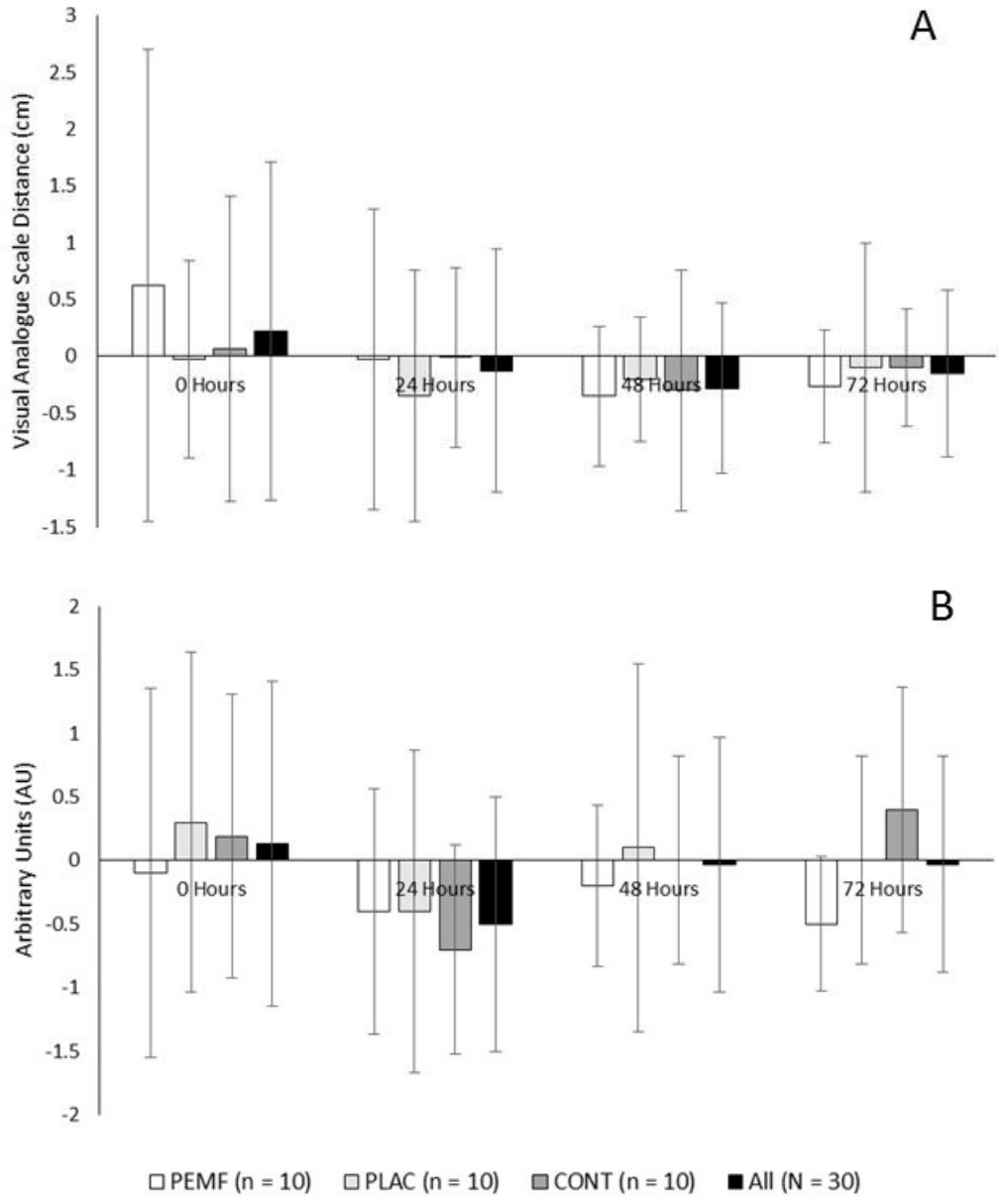

Figure 5. Descriptive (mean ± SD) data for change scores within each session for visual analogue scale (VAS; A) and Likert scale (B) values recorded at 0 hours, 24 hours, 48 hours, and 72 hours post-fatiguing protocol for college aged men and women who received pulsed electromagnetic therapy (PEMF),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

Discussion

The purpose of this investigation was to determine if using PEMF therapy following a fatiguing exercise protocol led to enhanced improved recovery when compared to a placebo and control group. It was

hypothesized that PEMF therapy would enhance recovery from fatiguing exercise as demonstrated 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). These hypotheses were generally not supported, as significant differences were not discovered between the treatments. However, larger, non-significant improvements in PP from a 6-s cycling sprint test were found for the PEMF group at 24, 48, and 72 hours. Additionally, although not significant, the qualitative measures (VAS and Likert scale) indicated recovery post-intervention at each time point, with a significant decrease in Likert scale score from pre- to post-intervention at 72 hours. While the current results were not statistically significant, these small changes in performance and perceived recovery may mean the difference in more effective training, in addition to success in competition and should not be quickly dismissed. This is especially true considering the small margins that could dictate athletic success at different levels of competition (Hall et al., 2012).

As stated, the results from this study indicated no significant differences between the recovery protocols in this study. Previous research has shown non-significant effects of recovery from different interventions, including massage (Robertson et al., 2004), stretching (Torres et al., 2013), and pneumatic compression (Overmayer & Driller, 2018), and there has been some skepticism in the literature as to the benefits of PEMF therapy in clinical environments (Wade, 2013). However, for PP measured during the 6-s cycling sprint test, the PEMF group exhibited greater change scores compared to the PLAC and CONT groups; 11-385% greater at 24 hours, 16-109% greater at 48 hours, and 31-190% greater at 72 hours. As recovery is the return to homeostasis of various physiological systems following the challenges incurred by exercise (Hausswirth & Le Meur, 2011), the data could indicate the PEMF group was experiencing a greater positive change in PP relative to baseline following the intervention. While not measured in this study, there are physiological mechanisms associated with PEMF therapy which could benefit recovery. Angiogenesis (creation of new blood vessels) and vasodilation (widening of blood vessels) occur with the use of PEMF therapy (Strauch et al., 2009). The use of PEMF therapy can cause a rise the structural integrity of the extracellular matrix of bone and cartilage, thus enhancing repair and alteration of the homeostatic balance (Peng et al., 2021). Previous research has suggested that PEMF therapy could positively influence ventilatory threshold in endurance runners across six running sessions (Tamulevicius et al., 2021). The results from this study suggest PP could be positively influenced by PEMF therapy during the 72 hours post-fatiguing exercise.

Although not significant, the relatively large percentage differences in change scores should not be quickly dismissed. Peak power in this study is derived from the formula: *force x (distance/time)*. Force and movement speed are clearly important for athletes across a range of sports. Any intervention that could encourage the faster restoration of these variables, especially within the context of time between training sessions and competition, would be invaluable for athletes. For example, the marginal gains theory postulated by Sir Dave Brailsford stated that making small improvements in a number of areas for an athlete can cumulatively lead to greater success (Hall et al., 2012). Small improvements in performance because of expedited recovery could be essential for an athlete whose margins for victory can be in the hundredths of seconds. Indeed, adequate recovery can result in the restoration of physiological and psychological processes so the athlete can meet or exceed performance in a particular activity (Bishop et al., 2008). It is plausible that PEMF therapy could be incorporated into an athlete's recovery regime and may be able to contribute to the improvements in performance following training or competition that are necessary for success.

Nonetheless, there were no discernible differences between the groups for PC from the cycling test, the VJ, and LBD, at any of the time points or for the change scores. What could have impacted the VJ and PBD, especially in light of the PP results and non-significant time course changes from baseline to 72 hours, was that rate of force development was not considered in these measures. For example, an individual may modify their VJ technique when fatigued to attain the same jump height (i.e., spending more time in the eccentric phase to generate force, resulting in a slower rate of force development but same resulting jump height)

(McMahon et al., 2018). The same could be also true for the LBD, where the time to achieve the maximal force output does not incorporate a time measurement (Magrini et al., 2018). It is a limitation of the current study where a force plate was not available to measure the VJ and LBD. Accordingly, future PEMF therapy research should incorporate force plates when measuring the VJ and a maximal isometric pull following a fatiguing protocol. Even though the absolute measure of jump height and maximal strength may not have a different recovery path compared to a placebo or control conditions, variables such as contraction time during a VJ (McMahon et al., 2018), and the rate of force development during a maximal pull (Haff et al., 2015), could exhibit different results.

As for the quantitative measures, there were no significant between-group differences for the VAS and Likert scale scores. There was a significant decrease in Likert scale score from pre to post intervention for the CONT group at 24 hours and for the PEMF group at 72 hours. Notably, and although not significant, the PEMF group was the only group to have decreases in their VAS or Likert scale scores from pre- to post-recovery intervention at all time points. These data would suggest that there was some perceived reduction in muscle soreness following the intervention. Delayed onset muscle soreness (DOMS) is the sensation of muscle pain or tenderness that generally develops 24 hours after exercise (Zainuddin et al., 2005). While DOMS is a complex phenomenon (Connolly et al., 2003), from an athlete's perspective it will negatively impact their ability to train. Following a review of literature, Connolly et al. (2003) noted that strength loss usually peaks immediately after exercise or within the first 48 hours, while pain and tenderness peaks 24-72 hours after exercise. While time and rest should influence the DOMS experienced by an individual (in part shown by the CONT group's significant result), PEMF therapy could help expedite this process for some individuals. To provide support to this theory, PEMF therapy has been used in the treatment of low back pain (Elshiwi et al., 2019; Lisi et al., 2019). A PEMF therapy treatment protocol that involved twice daily, 30-minute sessions for six weeks, followed by 30-minute sessions completed 2-3 times per week for the next six weeks, led to a decrease in pain measured by a VAS, and an improvement in low back function measured by the Oswestry Disability Index (Lisi et al., 2019). Elshiwi et al. (2019) found that 12 PEMF therapy sessions over four weeks led to a significant decrease in pain intensity measured by a VAS and improved low back function and range of motion in participants diagnosed clinically with chronic non-specific low back pain. The afore-mentioned studies did not measure any mechanisms for how pain could have been reduced, but there were suggestions that analgesia and other neurological adaptations, reduced inflammatory response, and anabolic effects on osteoblasts and chondrocytes could have contributed to reduced perception of low back pain (Elshiwi et al., 2019; Lisi et al., 2019). Although low back pain and muscle soreness are different, these studies do provide a foundation for why the PEMF group in the current study may have indicated lower VAS and Likert scale scores following their recovery treatment. Even with the non-significant results, the data does suggest potential value for using PEMF therapy in the reduction of perceived muscle soreness.

There were large standard deviations for many of the quantitative and qualitative measures across the three groups, indicating variation in individual responses to the recovery interventions. Following a review of PEMF therapy literature, Lockie (2020) also noted that this was the case in the clinical application of this technique, such as with the treatment of bone fractures. This would suggest that some individuals may be high or low responders to the PEMF device, in addition to the placebo and control conditions. Recognizing how the individual responds to a particular intervention is an important part of a strength and conditioning coaches' skillset. Anecdotally, some adverse reactions to PEMF therapy have been said to include fatigue, sleep pattern changes, pain, loss of energy, prickly sensations in the skin, dizziness, and heart palpitations (Pawluk, 2007). None of the participants in the PEMF group from this study reported any adverse reactions. Even though the frequencies associated with PEMF therapy should have no negative effects on human health (Wade, 2013), Lockie (2020) recommended that any negative experiences for athletes should be detailed, so coaches should do so with their athletes if they use this protocol. Positive experiences for athletes with PEMF therapy should also be documented by coaches. The results from this study suggest that some individuals will

respond well to EPMF therapy in the 72 hours post-fatiguing exercise. For these individuals, PEMF therapy could be included as part of their recovery protocols.

There are limitations for this research that should be discussed. The potential mechanisms for how PEMF therapy could be effective were not investigated in this study. Given the paucity of research analyzing PEMF therapy and athletic performance (Tamulevicius et al., 2021), the starting point for research in this area is to ascertain whether there is an absolute effect on variables such as force and power. However, future studies could investigate neuromuscular function or inflammatory markers and how they respond to PEMF therapy. This study attempted to isolate one recovery device (i.e., PEMF therapy). In practice, athletes will likely use multiple devices (e.g., nutrition and hydration, massage, compression) to assist with their recovery from training and competition (Barnett, 2006). Nonetheless, future studies could assess whether PEMF therapy used in conjunction with other modalities can expedite an athlete's recovery. Only one PEMF therapy application, which had a duration of 22:32 min:s, was analyzed in this study over the course of three days. There may be a dose:response relationship between PEMF therapy and recovery, which requires further investigation. The intensity of the PEMF device in this study may also not have been intense enough to induce more substantial recovery from the intensive exercise. This study only utilized a running assessment to induce fatigue (Gathercole et al., 2015); other protocols (e.g., cycling, resistance exercise) could lead to different results than what was shown in this research. As previously stated, the VJ and LBD measurements did not incorporate any time or rate of force development metrics (Haff et al., 2015; McMahon et al., 2018), which could have elucidated different results to those found in this study. To assist with sample size, the sexes were combined within each group. Moreover, due to the random allocation of participants into each group, there were unequal numbers of men and women in each group. Future research should investigate whether there are sex differences in recovery from fatiguing exercise with the use of PEMF therapy. The training history of participants in each group could have varied, which may have some influence on the observed results. The participants in this study were also recreationally-active men and women. Professional or elite athletes may respond differently to PEMF therapy than the participants in the current study.

Conclusion

Athletes seek any advantage that could assist with their performance and recovery. PEMF therapy may be beneficial to help with recovery from strenuous exercise among some individuals. While not conclusive, the results from this study suggest that PEMF therapy could be added to an athlete's recovery regime with some potential positive impacts (i.e., faster recovery of PP, improved perception of recovery after 24-72 hours). As previously stated, PEMF devices are designed to be non-invasive, so could be used in conjunction with other activities (e.g., users can sit with their device while doing other things such as working on a computer or watching film, while receiving a massage, during a meal, etc.). Although more research is needed to ascertain mechanisms for how PEMF therapy could affect recovery following strenuous exercise, the current results show potential for using PEMF devices as part of a recovery protocol for athletes, especially in the first 72 hours post-strenuous exercise.

Acknowledgements: Equipment for this research was provided by HAELO (Encino, CA, USA). The authors would like to thank Mara Ballard and Jeff Monroe for supporting this research, and the participants for their efforts.

References

Abdelhalim, N.M., Samhan, A.F., & Abdelbasset, W.K. (2019). Short-term impacts of pulsed electromagnetic field therapy in middle-aged university's employees with non-specific low back pain: A pilot study. *Pakistan Journal of Medical Sciences*, *35*(4), 987-991. https://doi.org/10.12669/pjms.35.4.49

Ascensão, A., Leite, M., Rebelo, A.N., Magalhães, S., & Magalhães, J. (2011). Effects of cold water immersion on the recovery of physical performance and muscle damage following a one-off soccer match. *Journal of Sports Sciences*, *29*(3), 217-225. https://doi.org/10.1080/02640414.2010.526132

Barnett, A. (2006). Using recovery modalities between training sessions in elite ethletes. *Sports Medicine*, *36*(9), 781-796. https://doi.org/10.2165/00007256-200636090-00005

Bishop, P.A., Jones, E., & Woods, A.K. (2008). Recovery from training: A brief review. *Journal of Strength and Conditioning Research*, *22*(3), 1015-1024. https://doi.org/10.1519/JSC.0b013e31816eb518

Chleboun, G.S., Howell, J.N., Baker, H.L., Ballard, T.N., Graham, J.L., Hallman, H.L., Perkins, L.E., Schauss, J.H., & Conatser, R.R. (1995). Intermittent pneumatic compression effect on eccentric exercise-induced swelling, stiffness, and strength loss. *Archives of Physical Medicine and Rehabilitation*, *76*(8), 744-749. https://doi.org/10.1016/s0003-9993(95)80529-x

Connolly, D.A., Sayers, S.P., & McHugh, M.P. (2003). Treatment and prevention of delayed onset muscle soreness. *Journal of Strength and Conditioning Research*, *17*(1), 197-208. https://doi.org/10.1519/1533-4287(2003)017<0197:tapodo>2.0.co;2

Delextrat, A., Calleja-González, J., Hippocrate, A., & Clarke, N.D. (2013). Effects of sports massage and intermittent cold-water immersion on recovery from matches by basketball players. *Journal of Sports Sciences*, *31*(1), 11-19. https://doi.org/10.1080/02640414.2012.719241

Duncan, R.L. & Turner, C.H. (1995). Mechanotransduction and the functional response of bone to mechanical strain. *Calcified Tissue International*, *57*(5), 344-358. https://doi.org/10.1007/BF00302070

Elshiwi, A.M., Hamada, H.A., Mosaad, D., Ragab, I.M.A., Koura, G.M., & Alrawaili, S.M. (2019). Effect of pulsed electromagnetic field on nonspecific low back pain patients: a randomized controlled trial. *Brazilian Journal of Physical Therapy*, *23*(3), 244-249. https://doi.org/10.1016/j.bjpt.2018.08.004

Gathercole, R.J., Sporer, B.C., Stellingwerff, T., & Sleivert, G.G. (2015). Comparison of the capacity of different jump and sprint field tests to detect neuromuscular fatigue. *Journal of Strength and Conditioning Research*, *29*(9), 2522-2531. https://doi.org/10.1519/jsc.0000000000000912

Gibson, W., Arendt-Nielsen, L., & Graven-Nielsen, T. (2006). Delayed onset muscle soreness at tendon-bone junction and muscle tissue is associated with facilitated referred pain. *Experimental Brain Research*, *174*(2), 351-360. https://doi.org/10.1007/s00221-006-0466-y

HAELO. (2021). *HAELO Symphony One*. Retrieved July 5, 2024, from https://www.haelo.com/pages/product-page-desktop.

Haff, G.G., Ruben, R.P., Lider, J., Twine, C., & Cormie, P. (2015). A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. *Journal of Strength and Conditioning Research*, *29*(2), 386-395. https://doi.org/10.1519/jsc.0000000000000705

Hall, D., James, D., & Marsden, N. (2012). Marginal gains: Olympic lessons in high performance for organisations. *HR Bulletin: Research and Practice*, *7*(2), 9-13.

Hannouche, D., Petite, H., & Sedel, L. (2001). Current trends in the enhancement of fracture healing. *The Journal of Bone and Joint Surgery. British Volume*, *83-B*(2), 157-164. https://doi.org/10.1302/0301-620x.83b2.0830157

Hanson, E., Stetter, K., Li, R., & Thomas, A. (2013). An intermittent pneumatic compression device reduces blood lactate concentrations more effectively than passive recovery after Wingate testing. *Journal of Athletic Enhancement*, *2*(3). https://doi.org/10.4172/2324-9080.1000115

Hausswirth, C. & Le Meur, Y. (2011). Physiological and nutritional aspects of post-exercise recovery. *Sports Medicine*, *41*(10), 861-882. https://doi.org/10.2165/11593180-000000000-00000

Hopkins, W.G. (2004). How to interpret changes in an athletic performance test. *Sportscience*, *8*, 1-7. https://sportsci.org/jour/04/wghtests.htm

Hug, K. & Röösli, M. (2012). Therapeutic effects of whole-body devices applying pulsed electromagnetic fields (PEMF): A systematic literature review. *Bioelectromagnetics*, *33*(2), 95-105. https://doi.org/10.1002/bem.20703

Jamieson, S. (2004). Likert scales: how to (ab)use them. *Medical Education*, *38*(12), 1217-1218. https://doi.org/10.1111/j.1365-2929.2004.02012.x

Lien, D. & Balakrishnan, N. (2005). On regression analysis with data cleaning via trimming, winsorization, and dichotomization. *Communications in Statistics-Simulation and Computation*, *34*(4), 839-849. https://doi.org/10.1080/03610910500307695

Lisi, A.J., Scheinowitz, M., Saporito, R., & Onorato, A. (2019). A pulsed electromagnetic field therapy device for non-specific low back pain: A pilot randomized controlled trial. *Pain and Therapy*, *8*(1), 133-140. https://doi.org/10.1007/s40122-019-0119-z

Lockie, R.G. (2020). Does pulsed electromagnetic field (PEMF) therapy have application to athletic performance? *NSCA Coach*, *7*(4), 12-16.

Longoria, K. & Gielen, W. (2021). *Investigating the physiological performance benefits of HAELO symphonic pulsed electromagnetic field (sPEMF) therapy measured by the Biostrap wrist-worn photoplethysmography device*. Zenodo. Retrieved July 5, 2024, from https://zenodo.org/records/4560785.

Magrini, M.A., Dawes, J., Elder, C.L., Orr, R.M., & Smith, B.B. (2018). Effectiveness of compression garments on selected physiological, perceptual and performance measures while traversing austere conditions at altitude: A pilot study. *Sports and Exercise Medicine Open Journal*, *4*(3), 83-89. https://doi.org/10.17140/SEMOJ-4-167

McMahon, J.J., Lake, J.P., & Comfort, P. (2018). Reliability of and relationship between flight time to contraction time ratio and reactive strength index modified. *Sports*, *6*(3), 81. https://doi.org/10.3390/sports6030081

National Cancer Institute. (2019). *Electromagnetic Fields and Cancer*. Retrieved October 15, 2021, from https://www.cancer.gov/about-cancer/causes-prevention/risk/radiation/electromagnetic-fields-fact-sheet#what-are-electric-and-magnetic-fields.

Norman, G. (2010). Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education: Theory and Practice*, *15*(5), 625-632. https://doi.org/10.1007/s10459-010-9222-y

Olejnik, S.F. & Algina, J. (1984). Parametric ANCOVA and the Rank Transform ANCOVA when the data are conditionally non-normal and heteroscedastic. *Journal of Educational Statistics*, *9*(2), 129-149. https://doi.org/10.3102/10769986009002129

Overmayer, R.G. & Driller, M.W. (2018). Pneumatic compression fails to improve performance recovery in trained cyclists. *International Journal of Sports Physiology and Performance*, *13*(4), 490-495. https://doi.org/10.1123/ijspp.2017-0207

Pawluk, W. (2007). *PEMF for Athletes*. Retrieved August 4, 2020, from https://www.magnusmagnetica.com/pemf-for-athletes.

Peng, L., Fu, C., Wang, L., Zhang, Q., Liang, Z., He, C., & Wei, Q. (2021). The effect of pulsed electromagnetic fields on angiogenesis. *Bioelectromagnetics*, *42*(3), 250-258. https://doi.org/10.1002/bem.22330

Robertson, A., Watt, J.M., & Galloway, S.D.R. (2004). Effects of leg massage on recovery from high intensity cycling exercise. *British Journal of Sports Medicine*, *38*(2), 173. https://doi.org/10.1136/bjsm.2002.003186

Strauch, B., Herman, C., Dabb, R., Ignarro, L.J., & Pilla, A.A. (2009). Evidence-based use of pulsed electromagnetic field therapy in clinical plastic surgery. *Aesthetic Surgery Journal*, *29*(2), 135-143. https://doi.org/10.1016/j.asj.2009.02.001

Suresh, K. (2011). An overview of randomization techniques: An unbiased assessment of outcome in clinical research. *Journal of Human Reproductive Sciences*, *4*(1), 8-11. https://doi.org/10.4103/0974-1208.82352

Tamulevicius, N., Wadhi, T., Oviedo, G.R., Anand, A.S., Tien, J.J., Houston, F., & Vlahov, E. (2021). Effects of acute low-frequency pulsed electromagnetic field therapy on aerobic performance during a preseason training camp: A pilot study. *International Journal of Environmental Research and Public Health*, *18*(14), 7691. https://doi.org/10.3390/ijerph18147691

Torres, R., Pinho, F., Duarte, J.A., & Cabri, J.M. (2013). Effect of single bout versus repeated bouts of stretching on muscle recovery following eccentric exercise. *Journal of Science and Medicine in Sport*, *16*(6), 583-588. https://doi.org/10.1016/j.jsams.2013.01.002

Wade, B. (2013). A review of Pulsed Electromagnetic Field (PEMF) mechanisms at a cellular level: A rationale for clinical use. *American Journal of Health Research*, *1*(3), 51-55. https://doi.org/10.11648/j.ajhr.20130103.13

Wu, Z., Ding, X., Lei, G., Zeng, C., Wei, J., Li, J., Li, H., Yang, T., Cui, Y., Xiong, Y., Wang, Y., & Xie, D. (2018). Efficacy and safety of the pulsed electromagnetic field in osteoarthritis: A meta-analysis. *BMJ Open*, *8*(12), e022879. https://doi.org/10.1136/bmjopen-2018-022879

Zainuddin, Z., Newton, M., Sacco, P., & Nosaka, K. (2005). Effects of massage on delayed-onset muscle soreness, swelling, and recovery of muscle function. *Journal of Athletic Training*, *40*(3), 174-180.