Journal of Translational Medicine

RESEARCH

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Influence of combined transcranial and peripheral electromagnetic stimulation on the autonomous nerve system on delayed onset muscle soreness in young athletes: a randomized clinical trial

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Abstract

Background Delayed Onset Muscle Soreness (DOMS) represents a common challenge for athletes and has been a focal point of research in sports science. Eccentric exercise, known to induce DOMS, significantly impacts recovery and physiological processes. Electromagnetic stimulation, both transcranial and peripheral, has gained attention in sports medicine due to its demonstrated benefits in various conditions, offering potential as a recovery-enhancing tool for athletes.

Purpose This study aimed to evaluate the effects of combined transcranial and peripheral electromagnetic stimulation on the autonomic nervous system response and recovery in young athletes experiencing DOMS.

Methods A randomized, double-blind study was conducted with 48 young athletes divided into four groups: Control (n = 12), Peripheral Stimulation (n = 13), Transcranial Stimulation (n = 11), and Combined Stimulation (n = 12). Participants underwent an eccentric exercise session to induce DOMS, followed by their respective interventions: no stimulation for the Control group, 5 min of peripheral electromagnetic stimulation (LTP protocol) for the Peripheral group, 20 min of transcranial stimulation for the Transcranial group, and a combination of both (30 min total) for the Combined group. The autonomic nervous system was assessed through Heart Rate Variability (HRV) parameters measured before, immediately after, and at 24 h, 48 h, and 72 h post-intervention.

Results The Combined Stimulation group exhibited significant improvements in HRV parameters, including increased Low Frequency (LF, $p < 0.001$), High Frequency (HF, $p < 0.001$), and LF/HF power ratio ($p < 0.001$) at 72 h post-intervention compared to other groups. These findings suggest that paired-associative electromagnetic stimulation effectively enhances autonomic regulation and promotes recovery after eccentric exercise-induced DOMS.

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Conclusions Combined transcranial and peripheral electromagnetic stimulation positively influences autonomic nervous system responses, accelerating recovery in young athletes without disrupting natural physiological recovery mechanisms. This approach presents a promising recovery intervention for athletes experiencing DOMS.

Keywords Delayed onset muscle soreness, Transcranial electromagnetic stimulation, Peripheral electromagnetic stimulation, Recovery, Heart rate variability, Athletes

Introduction

For nearly the last few decades, scientists and sports performance teams have diligently investigated the etiology and origins of Delayed Onset Muscle Soreness (DOMS). Substantial research, including notable contributions by Sonkodi in 2021 and Sonkodi et al. in 2020, has emphasized that DOMS may not only be a manifestation of muscle fatigue but could also serve as a precursor to more severe muscle injuries during athletic activities [41, 42]. This understanding necessitates a deeper recognition of DOMS' potential impacts on sports participation and performance. The ramifications for athletes and sports organizations are significant, as evidenced by the findings of Hayashi et al. [16] and Hickey et al. [19], who have documented the broad and sometimes severe consequences of these muscle conditions on the athletic community [16, 19]. Such insights underline the importance of comprehensive studies and targeted interventions aimed at mitigating the onset and severity of DOMS to enhance athletic performance and prevent injury.

Indeed, DOMS typically follows activities that involve a high degree of eccentric contractions, often occurring after periods of rest such as the preseason in various team sports [17, 32]. This condition is mediated by a cascade of biochemical events, including the secretion of bradykinin through perspiration and an upregulation of nerve growth factor, both of which contribute to the sensitization of nociceptors and consequently, an enhanced perception of muscle soreness [9, 34]. Furthermore, advancements in the understanding of DOMS propose that its underlying mechanism may be rooted in acute axonopathy, which results from the physical compression and damage of muscle fibers. This axonopathy is believed to trigger hyperalgesia, specifically at the neuromuscular spindle, a process that is characterized by two distinct phases: the initial acute muscle compression followed by excitotoxicity, which is primarily due to the release of glutamate [22, 46].

This conceptual framework is further reinforced by recent theories presented by Sonkodi et al. [42], which suggest that DOMS may arise specifically due to acute axonopathy, emphasizing the significant role of peripheral nerves and the inflammation of surrounding tissues [36, 42]. This perspective underscores a critical shift in understanding DOMS not just as a mere aftermath of physical exertion but as a complex interplay of neurological and inflammatory responses that are pivotal to developing more effective treatments and preventive measures in sports medicine. As precedent studies discussed the diagnosis or prognosis of such condition within the sport related industry up to date the evidence about such combined treatment is growing regarding the potential influence about the combined treatment, as many worked have showed that there is a potential disruption of the nervous messages send from the peripheric to the central nerve system [18, 20, 43].

Building on the newly developed theories about the pathophysiology of DOMS, recent research has demonstrated the pivotal role of the peripheral nervous system in individuals experiencing DOMS. This has led to the exploration of novel therapeutic approaches, including the combination of transcranial and peripheral electromagnetic stimulation [2, 21]. The innovative aspect of this treatment lies in its dual approach: targeting both central and peripheral components of the nervous system to potentially enhance recovery processes. In this line, Transcranial Electromagnetic Stimulation (TMS) has been utilized since 1985, primarily within the realm of sports medicine, to non-invasively examine cortical excitability and its implications on muscle function. Over the years, the application of TMS has expanded, showing safety and efficacy in treating neurological conditions like fibromyalgia and aiding post-stroke rehabilitation. It also plays a significant role in understanding the relationship between muscle fatigue and brain activation, thus influencing sports performance and recovery [11, 27, 33, 49].

On the other hand, Peripheral Electromagnetic Stimulation (PES) serves as a complementary technique, distinct from TMS due to its focus on the peripheral bodily regions. PES employs rapid pulses of high-intensity electricity combined with a magnetic field to stimulate peripheral afferents. This not only aids in the recruitment of these nerve pathways but also facilitates proprioceptive responses, which are crucial for initiating brain neuroplasticity and enhancing motor control [1, 14, 33, 40].

Together, these techniques have significantly advanced the field of neuromodulation, offering new insights into the integration of cortical and peripheral stimuli in managing conditions like DOMS. As the potential of the combined treatment in the recovery process by acting on the

fatigue generated by exercise but without affecting the natural physiological process involved within a DOMS condition. Their combined use underscores a strategic shift towards holistic approaches in sports medicine, focusing on the interconnectivity of brain and peripheral functions to optimize athlete recovery and performance.

Another critical aspect of this research is the demonstrated interrelationship between the central nervous system, specifically the motor cortex, and the modifications in Heart Rate Variability (HRV) observed following transcranial stimulation. This relationship is pivotal due to the direct connection between the cortical regions of the brain and the autonomic centers, which regulate bodily functions such as heart rate and stress responses [4]. HRV serves as a quantifiable index of the autonomic nervous system's response to environmental stressors. It provides insights into how personal conditions, such as psychological stress, may influence the recovery processes, thereby affecting overall athletic performance and rehabilitation [29]. In this line, extensive research has shown that modifications in HRV can be directly linked to the application of Transcranial Magnetic Stimulation (TMS) on the primary motor cortex (M1). These changes in HRV reflect alterations in muscle activity, potentially influencing the response of the autonomic nervous system. Such findings underscore the sensitivity of HRV as a marker for neurophysiological changes and its utility in assessing the impact of neurological interventions on systemic physiological functions [24, 39].

Thus, the primary objective of this study is to explore the potential effects of the innovative combined approach of transcranial and peripheral electromagnetic stimulation on the Autonomic Nervous System. Moreover, this investigation aims to thoroughly analyze the dual treatment's influence on the recovery process from physical sports activities, particularly assessing its efficacy in enhancing autonomic regulation and facilitating faster and more effective recovery in athletes. This holistic approach highlights the integration of neurostimulation techniques in sports medicine, aiming to optimize the recovery strategies post-exercise, which could significantly benefit athletic performance and well-being.

Methods

Study design

The present study was conducted as a randomized, double-blind investigation that examined young athletes, adhering to the ethical guidelines stipulated in the "World Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects" (World Medical Association, 1991). Furthermore, compliance with the Consolidated Standards of Reporting Trials (CONSORT) guidelines was ensured throughout the study.

The research was approved by the Research Ethics Committee (reference number: C.I.23/048-F), and it was also registered with the Australian New Zealand Clinical Trials Registry (ACTRN12623000677606), affirming its adherence to recognized ethical standards.

Employing a prospective, randomized trial design, the study included a control group to facilitate comparative analysis. Participants were systematically allocated into one of four distinct groups: the Control group (Cont), which received no intervention; the Super Induction group (P), subjected to Peripheral Electromagnetic Stimulation (PES); the Transcranial group (T), which underwent Transcranial Electromagnetic Stimulation (TES); and the Combination of Stimulation group (Comb), which experienced a synergistic application of both TES and PES modalities. This setup was designed to rigorously evaluate the individual and combined effects of the interventions on the autonomic nervous system and recovery processes in athletes.

Protocol for transcranial and peripheral electromagnetic stimulation in the study

The study employed various methods to administer electromagnetic stimulation treatments, tailored to the specific group each participant was assigned to.

Control (Cont) group

Participants in the Cont group interacted with the same device as those in the active treatment groups, but with a crucial modification: the machine was turned off. To sustain the placebo effect—particularly critical in the context of transcranial treatments—a recording of the machine's operation was played during the session. Additionally, for the transcranial aspect, simply wearing the device's flap, corresponding to TES, was deemed sufficient to maintain the placebo effect.

Super inductive (P) group

Participants in the P group were treated using PES according to the Long-Term Potentiation protocol. This involved five cycles of stimulation at 100 Hz for 5 s each, followed by a 55-s rest period. The total duration of treatment for this group was approximately 10 min, a protocol based on the findings by Lang et al. [26] and Milanović et al. [31] [26, 31].

Transcranial stimulation (T) group

In the T group, the treatment included 2000 pulses of TES administered over a minimum of 20 min, targeting the cortical area M1 [12, 47].

Comb stimulation (Comb) group

Participants in the Comb group underwent a total stimulation time of about 30 min, as a combination of both PES and TES treatments.

All groups commenced treatment one hour after the eccentric exercise session, aligning with the onset of fatigue denoted as time T2 in the study. The duration of the stimulation varied depending on the group assignment, ranging from 10 min for the P group to 30 min for those in the Comb group. A Magrex stimulator equipped with a ring-shaped coil/8-shaped coil was utilized to administer the TES and PES treatments (MR Inc., Republic of Korea, http://www.mrev.co.kr). The equipment was selected for its ability to deliver the specified electromagnetic stimulation protocols with pinpoint accuracy and efficiency (Fig. 1**).**

To enhance the blinding of the study and maintain objectivity, a specific, neutral location was designated for administering the treatments. This strategic approach was instrumental in ensuring that both participants and researchers remained unaware of the group allocations, thereby minimizing bias and enhancing the validity of the findings. Researchers assigned to the treatment stations were solely involved in delivering the interventions and were explicitly instructed not to engage in discussions with other members of the research team or with participants regarding group assignments or treatment specifics.

These meticulous measures were implemented to ensure that the study conformed to the highest standards of scientific rigor and ethical conduct. The aim was to collect unbiased data that could provide reliable and valuable insights into the effects of electromagnetic and electrical stimulation on young athletes. This commitment to rigorous methodology underpins the study's contribution to the field, potentially informing future therapeutic strategies and enhancing sports performance management.

Sample size calculation

The sample size was calculated using G-Power software (version 3.1) to ensure sufficient statistical power for detecting meaningful differences between groups. The calculation was based on the following parameters:

- Alpha error probability (Type I error): 0.05, representing a 5% chance of rejecting the null hypothesis when it is true.
- Beta error probability (Type II error): 0.20, corresponding to a statistical power of 80%, which is the standard threshold for minimizing the risk of failing to detect a true effect.
- Effect size: Derived from previous studies exploring electromagnetic stimulation in related contexts, with a standard deviation of 2.61. This value was chosen based on the expected variability in HRV parameters and recovery outcomes, as informed by Lang et al. [26] and Milanović et al. [31].
- Number of groups: Four (Control, PES, TES, and Combined).

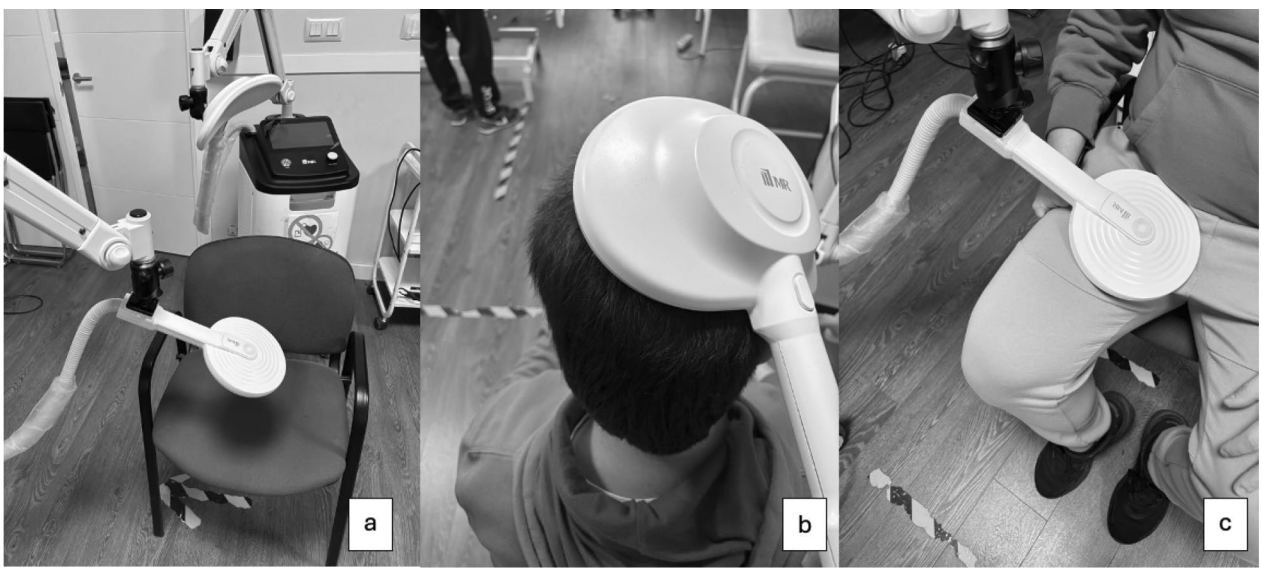

Fig. 1 Illustration of study participants undergoing electromagnetic stimulation: **a** Transcranial and peripheral stimulation devices; **b** Transcranial stimulation setup; **c** Peripheral stimulation setup

The calculation determined that 22 participants per group were required to detect statistically significant differences with the above parameters. To account for an anticipated 15% dropout rate, the target total sample size was increased to 80 participants, divided equally across the four groups.

This rigorous approach ensures that the study is adequately powered to detect the intended effects while considering the variability and feasibility of participant retention. These details have been incorporated into the manuscript for full transparency.

Participants

Students from the European University of Madrid were selectively recruited for the study, employing targeted strategies within the Faculty of Sports Sciences. Recruitment utilized multiple communication channels including flyers, posters, and strategically positioned advertisements, ensuring broad outreach within the university community.

The inclusion criteria were meticulously defined to capture a specific demographic and health profile conducive to the study's objectives. Participants were required to be:

- Male, as delineated by Chen et al. [7] which indicated a difference found within both Creatine Kinase (CK) and Lactate concentration between sex as we did not want to concluded wrongly our work it has been decided to only selected male for this experiment [7].
- Aged between 18 and 35 years
- Furthermore, these individuals were expected to engage in regular physical activity, defined as participating in exercise at least three times a week for a minimum duration of one year,
- Were to have no hypersensitivity in areas designated for peripheral stimulation.
- The screening process also included assessments for any diagnosed chronic diseases, recent musculoskeletal injuries to the lower extremity within the past six months, and smoking habits, as noted by Dominguez-Balmaseda et al. [13], all the presents characteristics would have had a negative impact over the excentric session necessary in the present work [13].

Exclusion criteria were rigorously applied to ensure the safety and appropriateness of the study participants. Individuals with medical conditions that were incompatible with exercise, those unable to understand the objectives of the exercise sessions, or those failing to meet any of the specified inclusion criteria were excluded from participation. This thorough screening process was integral to maintaining the integrity and reliability of the study's outcomes.

Randomization

The randomization of participants into study groups was meticulously conducted using the randomization function of Microsoft Office Excel (Microsoft Corporation, Redmond, Washington, USA). This approach ensured that the allocation of subjects to the four predefined study groups was carried out in an unbiased and systematic manner. By employing a widely recognized tool for data manipulation and randomization, the study upheld the principles of fairness and scientific integrity essential for experimental reliability. This methodological choice facilitated the equitable distribution of participants across the Control group, Super Induction group, Transcranial group, and the Combination of Stimulation group, as previously detailed.

Procedure

Participants were required to attend a total of five assessment sessions as delineated in the study's methodology outlined in Fig. 2. A preliminary familiarization session was held one week prior to the initial study assessment to ensure that all participants were well-acquainted with the experimental procedures and equipment.

The inaugural assessment session (Day 1) was dedicated to comprehensively evaluating various physiological and biomechanical data. This included the measurement of creatine kinase (CK) levels, blood lactate concentrations, and heart rate variability with parameters such as SDNN, LF, HF, and Power. Additionally, a suite of anthropometric data was collected, facilitating a thorough understanding of the study population's baseline physiological and physical state.

Subsequent sessions were meticulously scheduled at specific post-exercise intervals—1 h, 24 h, 48 h, and 72 h after the muscle-damaging exercise—to monitor the progression and recovery during these critical periods. During each session, the parameters previously mentioned were measured again to deepen the understanding of or observe any changes, thereby assessing the impact of the muscle-damaging protocol.

The analysis of blood concentrations of CK and lactate was prioritized as the primary method to gauge muscle damage. Blood samples were collected and analyzed using electrophoretic techniques (Lactate Scout Pro, Musimedic S.L Donostia, Spain), providing detailed insights into the extent of muscle damage and the recovery dynamics within the participant group.

To ensure the accuracy of enzyme measurements, participants were instructed to refrain from any physical activities two days prior to the study commencement.

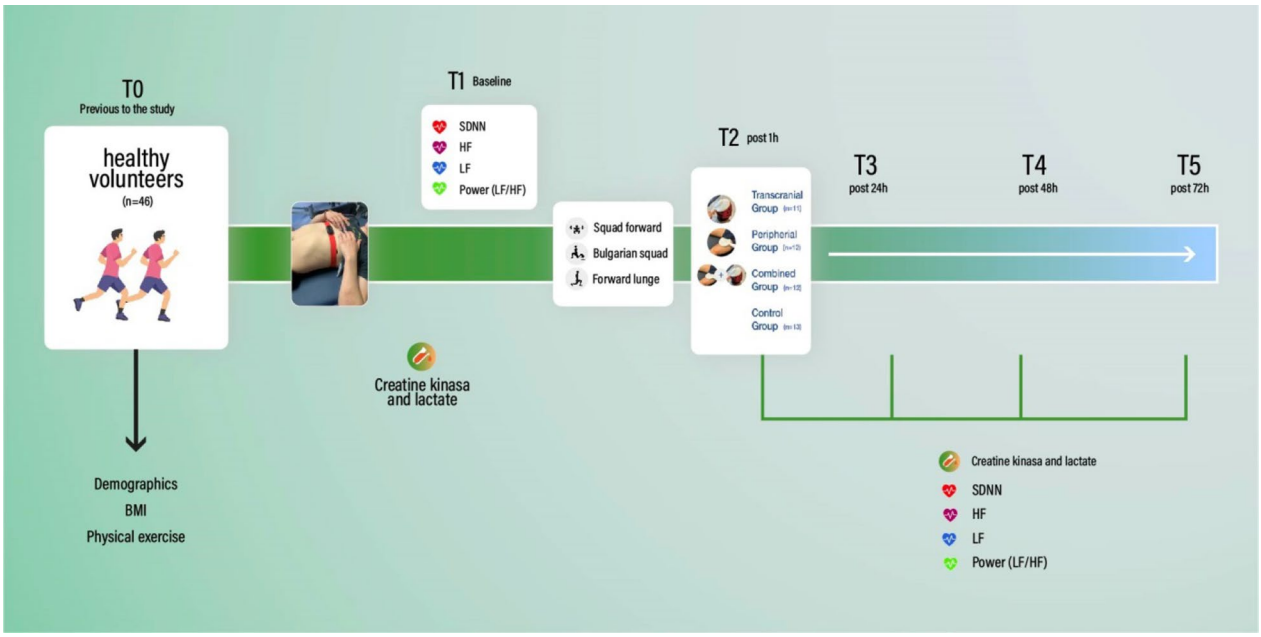

Fig. 2 Overview of the assessment timeline and intervention protocol

This precaution was essential to prevent the potential elevation of enzyme levels caused by recent physical exertion, which could skew the interpretation of the results, thus maintaining the integrity and accuracy of the study findings.

Intervention: eccentric exercise protocol

The exercise session was meticulously structured into three distinct phases, each designed to induce DOMS effectively while minimizing injury risks. These phases incorporated specific strength exercises tailored to meet the study's rigorous scientific objectives.

General warm-up

The initial phase comprised a warm-up aimed at enhancing joint mobility in the lower limbs, supplemented by bodyweight strength exercises. This preparatory phase was critical for acclimatizing athletes to the physical demands of the subsequent exercises designed to induce DOMS.

Intervention exercises

The second phase involved participants executing a series of three targeted exercises, with the encoder-controlled squat exercise serving as the focal point. The performance of the squat was meticulously monitored using a linear accelerometer, calibrated to assess 60% of each participant's one-repetition maximum. This specific intensity was determined based on a protocol developed by González-Badillo, which considers the speed (measured in meters per second) that a subject can manage the prescribed load [15].

Eccentric workout routine

The concluding phase of the session included the following three exercises (Fig. 3):

a) Squat Forward: Participants executed 10 sets of 10 repetitions at 60% of their 1-RM, as established during the pre-study assessment.
b) Bulgarian Squat: This exercise required participants to perform three sets of 10 repetitions on each leg, with the option of adding an additional 5 or 10 kg of weight.
c) Forward Beam (Split): This exercise also consisted of three sets of 10 repetitions on each leg, with participants having the option to add between 5 and 10 kg of weight.

Each phase was strategically planned to ensure that the exercises were both challenging and safe for participants, aligning meticulously with the study's objectives to investigate the effects and mechanisms of DOMS in an athletic population.

Outcome measures: heart rate variability

In this study, the response of the Autonomic Nervous System was meticulously analyzed through Heart Rate Variability (HRV). HRV measurements were recorded for each participant during a 10-min period in a supine

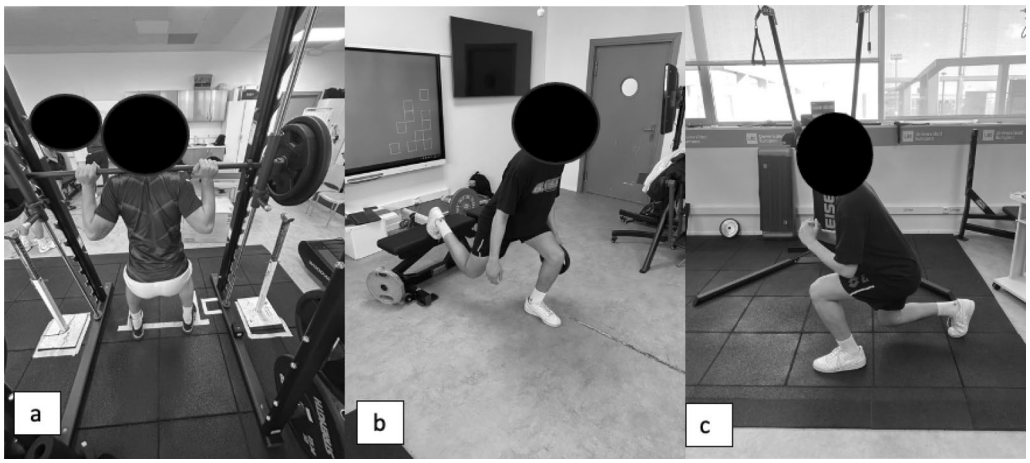

Fig. 3 Illustration of participants engaged in the eccentric exercise protocol. Exercise demonstrations include: **a** squat forward; **b** Bulgarian squat; **c** forward lunge

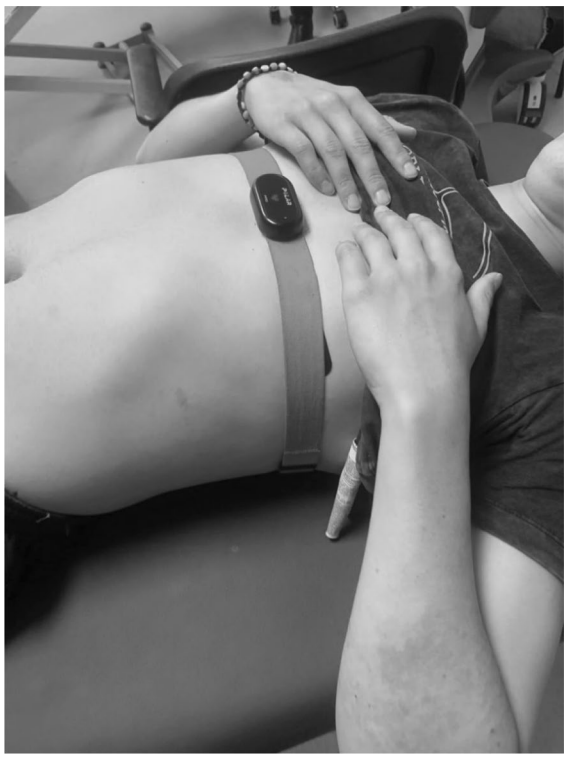

Fig. 4 Participant in supine position with the polar H10 sensor collocated

position to obtain data across different phases: baseline (T1), post-exercise (T2), and during the recovery procedure (T3 to T5), as depicted in Fig. 4. To adhere to established protocols and ensure the reliability of the data, participants were instructed to abstain from consuming substances such as alcohol, caffeine, and drugs that could affect the autonomic nervous system's response during the study period [38].

Measurements were conducted using the Polar H10 heart rate monitor, which is recognized for its accuracy in HRV assessments [30, 48]. Various parameters of HRV were extracted at each designated time point. In the time domain, the standard deviation of all normal-to-normal RR intervals (SDNN) was calculated. In the frequency domain, parameters such as the low frequency (LF) in ms^2, the high frequency (HF) in ms^2, the LF/HF ratio, and the total power were meticulously analyzed [30, 37]. These metrics provided a comprehensive overview of the autonomic nervous system's dynamics throughout the study's various stages.

Statistical analysis

All statistical analyses were conducted using SPSS (Statistical Package for Social Sciences, version 25, IBM, Armonk, NY, United States). Descriptive statistics for all variables were expressed as mean ± standard deviation (SD), and data distribution was tested for normality using the Kolmogorov–Smirnov test. For parametric data, one-way ANOVA was used to compare between-group differences, while paired t-tests were employed for within-group comparisons across different time points. For non-parametric data, the Wilcoxon signed-rank test was utilized for within-group analyses. A significance level of $p \leq 0.05$ was maintained for all tests.

For between-group comparisons where ANOVA revealed significant differences, post-hoc analyses with Bonferroni correction were applied to determine specific group-level contrasts. This ensured rigorous control of Type I errors while enabling precise identification of

differences among the Control, Peripheral, Transcranial, and Combined groups.

Effect sizes and confidence intervals

To enhance the interpretation of results, effect sizes were calculated:

- **Cohen's d** was used for paired t-tests to quantify within-group effect sizes, categorized as small (d = 0.2), medium (d = 0.5), and large (d = 0.8).
- **Partial eta squared (η^2p)** was calculated for ANOVA results to indicate the magnitude of between-group effects, with thresholds defined as small (η^2p = 0.01), medium (η^2p = 0.06), and large (η^2p = 0.14).
- **95% confidence intervals (CIs)** were provided for significant results to ensure transparency and precision, allowing readers to assess the reliability of the observed differences.

Results interpretation

The statistical results were carefully interpreted to clarify both significant and non-significant findings:

- For example, at 72 h post-DOMS (T5), ANOVA results indicated significant differences among groups for LF ($p < 0.001$, $\eta^2p = 0.82$), HF ($p < 0.001$, $\eta^2p = 0.767$), and Power ($p < 0.001$, $\eta^2p = 0.679$). Post-hoc analysis confirmed that the Combined group demonstrated significantly better outcomes compared to the Control group for these variables.
- For SDNN, no significant differences were detected between groups ($p = 0.42$), ensuring a balanced interpretation of the data.

Data presentation

Tables were updated to include the following information for all analyzed variables:

- Means ± SD for each group and time point.
- Corresponding p-values for each test.
- Effect sizes (Cohen's d or η^2p) for all significant results.
- 95% CIs for significant findings to ensure interpretability.

An amount of 80 volunteers consented to participate in the present work. Nevertheless, 26 participants could not to begin the study at the initial assessment time, and a total of 4 more participants did not complete all the timeline and evaluation needed (Fig. 5). Therefore, 48 male athletes completed all the assessment and were comprised in the final analysis, with a standard of 21.95 ± 4.23 years, 74.58 ± 8.94 kg of weight, 179.00 ± 7.31 cm of height, and 23.27 ± 2.41 kg/m^2 for the Body Mass Index. With no significant differences detected between the study groups for all the demographics variables ($p > 0.005$).

Results

In an aim to confirm these highlights, a T1 measurement analysis was handling specifically. The present analysis corroborates the homogeneity of the population, as no significant differences were observed between the study groups (Table 1).

Enzymes monitored during the study as was the CK did showed an increase in concentrations at 1-, 24-, 48-, and 72-h post-exercise in all groups ($p < 0.001$). Although, no significant differences were detected between the study groups at the pre-exercise ($p = 0.972$), 1-hout post-exercise, 24 h post-exercise ($p = 0.103$), 48-h post exercise ($p = 0.105$), and 72-h post-exercise ($p = 0.616$). Similar tendance was noted for the blood lactate levels express with a significant increase at 1-h post exercise comparing to the base line time ($p < 0.001$). Following the analysis, no significant differences were detected between groups at pre-exercise ($p = 0.560$), 1-h post-exercise ($p = 0.782$), 24-h post-exercise ($p = 0.687$), 48-h post-exercise ($p = 0.389$), and post 72-h post-exercise ($p = 0.170$) (Table 1).

Outcome measure

A first perspective, after caring out an analysis using ANOVA statistically significant differences was observed among the study groups at 72 h post-DOMS (T5), those results are shown in Table 2. The insights bring by the results show significant differences between the four groups for LF, HF and Power ($p < 0.05$), but no for the SDNN parameter.

The clinical outcome analysis reveals significant differences within the groups for two study time, as shown in Table 3. Statistically significant differences in mean values of all outcome variables measures were found whitin a group comparing the baseline (T1) and at 24 h post-DOMS (T3) as a mid-term treatment analysis and, comparing the baseline (T1) and at 72 h post-DOMS (T5) as a long-term analysis, in all groups ($p < 0.05$).

Afterwards, a post-hoc analysis for both T3 (24 h post-DOMS) and T5 (72 h post-DOMS) was applied with the Comb group as the reference respectful the three other study groups, to find out where the differences between groups took place as giving perspective for mid-term and long-term analysis. Statistically significant differences at the T3 (24 h post-DOMS) express as improvement changes in the outcome measures were found between the Comb group and the Cont group ($p < 0.05$), except for

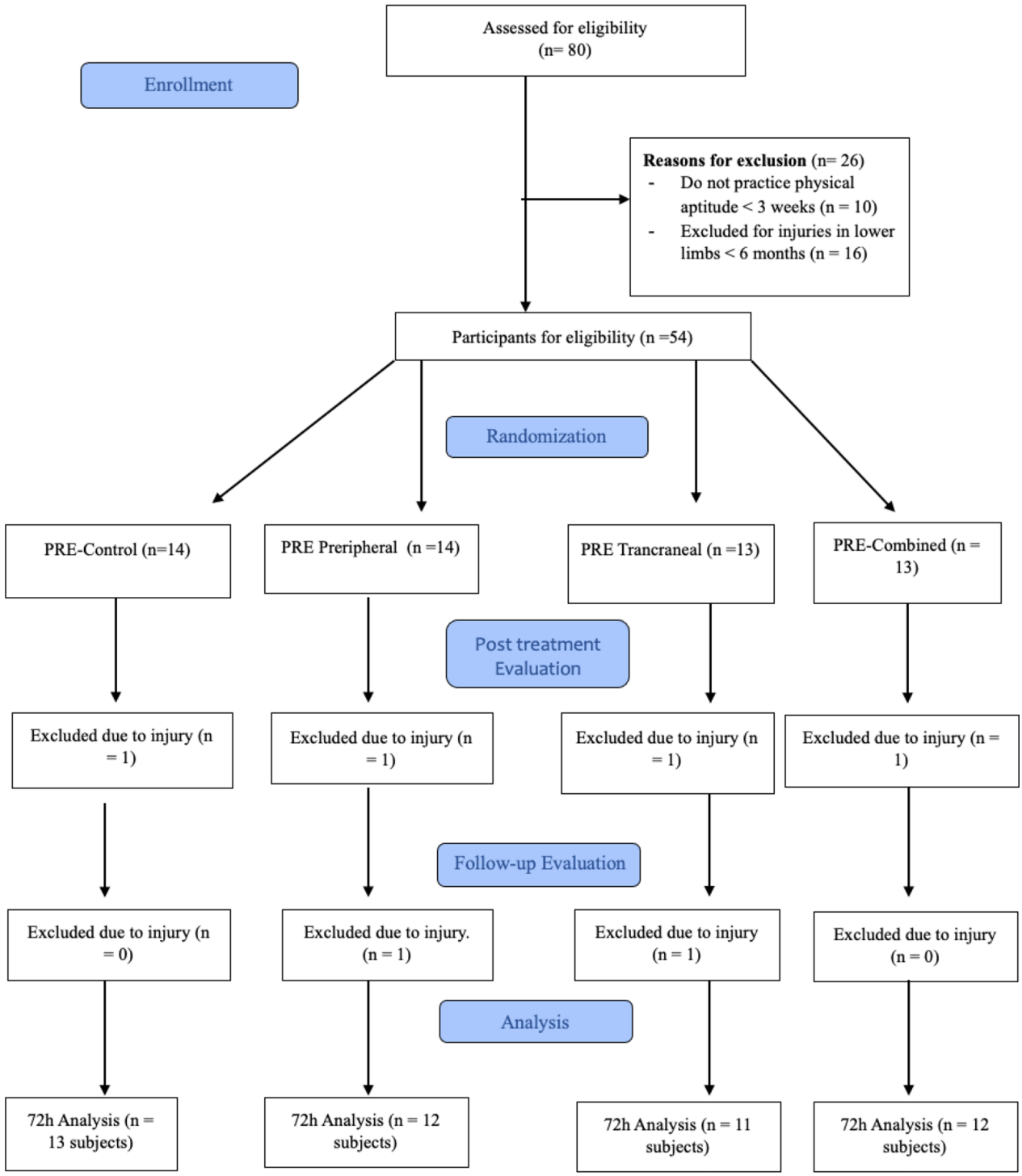

Fig. 5 Flowchart of the study following the CONSORT regulations

the SDNN. No other significant differences were found between the Comb group and both P group and T group, for the T3 study time analysis, as shown in Table 4.

Finally, the same post-hoc analysis showed statistically significant differences at the T5 study time (72 h post-DOMS) respect the outcome measures between the Comb group and the Cont group for every outcome ($p < 0.05$), except for the SDNN. Similar findings at the same time were shown between the Comb group and the P group ($p < 0.05$), except for the SDNN parameter.

Table 1 Analysis of the general measures in the pre-exercise (T1)

Variable	Cont (n = 12)	P (n = 13)	T (n = 11)	Comb (n = 12)	P-value
Lactate (mmol/L)	2.34 ± 3.04	1.38 ± 0.17	2.43 ± 3.50	1.52 ± 0.24	0.560
Creatin Kinase (mmol/L)	66.58 ± 6.88	65.61 ± 6.22	67 ± 7.91	66.25 ± 8.41	0.972
SDNN (ms)	135.53 ± 2.88	135.66 ± 2.77	134.91 ± 3.01	135.93 ± 2.88	0.996
LF (Hz)	67.13 ± 1.8	62.67 ± 1.73	67.73 ± 1.88	65.1 ± 1.8	0.192
HF (Hz)	32.12 ± 2.03	37.24 ± 1.95	32.19 ± 2.12	36.43 ± 2.03	0.161
Power (n.u)	2.15 ± 0.18	1.8 ± 0.17	2.19 ± 0.19	1.95 ± 0.18	0.419

P, super inductive group; Cont, control group; T, transcranial group; Comb, combined group; SDNN, RR-interval; LF, Low Frequency; HF, High Frequency; Power, LF/HF

Table 2 Differences between the study groups for the dependent variables

	SDNN (ms)							
		F	p value	η^2p				
Cont (n = 12)	135.53 ± 2.88	110 ± 1.64	122.55 ± 1.32	121.99 ± 1.34	126.76 ± 1.09	0.957	0.42	0.01
P (n = 13)	135.66 ± 2.77	110.4 ± 1.57	122.47 ± 1.27	122.41 ± 1.28	124.43 ± 1.04			
T (n = 11)	134.91 ± 3.01	110.88 ± 1.71	122.68 ± 1.38	122.97 ± 1.4	125.46 ± 1.13			
Comb (n = 12)	135.93 ± 2.88	109.64 ± 1.64	123.01 ± 1.32	124.18 ± 1.34	126.4 ± 1.09			
	LF (Hz)							
Cont (n = 12)	67.13 ± 1.8	76.34 ± 1.95	70.57 ± 2.13[a,c]	68.96 ± 1.9[a,c]	69.55 ± 1.73[a,c]	66.876	< 0.001	0.82
P (n = 13)	62.67 ± 1.73	71.09 ± 1.87	64.86 ± 2.05	65.13 ± 1.83[a,c]	65.03 ± 1.66[a,c]			
T (n = 11)	67.73 ± 1.88	74.51 ± 2.03	62 ± 2.23	56.11 ± 1.99	48.79 ± 1.81[a]			
Comb (n = 12)	65.1 ± 1.8	73.71 ± 1.95	58.76 ± 2.13	49.24 ± 1.9	39.09 ± 1.73			
	HF (Hz)							
Cont (n = 12)	32.12 ± 2.03	24.18 ± 2.13	29.48 ± 2.15[a,c]	31.04 ± 2.12[a,c]	32.25 ± 1.96[a,c]	48.224	< 0.001	0.767
P (n = 13)	37.24 ± 1.95	29.17 ± 2.04	35.57 ± 2.07	35.65 ± 2.03[a]	34.87 ± 1.89[a,c]			
T (n = 11)	32.19 ± 2.12	25.53 ± 2.22	38.17 ± 2.25	43.95 ± 2.21	51.14 ± 2.05[a]			
Comb (n = 12)	36.43 ± 2.03	27.06 ± 2.13	41.5 ± 2.15	49.33 ± 2.12	60.9 ± 1.96			
	Power (n.u)							
Cont (n = 12)	2.15 ± 0.18	3.37 ± 0.36	2.61 ± 0.18[a,c]	2.41 ± 0.15[a,c]	2.34 ± 0.14[a,c]	31.082	< 0.001	0.679
P (n = 13)	1.8 ± 0.17	2.62 ± 0.35	1.92 ± 0.17	1.9 ± 0.14[a]	1.92 ± 0.13[a,c]			
T (n = 11)	2.19 ± 0.19	3.1 ± 0.38	1.72 ± 0.19	1.31 ± 0.16	0.98 ± 0.14			
Comb (n = 12)	1.95 ± 0.18	3.29 ± 0.36	1.48 ± 0.18	1.04 ± 0.15	0.65 ± 0.14			

P, super inductive group; Cont, control group; T, transcranial group; Comb, combined group; SDNN, RR-interval; LF, Low Frequency; HF, High Frequency; Power, LF/HF; η^2p, partial eta squared

[a] interaction with the Comb group ($p < 0.001$)

[b] interaction with the P group ($p < 0.001$)

[c] interaction with the T group ($p < 0.001$)

The last comparison between the Comb group and the T group showed also significant differences for the LF and HF parameter ($p < 0.05$), but no differences were found for the SDNN and Power outcome, as shown in Table 5.

Discussion

In our study, we observed discernible differences among the intervention groups, reflecting diverse effects on autonomic nervous system regulation. Notably, the Super Inductive Group (P) and the Transcranial Group (T) demonstrated distinct changes in Heart Rate Variability (HRV) metrics over time, which suggested differential modulation of sympathetic and parasympathetic nervous system activities. A reduction in low-frequency (LF) components across these groups may indicate a decrease in sympathetic nervous system dominance, typically associated with stress and arousal states. Conversely, an increase in high-frequency (HF) components, especially observed in the Combined Group (Comb), highlighted a shift toward parasympathetic dominance, emphasizing enhanced vagal tone and potential improvements in recovery and stress resilience [8]. Such a shift is crucial for athletes and individuals experiencing stress, as higher vagal tone is linked to better stress management,

Table 3 Analysis of clinical outcome measures among the group for T3 and T5 study time

Variables	SDNN (ms) Mean ± SD	LF (Hz) Mean ± SD	HF (Hz) Mean ± SD	Power Mean ± SD
T3–T1 analysis				
Cont group				
T1	135.53 ± 2.89	67.13 ± 1.82	32.12 ± 2.05	2.15 ± 0.18
T3	122.55 ± 1.32	70.57 ± 2.15	29.48 ± 2.17	2.61 ± 0.18
95% Confidence interval	− 9.57	5.12	− 8.21	21.39
p-values	0.003*	0.328	1.000	0.084
P group				
T1	136.24 ± 2.89	62.88 ± 1.82	37.02 ± 2.05	1.82 ± 0.18
T3	122.83 ± 1.32	64.53 ± 2.15	35.94 ± 2.17	1.89 ± 0.18
95% Confidence interval	− 9.84	2.62	− 2.91	3.84
p-values	0.002*	1.000	1.000	1.000
T group				
T1	134.91 ± 3.02	67.73 ± 1.9	32.19 ± 2.14	2.19 ± 0.19
T3	122.68 ± 1.38	62 ± 2.25	38.17 ± 2.26	1.72 ± 0.19
95% Confidence interval	− 9.06	− 8.46	18.57	− 21.46
p-values	0.009*	0.010*	0.025*	0.098
Comb group				
T1	135.93 ± 2.89	65.1 ± 1.82	36.43 ± 2.05	1.95 ± 0.18
T3	123.01 ± 1.32	58.76 ± 2.15	41.5 ± 2.17	1.48 ± 0.18
95% Confidence interval	− 9.5	− 9.73	13.91	− 24.1
p-values	0.003*	0.002*	0.069	0.075
T5-T1 analysis				
Cont group				
T1	135.53 ± 2.89	67.13 ± 1.82	32.12 ± 2.05	2.15 ± 0.18
T5	126.76 ± 1.1	69.55 ± 1.74	32.25 ± 1.97	2.34 ± 0.14
95% Confidence interval	− 6.47	3.6	0.4	8.83
p-values	0.154	1.000	1.000	1.000
P group				
T1	136.24 ± 2.89	62.88 ± 1.82	37.02 ± 2.05	1.82 ± 0.18
T5	124.36 ± 1.1	64.63 ± 1.74	35.26 ± 1.97	1.89 ± 0.14
95% Confidence interval	− 8.71	2.78	− 4.75	3.84
p-values	0.014*	1.000	1.000	1.000
T group				
T1	134.91 ± 3.02	67.73 ± 1.9	32.19 ± 2.14	2.19 ± 0.19
T5	125.46 ± 1.15	48.79 ± 1.82	51.14 ± 2.06	0.98 ± 0.14
95% Confidence interval	− 7	− 27.96	58.86	− 55.25
p-values	0.126	< 0.001**	< 0.001**	< 0.001**
Comb group				
T1	135.93 ± 2.89	65.1 ± 1.82	36.43 ± 2.05	1.95 ± 0.18
T5	126.4 ± 1.1	39.09 ± 1.74	60.9 ± 1.97	0.65 ± 0.14
95% Confidence interval	− 7.01	− 39.95	67.16	− 66.67
p-values	0.188	< 0.001**	< 0.001**	< 0.001**

P, super inductive group; Cont, control group; T, transcranial group; Comb, combined group; SDNN, RR-interval; LF, Low Frequency; HF, High Frequency; Power, LF/HF
∗significant differences with $p < 0.05$; **Significant differences with $p < 0.001$

recovery, and overall cardiovascular health [3]. These findings imply that specific interventions, either alone or in combination, can significantly influence the balance of the autonomic nervous system, with potential implications for enhancing human performance and well-being.

The P group likely experienced changes due to the direct impact of physical stimuli on muscle and neural

Table 4 Post-hoc analysis of changes in clinical outcome measures between Comb and Cont, Comb and P and Comb and T for the T3 study time

	Post-hoc analysis between Comb and Cont groups at 24 h (T3 vs T1 across groups)		
	Comb group Mean ± SD	**Cont group Mean ± SD**	***p***
Outcome measures			
SDNN	123.01 ± 1.32	122.55 ± 1.32	1.000
LF	58.76 ± 2.15	70.57 ± 2.15	0.002*
HF	41.5 ± 2.17	29.48 ± 2.17	0.002*
Power	1.48 ± 0.18	2.61 ± 0.18	< 0.001**
Outcome measures	**Post-hoc analysis Between Comb and P groups at 24 h (T3)**		
	Comb group Mean ± SD	**P Group** Mean ± SD	*P*
SDNN	123.01 ± 1.32	122.83 ± 1.32	1.000
LF	58.76 ± 2.15	64.53 ± 2.15	0.393
HF	41.5 ± 2.17	35.94 ± 2.17	0.462
Power	1.48 ± 0.18	1.89 ± 0.18	0.779
Outcome measures	**Post-hoc analysis Between Comb and T groups at 24 h (T3)**		
	Comb group Mean ± SD	**T Group** Mean ± SD	*P*
SDNN	123.01 ± 1.32	122.68 ± 1.38	1.000
LF	58.76 ± 2.15	62 ± 2.25	1.000
HF	41.5 ± 2.17	38.17 ± 2.26	1.000
Power	1.48 ± 0.18	1.72 ± 0.19	1.000

P, super inductive group; Cont, control group; T, transcranial group; Comb, combined group; SDNN, RR-interval; LF, Low Frequency; HF, High Frequency; Power, LF/HF

∗significant differences with $p < 0.05$

**significant differences with $p < 0.001$

Table 5 Post-hoc analysis of changes in clinical outcome measures between Comb and Cont, Comb and P and Comb and T for the T5 study time

	Post-hoc analysis between Comb and Cont groups at 72 h (T5 vs T1 across groups)		
	Comb group Mean ± SD	**Cont group Mean ± SD**	***P***
Outcome measures			
SDNN	126.4 ± 1.1	126.76 ± 1.1	1.000
LF	39.09 ± 1.74	69.55 ± 1.74	< 0.001**
HF	60.9 ± 1.97	32.25 ± 1.97	< 0.001**
Power	0.65 ± 0.14	2.34 ± 0.14	< 0.001**
Outcome measures	**Post-hoc analysis Between Comb and P groups at 72 h (T5)**		
	Comb group Mean ± SD	P Mean ± SD	*P*
SDNN	126.4 ± 1.1	124.36 ± 1.1	1.000
LF	39.09 ± 1.74	64.63 ± 1.74	< 0.001**
HF	60.9 ± 1.97	35.26 ± 1.97	< 0.001**
Power	0.65 ± 0.14	1.89 ± 0.14	< 0.001**
Outcome measures	**Post-hoc analysis Between Comb and T groups at 72 h (T5)**		
	Comb group Mean ± SD	T Mean ± SD	*P*
SDNN	126.4 ± 1.1	125.46 ± 1.15	1.000
LF	39.09 ± 1.74	48.79 ± 1.82	0.002*
HF	60.9 ± 1.97	51.14 ± 2.06	0.009*
Power	0.65 ± 0.14	0.98 ± 0.14	0.694

P, super inductive group; Cont, control group; T, transcranial group; Comb, combined group; SDNN, RR-interval; LF, Low Frequency; HF, High Frequency; Power, LF/HF

∗significant differences with $p < 0.05$

**significant differences with $p < 0.001$

pathways, influencing sympathetic nervous system activity. The Super Inductive System employs high-intensity electromagnetic fields to treat conditions of the neuromusculoskeletal system, potentially affecting muscle and neural pathways [35]. In contrast, the T group, through non-invasive brain stimulation, might have affected the central nervous system's regulation of autonomic functions, altering the balance towards either increased sympathetic or parasympathetic activity, depending on the stimulation parameters [45]. The Comb group experienced the synergistic effects of both physical and neural interventions, leading to a more pronounced shift towards parasympathetic dominance. This comprehensive approach potentially maximizes benefits by targeting multiple pathways for autonomic regulation, illustrating the intricate interplay between different types of interventions and the autonomic nervous system's adaptability [10].

The variations in HRV responses observed in our study, as compared to prior research, underscore the complex interplay between intervention specifics and individual differences. Foundational insights provided by Thayer et al. [44] and Laborde et al. [25] on how lifestyle modifications can modulate autonomic functions emphasize HRV's role as a biomarker for stress and recovery [25, 44]. Our results extend this narrative, illustrating that interventions do not exert uniform effects on HRV, likely due to variances in methodological approaches, including the intensity, duration, and nature of the interventions. Additionally, the distinct physiological and psychological backgrounds of participants introduce another layer of complexity, as evidenced by Kiviniemi et al. [23], where the impact of aerobic training on HRV varied with the fitness level of the individuals [23]. These discrepancies highlight the need for personalized approaches in designing interventions aimed at optimizing autonomic balance

and underscore the necessity for further research to unravel the mechanisms underlying these effects.

Delving deeper into the influence of electromagnetic stimulation on the autonomic nervous system, it is imperative to highlight the significant parasympathetic activation observed in our results, particularly concerning the HRV parameters across different groups. The use of both Transcranial Magnetic Stimulation (TMS) and Peripheral Electromagnetic Stimulation (PES) in our Comb group not only enhanced parasympathetic activity but also suggests an optimization of recovery processes in athletes. This contrasts with studies focusing solely on TMS, where results often show increased sympathetic activity, particularly in clinical settings involving patients with depression. The parasympathetic influence, critical for recovery and stress resilience, is supported by our findings showing significant differences in HRV measures among the groups, with a notable increase in HF components [6]. Such observations are crucial, as they indicate a shift towards parasympathetic dominance. This shift, associated with improved vagal tone, underscores the compounded benefits of combining TMS with PES.

Moreover, the absence of negative effects on the autonomic nervous system underscores the safety and suitability of these treatments. Our treatments did not disrupt the normal physiological recovery processes associated DOMS. Furthermore, the data provided in Table 1 further substantiates these points. While the creatine kinase and lactate levels indicated increases post-exercise—a typical response indicating muscle stress and recovery—there were no significant differences between the groups at any measured time point [5]. This uniformity suggests that while the exercise protocol effectively induced muscle stress, the electromagnetic treatments managed to modulate recovery without exacerbating muscle damage or stress response, as evidenced by stable enzyme levels across all groups. In contrast to other studies, such as those analyzing the effects of nutritional interventions on HRV (e.g., energy drinks leading to changes primarily in high-frequency indices), our approach using TMS combined with PES showcases a broader regulatory impact on both high and low-frequency components of HRV. This suggests a more comprehensive modulation of the autonomic nervous system, potentially offering a more effective means of enhancing athletic recovery and performance.

In contrast to other studies, such as those analyzing the effects of nutritional interventions on HRV, our approach using TMS combined with PES showcases a broader regulatory impact on both high and low-frequency components of HRV [28],"Nutrition and Athletic Performance," 2016; [50]. This suggests a more comprehensive modulation of the autonomic nervous system, potentially offering a more effective means of enhancing athletic recovery and performance.

Furthermore, our study's group-by-time interactions, as detailed in the subsequent analysis, reveal significant differences in HRV parameters such as LF and HF, not just at a single post-exercise point but across multiple recovery phases. This progressive monitoring highlights the dynamic changes in autonomic nervous system activity and provides a more detailed understanding of how these interventions influence recovery over time.

In conclusion, our research highlights the significant potential of combined electromagnetic stimulation therapies, specifically the synergistic effects of transcranial and peripheral electromagnetic stimulation, in enhancing recovery from Delayed Onset Muscle Soreness (DOMS). The findings demonstrate substantial improvements in autonomic regulation, particularly through increased parasympathetic activity and vagal tone, as evidenced by changes in HRV parameters such as HF and LF components. These results underscore the efficacy of these interventions in promoting physiological recovery and stress resilience, key factors for optimizing athletic performance. Importantly, the study confirms the safety of these therapies, as no adverse effects were observed on muscle damage markers such as creatine kinase and lactate levels.

While the study provides robust evidence for the benefits of electromagnetic stimulation in young male athletes, it also emphasizes the need for future research to expand on these findings. Future studies should explore long-term adaptations, investigate responses across a broader demographic, and assess the applicability of these therapies in varied athletic disciplines. By addressing these areas, future research could further validate and refine the use of electromagnetic stimulation as an innovative and effective tool in sports medicine and rehabilitation.

Study limitations and future research lines

While our findings provide valuable insights into the effects of combined electromagnetic stimulation on autonomic nervous system regulation and recovery processes, certain limitations must be acknowledged. First, the study's focus on active, young male athletes limits the generalizability of the results to other populations, such as women, older adults, or less active individuals. Future research should aim to include more diverse demographic groups to evaluate the broader applicability of these interventions in varied populations and athletic disciplines.

Additionally, while creatine kinase and lactate levels were utilized as biomarkers of muscle stress and recovery, these measures, though relevant, offer a

limited perspective on the complex physiological changes induced by electromagnetic stimulation. Expanding future studies to include a more comprehensive panel of biomarkers, such as inflammatory markers (e.g., IL-6, CRP), oxidative stress indicators, and additional metabolic enzymes, could provide deeper insights into the underlying mechanisms of recovery and the broader effects of these treatments on the human body.

The potential for combined electromagnetic stimulation to interact with long-term medication use or chronic conditions also represents an important avenue for exploration. For instance, examining its effects in populations with conditions such as cancer or autoimmune disorders could reveal therapeutic potential beyond athletic recovery. Understanding how these interventions influence systemic inflammation, immune function, and other chronic physiological challenges could significantly expand their clinical relevance.

From a practical standpoint, this study underscores the potential for translating combined electromagnetic stimulation into sports medicine and daily recovery strategies. The significant improvements observed in parasympathetic activity, vagal tone, and HRV parameters suggest that these therapies can be integrated into training and rehabilitation protocols to enhance recovery and stress resilience. For athletes, the convenience and non-invasive nature of these interventions make them suitable for frequent use alongside traditional methods such as active recovery, physiotherapy, and nutritional support.

Lastly, future research should consider integrating psychological assessments to complement the physiological data collected. Recovery involves not only physical restoration but also mental and emotional well-being. Including measures of perceived fatigue, recovery sensation, and psychological resilience through validated questionnaires would provide a more holistic view of recovery processes. By addressing central fatigue and subjective well-being, future studies could offer a more complete understanding of how these interventions contribute to overall health and performance.

In conclusion, while our study highlights the efficacy and safety of combined electromagnetic stimulation, addressing these limitations and exploring the outlined future directions will help refine and broaden the applicability of these therapies. These advancements could ultimately make electromagnetic stimulation an integral component of sports medicine, rehabilitation, and even clinical treatment frameworks.

Practical applications and keypoints

Enhanced Recovery Protocols: The study demonstrates the potential of combined transcranial and peripheral electromagnetic stimulation to facilitate recovery in athletes. This can be incorporated into sports medicine practices to reduce downtime and improve recovery rates after intense physical activities.

Non-Invasive Treatment Options: The safety and efficacy of the non-invasive treatment modalities presented in the study suggest that they can be used as alternatives to more invasive recovery methods. This is particularly relevant for athletes who are sensitive to traditional medical treatments or who prefer less invasive recovery techniques.

Autonomic Nervous System Regulation: The findings emphasize the role of autonomic nervous system regulation in athletic performance and recovery. Training programs and rehabilitation protocols can be designed to target this system, potentially enhancing overall athletic performance and well-being.

Holistic Approach to Athlete Health: The study supports a holistic approach to athlete health, where both physical and neurological aspects are considered. This could lead to more comprehensive health management strategies in sports organizations and teams.

Tailored Therapeutic Strategies: Given the differential effects observed across various groups in the study, sports medicine professionals can tailor electromagnetic stimulation protocols based on individual athlete needs and responses, optimizing performance outcomes.

Research and Development: The findings encourage further research and development in electromagnetic stimulation technologies. This could lead to more refined devices and treatment protocols specifically optimized for different sports and activities.

Contribution to the field

This work represents an advance in finding the appropriate therapeutic strategies to improve the symptoms of DOMS and thus be able to anticipate athletes to their training without risk of injury, and with the certainty of adding stimuli to the muscles to be able to provoke physiological adaptations derived from eccentric exercise. Therefore, based on the new theory of DOMS caused by axonopathy, paired-associative electromagnetic stimulation peripheral and transcranial treatment could improve muscle pain and sports performance in athletes.

Conclusion

This clinical trial underscores the significant potential and safety of combined transcranial and peripheral electromagnetic stimulation as a therapeutic modality in sports medicine and rehabilitation. By focusing on the recovery processes within the autonomic nervous system, this study provides valuable insights into the mechanisms underlying Delayed Onset Muscle Soreness (DOMS) recovery. The findings demonstrate that these

treatments effectively enhance autonomic regulation, particularly through increased parasympathetic activity, without disrupting the body's natural physiological recovery processes. This highlights the compatibility of electromagnetic stimulation with the inherent recovery dynamics of the human body.

The non-invasive nature of this approach, coupled with its demonstrated efficacy in promoting recovery and stress resilience, positions combined electromagnetic stimulation as a promising tool for optimizing athletic performance and rehabilitation. Its ability to enhance recovery while maintaining the body's natural balance offers a novel and potentially transformative strategy for athlete care.

Future research should build on these findings by exploring the long-term effects of these interventions, expanding the demographic scope to include diverse populations, and investigating their application across varied athletic disciplines and clinical contexts. By addressing these areas, combined electromagnetic stimulation could become an integral component of modern sports medicine, setting a new standard for recovery and performance enhancement.

Acknowledgements
We would like to thank to the students at the European University of Madrid for participating in the study and to the University itself. And MR Inc. (Republic of Korea) for provide us the devices MagRex magnetic stimulator.

Author contributions
ASS and HK carried out the design and idea of the project, HK, JFTA and DDB wrote the introduction to the manuscript, AGF, MGA and MBA wrote the methodology and statistics part, DDB, MPSF and HK wrote the Discussion and conclusions part, GGPS, VJCS and AGF prepared Figs. 1 and 2. All authors reviewed the manuscript.

Funding
The authors received no financial support for the research, authorship, and/or publication of this article.

Availability of data and materials
We have the availability of the data, and the materials are available at the request of the publisher.

Declarations

Ethics approval and consent to participate
The study was approved by the Research Ethics Committee of the Clinical Hospital San Carlos (reference number: C.I. 23/048-E).

Consent for publication
We have the consent for publication. We register our study in the Australian New Zealand Clinical Trials Registry (reference number: ACTRN12623000677606).

Competing interests
The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Received: 8 October 2024 Accepted: 11 February 2025
Published online: 10 March 2025

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