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The Effects of High-Intensity Interval Training Cooperated with Repetitive Peripheral Magnetic Stimulation (rPMS) on Sport Physical Performance and Blood Chemistry Level in Male Team Sport Athletes: A Randomized Controlled Trial

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Highlights

Public health relevance—How does this work relate to a public health issue?

- Maintaining adequate muscular strength, muscular endurance, and cardiorespiratory fitness during the transition from late adolescence to young adulthood is relevant to public health because these attributes are key components of health-related physical fitness and support continued engagement in physically active lifestyles.
- This study examines whether a non-invasive neuromuscular intervention, repetitive peripheral magnetic stimulation (rPMS), can provide additional benefits when integrated with structured high-intensity interval training in trained male collegiate team-sport athletes.

Public health significance—Why is this work of significance to public health?

- Adding active rPMS to HIIT was associated with greater quadriceps strength and fixed-load knee-extension repetitions-to-failure improvements than HIIT alone.

Public health implications—What are the key implications or messages for practitioners, policy makers and/or researchers in public health?

- The findings support further sham-controlled investigation in comparable athletic populations; broader effectiveness, feasibility, accessibility, and cost-effectiveness in general young-adult health-promotion settings remain unestablished.

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Abstract

Health-related physical fitness is relevant to health promotion, but adjunctive technologies should be evaluated within the populations studied. This randomized controlled trial examined whether repetitive peripheral magnetic stimulation (rPMS) after repeated sprint high intensity interval training (HIIT) provided additional benefits in 52 healthy male collegiate football and futsal athletes aged 18–24 years. Participants were randomized 1:1 to HIIT + rPMS or HIIT alone for six weeks. Relative quadriceps strength was the prespecified primary outcome. HIIT + rPMS produced a greater improvement in relative quadriceps strength (mean difference in change, 0.16 kg·kg^{-1}; 95% CI, 0.09–0.22; $p < 0.001$; Hedges' g = 1.35), which remained robust in baseline-adjusted sensitivity analysis.

Fixed-load knee-extension repetitions-to-failure performance also improved more (2.12 repetitions; 95% CI, 1.17–3.06; $p < 0.001$), although this may partly reflect the greater strength gain because the same absolute load was retained at week 6. No between-group difference was supported for hamstring strength or serum IGF-1. The nominal estimated VO_2max difference ($p = 0.0498$) was not robust to sensitivity analyses and was considered inconclusive. Because no sham-rPMS condition was used, the observed differences cannot be attributed exclusively to magnetic stimulation. Further sham-controlled studies are required before broader health promotion or public health application.

Keywords: HIIT; repetitive peripheral magnetic stimulation; collegiate athletes; quadriceps strength; fixed-load repetitions-to-failure; estimated maximal oxygen uptake; IGF-1

1. Introduction

Regular physical activity and adequate physical fitness are fundamental to health promotion and the prevention of lifestyle-related health risks across the life course [1,2]. Of particular public health importance is the transition from late adolescence to young adulthood, a period during which physical activity patterns may change substantially and may influence later participation in active lifestyles [3,4]. These observations provide general public-health context for promoting physical fitness in young people; however, they do not imply that findings obtained in trained athletes can be generalized to the broader young-adult population.

Health-related physical fitness is multidimensional and includes cardiorespiratory fitness, muscular strength, and muscular endurance. These attributes are relevant to sport participation, physical functioning, and the capacity to remain physically active [5,6]. University settings may provide opportunities for structured physical-activity promotion, although barriers to regular exercise are also common [7,8]. In the present study, these concepts are used to frame the potential relevance of the measured fitness attributes; the direct applicability of the trial remains limited to trained male collegiate team-sport athletes.

High-intensity interval training (HIIT) is a structured exercise strategy capable of producing substantial cardiorespiratory and metabolic adaptations within a relatively time efficient format [9]. Systematic reviews and meta-analyses have demonstrated improvements in aerobic fitness and several components of physical performance following HIIT in soccer players and other trained populations [10–13]. Accordingly, HIIT provides an established training stimulus against which the potential add-on effect of another intervention can be evaluated in physically trained young adults.

Repeated high-intensity exercise imposes substantial metabolic and neuromuscular demands, and appropriate recovery is important for subsequent exercise capacity and training adaptation [14]. Simply increasing active exercise volume or intensity may not always be desirable. An adjunctive intervention that provides a neuromuscular stimulus without requiring additional externally performed high-impact running or resistance exercise volume may therefore be of interest in supervised training settings. Importantly, such an adjunct does not represent an absence of training stimulus; rather, it provides a different form of neuromuscular stimulation.

Repetitive peripheral magnetic stimulation (rPMS) is a non-invasive neuromuscular intervention that uses rapidly changing magnetic fields to induce electrical currents in peripheral neural and muscular tissues. Compared with conventional surface electrical stimulation, rPMS does not require direct electrical contact with the skin and can stimulate

peripheral structures with relatively low discomfort [15]. Experimental work has shown effects on sensorimotor function and neuromuscular activation [15,16]. Repeated neuromuscular magnetic stimulation has also been associated with improvements in quadriceps strength in healthy adults [17], while lower-extremity strength effects have been investigated in older rehabilitation populations [18].

Most previous rPMS research has been conducted in rehabilitation, pain management, neurophysiological, or acute recovery contexts [15,18–21]. Acute post-exercise studies in healthy young adults and studies after muscle-damaging exercise provide physiological and recovery related context [19–21], but they do not establish a repeated training effect in already trained athletes. To our knowledge, no previous study had established whether repeated post-exercise rPMS adds to the effects of a structured HIIT program on muscular fitness in healthy trained collegiate athletes. This specific evidence gap provided the rationale for the present trial.

Evaluation of the combined intervention included both functional outcomes and two prespecified circulating markers. Insulin-like growth factor-1 (IGF-1) was selected to provide limited information on an exercise-responsive anabolic/endocrine pathway [22,23], whereas interleukin-6 (IL-6) was selected because of its established exercise responsive myokine and metabolic roles [24]. These biomarkers were intended to complement the functional outcomes rather than constitute a comprehensive biomarker panel, and neither was considered a direct measure of local muscle adaptation, systemic inflammation, disease prevention, or recovery.

The potential broader relevance of combining structured exercise with a non-invasive neuromuscular intervention lies in determining whether such technology can augment selected components of health-related physical fitness within an established exercise program. However, the present study was conducted in trained male collegiate athletes; therefore, any relevance to broader health promotion or young adult populations is indirect and requires separate evaluation. The study does not test population-level preventive-health effectiveness.

The quadriceps, hamstring, and gastrocnemius regions were selected as a combined lower-limb protocol involving muscles that contribute to running and lower-limb force production and control. The protocol was not designed as selective quadriceps stimulation. Prior quadriceps-strength findings [17] supported investigating knee-extension strength but did not establish that stimulating all three regions after HIIT would preferentially enhance quadriceps adaptation. Parameter selection was informed primarily by the manufacturer's operating guidance and participant tolerance, rather than an established optimal dose for trained athletes.

Based on prior evidence that repeated neuromuscular magnetic stimulation can elicit quadriceps contractions and has been associated with improvements in knee extensor strength in healthy adults [17], we hypothesized that adding post-exercise rPMS to repeated sprint HIIT would produce a greater improvement in relative quadriceps strength than HIIT alone. Relative quadriceps strength was prespecified in the ethics-approved protocol as the primary outcome and formed the basis of the a priori sample size calculation. Therefore, the present randomized controlled trial compared six weeks of repeated sprint HIIT followed by active rPMS with the same HIIT program alone in healthy male collegiate football and futsal athletes aged 18–24 years. Secondary outcomes were relative hamstring strength, fixed-load knee extension repetitions to failure performance, estimated maximal oxygen uptake, serum IGF-1, and serum IL-6. The proposed neuromuscular rationale was considered a hypothesis to be tested rather than a mechanism demonstrated by the trial.

2. Materials and Methods

2.1. Participants and Trial Design

This study was a two-arm, parallel group randomized controlled trial designed to determine whether repetitive peripheral magnetic stimulation (rPMS) administered immediately after repeated sprint high-intensity interval training (HIIT) provided additional benefits for lower limb neuromuscular performance, estimated cardiorespiratory fitness, and circulating biochemical responses compared with HIIT alone in male collegiate team sport athletes. Participants were randomly allocated in a 1:1 ratio to either an HIIT plus rPMS group or an HIIT only control group.

The trial is reported in accordance with the CONSORT 2025 Statement and its Explanation and Elaboration guidance [25,26], with additional consideration of recommendations for randomized trials of nonpharmacological interventions [27]. Intervention descriptions were structured with reference to the Template for Intervention Description and Replication (TIDieR) [28] and the Consensus on Exercise Reporting Template (CERT) [29] to enhance transparency and reproducibility. Recruitment publicity took place during January–February 2026. Eligibility screening and baseline data collection took place during February–June 2026. The six-week intervention phase ended in July 2026, and all study data collection closed on 5 August 2026. This closure date does not imply that every participant underwent final assessment on that date.

The study was conducted at the Sports Science Professional Experience Training Center, Uttaradit Rajabhat University, and the Sports Science Laboratory of the Sports Authority of Thailand, Uttaradit Province, Thailand. Training sessions and outcome assessments were performed under standardized laboratory conditions. The source population comprised 86 registered male football and futsal athletes. Following eligibility screening and enrollment, 52 participants were randomized, with 26 allocated to the HIIT plus rPMS group and 26 to the HIIT-only group.

2.2. Ethical Approval and Trial Registration

The study protocol was submitted on 24 October 2025 and approved on 30 December 2025 by the Human Research Ethics Committee of Uttaradit Rajabhat University (URU-REC No. 075/2568; COA No. 0589/2025) and was conducted in accordance with the ethical principles of the Declaration of Helsinki. All participants provided written informed consent before enrollment and before any study specific procedures.

The trial was retrospectively registered with the Thai Clinical Trials Registry (TCTR) on 7 August 2026, after completion of participant recruitment and data collection, under registration number TCTR20260807005. All primary and secondary outcomes and the original statistical analysis plan reported for the trial had been specified in the ethics approved study protocol before participant recruitment and data collection. Relative quadriceps strength was prespecified as the primary outcome and formed the basis of the a priori sample size calculation; relative hamstring strength, fixed-load knee-extension repetitions-to-failure performance, estimated VO_2max, serum IGF-1, and serum IL-6 were prespecified as secondary outcomes. No study outcome was added, removed, substituted, or modified after data collection, and the prespecified primary analysis was not changed after examination of the results. Nevertheless, because public trial registration occurred retrospectively, the registry itself does not provide an independently time stamped prospective record of this prespecification; this remains an important reporting limitation [25,26]. No protocol changes were made after ethics approval. Registration occurred two days after closure of all data collection. The submission and approval dates clarify the reported chronology but do not, by themselves, independently verify the original outcome definitions or analysis plan; retrospective public registration remains a substantial limitation.

2.3. Participants and Eligibility Criteria

Initial recruitment and eligibility screening were performed by personnel from the Sports Authority of Thailand, Uttaradit Province, who were independent of the research team. Participants were eligible if they met all of the following criteria: (1) male football or futsal athletes aged 18–24 years; (2) registered members of a university sports team; (3) previous participation in at least one university-level, regional, national, or international competition; (4) relative back squat strength of at least 1.5 times body mass, assessed using a Smith machine; (5) no severe muscle, tendon, ligament, or bone injury during the preceding three months; (6) no clinically relevant malnutrition identified during screening; (7) no current use of hormones, medications, or nutritional products expected to substantially influence physical growth, muscular adaptation, or the selected biochemical outcomes; and (8) willingness to participate and provision of written informed consent.

Participants were excluded if they had uncontrolled cardiovascular or pulmonary disease, clinically relevant neurological impairment, an acute musculoskeletal injury, a medical condition that precluded participation in high-intensity exercise, or a contraindication to peripheral magnetic stimulation.

Participants were discontinued from the intervention if they developed a serious illness or injury, experienced an adverse event that precluded further participation, voluntarily withdrew consent, or attended fewer than 80% of the prescribed intervention sessions. Randomized participants were retained in their originally assigned groups for intention to treat analysis whenever outcome data were available, consistent with contemporary randomized trial reporting principles [25–27].

Before enrollment, all participants received verbal and written explanations regarding the study objectives, procedures, anticipated benefits, possible risks, confidentiality, and their right to withdraw without penalty. Written informed consent was obtained before any study-specific assessment.

2.4. Sample Size Calculation

The sample size was calculated a priori using G*Power version 3.1.9.7 [30]. Relative quadriceps strength was prespecified as the primary outcome in the ethics approved protocol and formed the basis of the sample size calculation. The calculation assumed a two-sided independent samples *t*-test comparing two parallel groups.

An anticipated standardized effect size of Cohen's d = 0.85 was derived from an unpublished investigator-led preliminary study involving seven collegiate athletes from a nearby institution. The preliminary study used a fixed within subject sequence: six weeks of the same HIIT protocol, a four-week washout period, and six weeks of the same HIIT + rPMS protocol. Relative quadriceps strength was the outcome used to derive the planning effect size; other lower limb strength measures were exploratory. Because estimates from very small preliminary samples are imprecise, the assumed effect should be considered uncertain. With $\alpha = 0.05$, 80% power, and equal allocation, the minimum required sample was 46 participants (23 per group), and the recruitment target was increased to 52 to allow for approximately 10% attrition. For context, under the same assumptions, effects of d = 0.70, 0.60, and 0.50 would require approximately 34, 45, and 64 participants per group, respectively. The trial was therefore powered for the large prespecified primary outcome effect assumed a priori, not separately for smaller effects or each secondary outcome.

2.5. Randomization, Allocation Concealment, and Blinding

After eligibility had been confirmed and baseline assessment completed, participants were randomly assigned in a 1:1 ratio to the HIIT + rPMS group or HIIT only group. The

random allocation sequence was generated using Microsoft Excel by an independent statistician who was not involved in recruitment, outcome assessment, or intervention delivery. Simple randomization without blocking or stratification was used. The sequence generation, concealment, and masking procedures were reported in accordance with CONSORT recommendations [25–27].

Allocation concealment was maintained by having the complete allocation list retained by an independent third party who was not involved in recruitment or outcome assessment. The intervention coordinator received the group assignment only after the participant had completed eligibility screening and baseline assessment. The coordinator subsequently informed participants of their assigned intervention and coordinated intervention delivery.

The trial was designed to evaluate the added effect of active rPMS when incorporated into a standardized HIIT program, with the HIIT-only group receiving the identical exercise intervention. Because no sham-rPMS condition was included, participants and the treating physical therapist were aware of group allocation, and the experimental group received approximately 30 min of additional therapist administered intervention after HIIT. Accordingly, expectancy, contextual influences, additional therapist contact, and participant-related performance effects cannot be completely separated from the observed between group differences. This consideration is particularly relevant for effort dependent outcomes such as strength and repetitions to failure performance. To reduce potential assessment and analysis bias, outcome measurements were performed by trained assessors blinded to treatment allocation, and statistical analyses were conducted with group coding masked until completion of the principal analyses. The findings should therefore be interpreted as the effect of adding active rPMS to HIIT under the present study conditions rather than as an isolated, mechanism specific effect of magnetic stimulation.

Outcome measurements were performed by trained assessors blinded to treatment allocation, and statistical analyses were conducted with group coding masked until completion of the principal analyses. Trained research assistants provided standardized verbal encouragement in both groups using the same wording and tone. These procedures reduced procedural differences but could not eliminate expectancy or participant-performance bias, and the comparison cannot isolate the physiological effect.

2.6. Intervention Protocol

2.6.1. Repeated Sprint HIIT Protocol

Participants in both groups completed an identical six-week repeated sprint HIIT program using an h/p/cosmos pulsar 3p motorized treadmill (h/p/cosmos sports and medical GmbH, Nussdorf-Traunstein, Germany). The treadmill had a running surface of 190 × 65 cm, a maximum speed of 40 km·h−1, and an inclination range from −25% to +25%.

Repeated sprint running was selected because intermittent high intensity running is a major physiological demand in football and futsal. Systematic review evidence supports HIIT as an effective strategy for improving aerobic and physical fitness in male soccer and trained team sport athletes [10], while established HIIT programming principles emphasize the combined influence of exercise intensity, interval duration, recovery duration, and accumulated high intensity work [14]. Reporting of the exercise intervention was additionally structured with reference to CERT [29].

The intervention comprised 15 supervised training sessions over six consecutive weeks. Participants completed two sessions during weeks 1, 3, and 5 and three sessions during weeks 2, 4, and 6. Before each session, participants underwent a brief health status assessment, including resting heart rate and blood pressure, followed by a standardized

15 min warm-up consisting of low-intensity treadmill running, dynamic mobility exercises, and muscle-specific preparation.

Training intensity was individualized to approximately 85–95% of age-predicted maximal heart rate (HRmax). HRmax was calculated using HRmax = 208 − (0.7 × age), as described by Tanaka et al. [31]. Heart rate was continuously monitored using a Polar H10 chest-strap sensor (Polar Electro Oy, Kempele, Finland), which has demonstrated high validity for heart rate measurement during resting and incremental exercise conditions [32]. Running speed was individually adjusted rather than prescribed as a fixed absolute velocity because the external speed required to maintain the target relative cardiovascular intensity differed among participants. The same individualized adjustment procedure was applied to both groups. All treadmill intervals were performed at 0% incline.

The repeated sprint protocol progressed through three levels; Level 1 consisted of six 20 s high-intensity intervals separated by 10 s of active recovery; Level 2 consisted of four 30 s intervals separated by 15 s of active recovery; and Level 3 consisted of three 40 s intervals separated by 20 s of active recovery. Five sets were completed per session, with 3 min of recovery between sets. The work-to-recovery ratio within each set was maintained at 2:1, and each set contained approximately 120 s of high intensity work (Level 1: 6 × 20 s; Level 2: 4 × 30 s; Level 3: 3 × 40 s). Across five sets, each session therefore included approximately 10 min of accumulated high-intensity running, excluding recovery periods, warm up, and cool down.

Ratings of perceived exertion were monitored throughout training using the Borg 6–20 scale [33], together with symptoms of exercise intolerance. Running speed, heart rate, perceived exertion, and progression were recorded during training to support intervention fidelity monitoring. After the five sets, participants completed a standardized 5–10 min cool down consisting of low intensity walking or jogging and flexibility exercises. All HIIT sessions were supervised by trained sports scientists and research personnel. Session-level RPE and running-speed records were not available to the authors for verification and aggregation during revision; actual group distributions could therefore not be summarized.

2.6.2. Repetitive Peripheral Magnetic Stimulation (rPMS)

Immediately after each HIIT session, participants allocated to the experimental group received rPMS using a BTL-6000 Super Inductive System Elite (BTL Industries Ltd., Stevenage, UK; Part No. P6000.901) equipped with a focused-field applicator. According to the manufacturer's technical specifications, the system is capable of delivering frequencies up to 150 Hz and a maximum device magnetic field intensity of 2.5 T (maximum dB/dt, 28 kT/s). The present protocol used substantially lower, protocol defined settings. rPMS provides a neuromuscular stimulus through magnetically induced peripheral activation and muscle contraction; it should not be interpreted as an intervention that adds no training stimulus simply because it does not require additional active running or resistance exercise volume.

The rectus femoris, hamstring, and gastrocnemius regions were stimulated bilaterally in a standardized sequence. For the quadriceps region, the center of the applicator was positioned over the rectus femoris as a reproducible anatomical reference because of its superficial location and readily identifiable landmarks. This positioning was not based on an assumption that the rectus femoris is the predominant contributor to knee-extension force. The stimulation field was not anatomically confined to the rectus femoris and may have exposed adjacent quadriceps tissue; however, muscle-specific electromyographic activity was not recorded, so recruitment of the vastus lateralis, vastus medialis, or vastus intermedius cannot be confirmed or quantified. Participants were

positioned supine for quadriceps region stimulation and prone for hamstring and gastrocnemius stimulation.

Each muscle-side site received approximately 5 min of stimulation using a 3 s ON and 7 s OFF duty cycle, resulting in approximately 30 stimulation cycles and 90 s of active stimulation per site and approximately 30 min of total treatment per session across the three bilateral target regions. Frequency was adjusted within 40–50 Hz. Stimulation intensity was maintained within 70–80% of maximum stimulator output (%MSO) and was progressively increased within that range until a clearly visible muscle contraction was obtained without pain or intolerable discomfort. The exact %MSO could therefore differ among participants, target muscles, and sessions. Session level frequency, %MSO, duration, target muscle, side, participant tolerance, and adverse responses were recorded for intervention fidelity monitoring, although aggregate %MSO mean ± SD or range values were not prospectively summarized and were not retrospectively estimated.

At 40–50 Hz with the programmed 3 s ON/7 s OFF duty cycle, the nominal calculated pulse exposure was approximately 3600–4500 pulses per muscle side site and approximately 21,600–27,000 pulses across the six bilateral sites per session. These values were calculated from the programmed frequency and duty cycle and were not independently measured pulse counts. Magnetic field intensity at the target tissue was not directly measured; therefore, %MSO was not converted to a tissue-level Tesla value. Pulse width was not independently measured and was not available in the retained technical documentation. All rPMS treatments were delivered by the same physical therapist to standardize positioning, applicator placement, technique, and participant instruction. The HIIT-only group completed the identical HIIT program but received neither active rPMS nor sham magnetic stimulation.

2.7. Outcome Measurements

The primary outcome was relative quadriceps strength, expressed relative to body mass ($kg \cdot kg^{-1}$ body mass). Prespecified secondary outcomes were relative hamstring strength, fixed-load knee-extension repetitions-to-failure performance, Wattbike-derived estimated maximal oxygen uptake (estimated VO_2max), serum insulin-like growth factor-1 (IGF-1), and serum interleukin-6 (IL-6). Anthropometric, body-composition, and resting physiological variables were collected primarily to characterize the participants and describe baseline comparability.

Outcome measurements were performed at baseline and following completion of the six-week intervention. Assessments were undertaken by trained personnel blinded to treatment allocation. The same equipment, participant positioning, testing order, verbal instructions, and environmental conditions were maintained across assessment occasions, consistent with intervention and measurement reproducibility principles [28,29].

2.7.1. Anthropometric and Resting Physiological Measurements

Participant characteristics included age, body mass, height, body mass index, percentage body fat, and muscle mass. Body composition was assessed using a calibrated bioelectrical impedance-based body composition analyzer under standardized measurement conditions. Because the accuracy of bioelectrical impedance analysis is influenced by device characteristics and pre-measurement standardization, measurement conditions were kept consistent between assessment occasions [34].

Resting respiratory rate, resting heart rate, systolic and diastolic blood pressure, and peripheral oxygen saturation were recorded after an appropriate period of seated or supine rest. Blood pressure measurement procedures followed standardized principles regarding participant positioning, pre-measurement rest, cuff application, and calibrated oscillometric measurement [35].

2.7.2. Estimated Maximal Oxygen Uptake

Cardiorespiratory fitness was assessed using a Wattbike Pro cycle ergometer (Wattbike Ltd., Nottingham, UK). Saddle and handlebar positions were individually adjusted and recorded so that identical configurations could be reproduced at post-intervention testing.

Participants completed a standardized warm up followed by a maximal incremental ramp test. The test commenced at 50 W, after which workload increased by 30 W every minute. Participants were instructed to maintain a cadence of approximately 80 revolutions·min−1. Heart rate was continuously monitored using the Polar H10 sensor [32]. The test continued until volitional exhaustion or until the participant could no longer maintain the required cadence and workload. Testing was also terminated if an abnormal cardiovascular or clinical response occurred, if the participant requested termination, or if the supervising investigator considered continuation unsafe.

The value generated by the Wattbike system/software was recorded as the Wattbike-derived estimated VO_2max and expressed as $mL \cdot kg^{-1} \cdot min^{-1}$. Wattbike-based procedures have demonstrated validity for estimating VO_2max in previous research [36]. However, the previously validated 3 min aerobic test differs from the maximal incremental protocol used in the present study; therefore, because respiratory gases were not directly measured, the outcome is conservatively reported throughout the manuscript as estimated VO_2max rather than directly measured VO_2max.

2.7.3. Lower Limb Muscle Strength

Knee extensor and knee flexor strength were assessed using a Life Fitness Axiom Series Seated Leg Curl/Extension machine (model OP-SLCE; Life Fitness). One repetition maximum testing is widely used to assess dynamic muscular strength and generally demonstrates good-to-excellent test–retest reliability across exercises and populations [37]. Reliability has also been demonstrated for seated knee extension testing [38]. A submaximal repetition-based estimate was selected principally because it was compatible with the available resistance equipment and study testing setting. The same machine-based procedure could be applied at both visits; this practical choice does not establish equivalence to dynamometry or maximal isokinetic testing.

To minimize learning effects, participants completed one familiarization session approximately 48–72 h before baseline testing. During familiarization, participants practiced seating position, knee joint alignment, ankle pad positioning, range of motion, and movement technique using low-to-moderate loads that did not induce substantial fatigue.

Before formal strength testing, participants completed a progressive warm-up using approximately 40–80% of estimated 1RM, with approximately 1–10 repetitions depending on the load employed. Strength was then estimated using a 5–10 repetition maximum procedure. Resistance was progressively adjusted until the participant could complete between five and ten technically acceptable repetitions before repetition failure. A maximum of five testing attempts was permitted, with approximately 3 min of recovery between attempts.

Estimated 1RM was calculated using the Brzycki equation [39]. Reliability of maximal strength assessment is supported by systematic review evidence [37], and seated knee-extension testing has demonstrated test–retest reliability [38]:

$$\text{Estimated 1RM} = \text{load lifted}/[1.0278 - (0.0278 \times \text{number of repetitions})]$$

Relative strength was calculated as estimated 1RM divided by that participant's baseline body mass at both visits and expressed as kg·kg−1 baseline body mass. Relative knee extension strength represented quadriceps strength, whereas relative knee flexion

strength represented hamstring strength. Identical machine settings, range of motion, joint alignment, and testing instructions were reproduced at post-intervention assessment.

2.7.4. Fixed-Load Knee-Extension Repetitions-to-Failure Performance

Fixed-load knee-extension repetitions-to-failure performance was assessed using the seated knee-extension configuration on the same resistance equipment and with the same standardized positioning used for strength assessment. The test load was set at 70% of each participant's baseline estimated 1RM and the same absolute load was retained at week 6; it was not recalculated from the week-6 strength value. Participants performed repeated knee-extension contractions through the standardized range of motion until task failure. Consequently, the follow-up task represented performance at a fixed absolute external load rather than at a constant relative percentage of current 1RM. Repetitions-to-failure testing at standardized loads has demonstrated reproducibility, although available evidence includes exercise modes other than knee extension [40].

A repetition was accepted only when the participant completed the predefined knee-extension range of motion without substantial compensatory movement of the trunk or hip. The test was terminated when the participant failed to complete the required range of motion, could not maintain the standardized movement pattern, demonstrated substantial compensatory movement, could not complete an additional repetition, or voluntarily stopped because of fatigue. The total number of technically acceptable repetitions was recorded as the fixed-load repetitions-to-failure outcome.

2.7.5. Blood Chemistry

Venous blood samples were collected at baseline and 24–48 h after the final intervention session, using the same post-session interval and the same 16:00–18:00 h collection window in both groups. Participants fasted for at least 8 h before blood collection and were instructed to refrain from caffeine, alcohol, and additional strenuous exercise for at least 24 h before each assessment. Venous sampling and pre-analytical procedures were standardized with reference to international recommendations for venous blood collection and specimen handling [41].

Approximately 5 mL of venous blood was collected from an antecubital vein by a registered nurse using standard aseptic procedures. Blood allocated for IGF-1 and IL-6 analysis was placed into separate serum tubes so that assay-specific pre-analytical procedures could be applied independently.

IGF-1. Blood was allowed to clot for approximately 30 min and centrifuged at 1000× *g* for 15 min. Serum was separated, aliquoted, and stored at −20 °C until analysis. Serum IGF-1 concentrations were measured using the Human IGF-I/IGF-1 Quantikine ELISA Kit (R&D Systems/Bio-Techne, Minneapolis, MN, USA; catalog no. DG100). Because IGF-1 measurement is sensitive to assay standardization, pre-analytical conditions, quality control, and binding-protein interference, the use of a single assay platform and standardized processing was maintained throughout the study [42]. Samples were analyzed in duplicate according to the manufacturer's instructions and results were expressed as ng/mL. The manufacturer reported intra assay coefficient of variation was approximately 3.5–4.3%, and the inter assay coefficient of variation was approximately 7.5–8.3%.

IL-6. Serum IL-6 was measured using the Human IL-6 SimpleStep ELISA Kit (Abcam, Cambridge, UK; catalog no. ab178013). According to the laboratory procedure, samples were analyzed in duplicate. During revision, re-examination of the retained assay documentation identified analytical limitations that precluded reliable quantitative interpretation: the reported concentration values were below the assay's stated calibration

range (7.8–500 pg/mL), several were below the manufacturer-reported minimal detectable dose of 1.6 pg/mL, and baseline and week-6 samples had been analyzed on different plates/batches. In addition, the actual kit lot number, original raw optical-density files, 4PL curve output, and concentration-calculation sheets were not available for independent re-verification.

Accordingly, IL-6 was not included in the inferential statistical analyses in the revised manuscript because of limitations related to assay range, batch differences, and the availability of the original laboratory records.

2.8. Environmental Control

Training and assessment sessions were conducted under controlled laboratory conditions. Room temperature was maintained at approximately 25 ± 1 °C, with relative humidity between 40% and 60%. Baseline and post-intervention assessments were scheduled at comparable times of day, and blood sampling was standardized between 16:00 and 18:00 h.

Participants were instructed to maintain their usual dietary intake, hydration practices, sleep patterns, and routine team training schedule throughout the intervention period and not to initiate additional structured exercise programs, medications, hormonal products, or nutritional supplements that could materially influence study outcomes. Measurement devices were inspected and calibrated according to laboratory standard operating procedures. Equipment configuration, participant positioning, measurement order, and standardized verbal instructions were maintained across assessment occasions in accordance with the reproducibility principles emphasized by TIDieR and CERT [28,29].

Training attendance and intervention fidelity were monitored throughout the six-week period. Attendance below 80% of prescribed sessions constituted a predefined criterion for intervention discontinuation. Mean attendance was 14.85 ± 0.37 of 15 prescribed sessions (98.97%) in the HIIT + rPMS group and 14.77 ± 0.43 sessions (98.46%) in the HIIT-only group; no participant fell below the adherence threshold. Mean work-interval heart rate was 91.24 ± 1.25% HRmax in the HIIT + rPMS group and 91.15 ± 1.08% HRmax in the HIIT-only group, indicating very similar relative cardiovascular intensity. RPE was monitored using the Borg 6–20 scale, but group-level mean ± SD values were not prospectively summarized. Running speed was individually adjusted to maintain the prescribed 85–95% HRmax range, and all intervals were performed at 0% incline. For rPMS, session-level frequency, %MSO, duration, target muscle, side of application, participant tolerance, and adverse responses were recorded, but aggregate %MSO mean ± SD or range values were not prospectively summarized. Participants were monitored for adverse symptoms throughout HIIT and rPMS sessions, and exercise or stimulation was discontinued when supervising personnel considered continuation unsafe.

2.9. Data Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA). All randomized participants were analyzed according to their originally assigned groups under the intention to treat principle, which preserves the benefits of randomization and is recommended for randomized controlled trials [25,26,43]. Because no randomized participant had missing post-intervention outcome data, statistical imputation was not required.

Before inferential analysis, data were examined for completeness, plausibility, and distributional characteristics. Normality of continuous variables was evaluated using the Shapiro–Wilk test together with visual inspection of histograms and normal quantile

plots. Homogeneity of variance for between-group parametric comparisons was evaluated using Levene's test.

Statistical treatment of baseline descriptive characteristics was distinguished from analysis of the prespecified study outcomes. Normally distributed baseline continuous characteristics were summarized as mean and standard deviation and, where inferential comparisons were presented, were compared using the independent samples *t*-test. Baseline variables that did not satisfy the normality assumption were analyzed using the Mann–Whitney U test.

For the primary and secondary study outcomes, the original statistical analysis plan specified individual change scores as Δ = post-intervention value—baseline value, with between-group comparisons using independent-samples *t*-tests or Welch's *t*-test when homogeneity of variance was not satisfied. This prespecified analysis was retained. Because simple randomization in a modest sample can leave residual baseline imbalance, post hoc baseline-adjusted ANCOVA sensitivity analyses were additionally performed for quantitatively interpretable outcomes, with the week-6 value as the dependent variable, treatment group as the fixed factor, and the corresponding baseline value as a covariate [44]. Homogeneity of regression slopes was evaluated using the group by baseline interaction.

For each outcome, results were reported as mean change with standard deviation, between group mean difference in change, corresponding 95% confidence interval, t statistic, degrees of freedom, and *p*-value. Within group pre–post comparisons using paired samples *t*-tests were treated as supplementary analyses and were not used as the primary basis for determining comparative intervention effects.

Standardized between group effects were expressed as Hedges' g, which applies a small sample correction to standardized mean differences. Effect sizes were interpreted together with raw mean differences, confidence intervals, direction of effect, and physiological context rather than by statistical significance alone, consistent with recommendations for transparent effect size reporting [45].

All statistical tests were two-sided, with $\alpha = 0.05$. Relative quadriceps strength was the prespecified primary outcome. No formal multiplicity adjustment was prespecified or applied to the five secondary outcomes; therefore, secondary outcome *p*-values were treated as nominal and findings were interpreted as exploratory or supportive rather than confirmatory. For context, a simple Bonferroni threshold across the five prespecified secondary outcomes would be $\alpha = 0.01$. Nonparametric Mann–Whitney U sensitivity analyses of change scores were also performed to evaluate robustness where distributional concerns existed. These sensitivity analyses were added post hoc during revision and did not replace the prespecified primary analysis. IL-6 was not included in post hoc inferential sensitivity analyses because the assay-documentation review precluded reliable quantitative interpretation.

Post hoc sensitivity analyses were interpreted by consistency of direction, adjusted effect estimates, confidence intervals, and *p*-values rather than as a redefinition of the prespecified outcome hierarchy.

3. Results

3.1. Participant Flow and Study Completion

A total of 86 male collegiate football and futsal athletes were assessed for eligibility. Of these, 34 were excluded: 18 did not meet the eligibility criteria, 10 declined to participate, and 6 were unable to participate because of competition commitments during the study period. The remaining 52 participants were enrolled and randomly allocated in a 1:1 ratio to the HIIT + rPMS group (n = 26) or the HIIT-only group (n = 26). The flow of participants through the trial is shown in Figure 1.

All 52 randomized participants remained in the study and completed the final assessment, with no loss to follow-up or intervention discontinuation. Mean attendance was 14.85 ± 0.37 of 15 prescribed sessions (98.97%) in the HIIT + rPMS group and 14.77 ± 0.43 sessions (98.46%) in the HIIT-only group. Attendance ranged from 14 to 15 sessions in both groups, and no participant attended fewer than 80% of the prescribed sessions. Mean work-interval heart rate was 91.24 ± 1.25% HRmax and 91.15 ± 1.08% HRmax, respectively. RPE was monitored with the Borg 6–20 scale, but group-level mean ± SD values were not prospectively summarized. Running speed was individually adjusted to maintain the target HR range, and all treadmill intervals were performed at 0% incline. No outcome data were missing, and statistical imputation was not required.

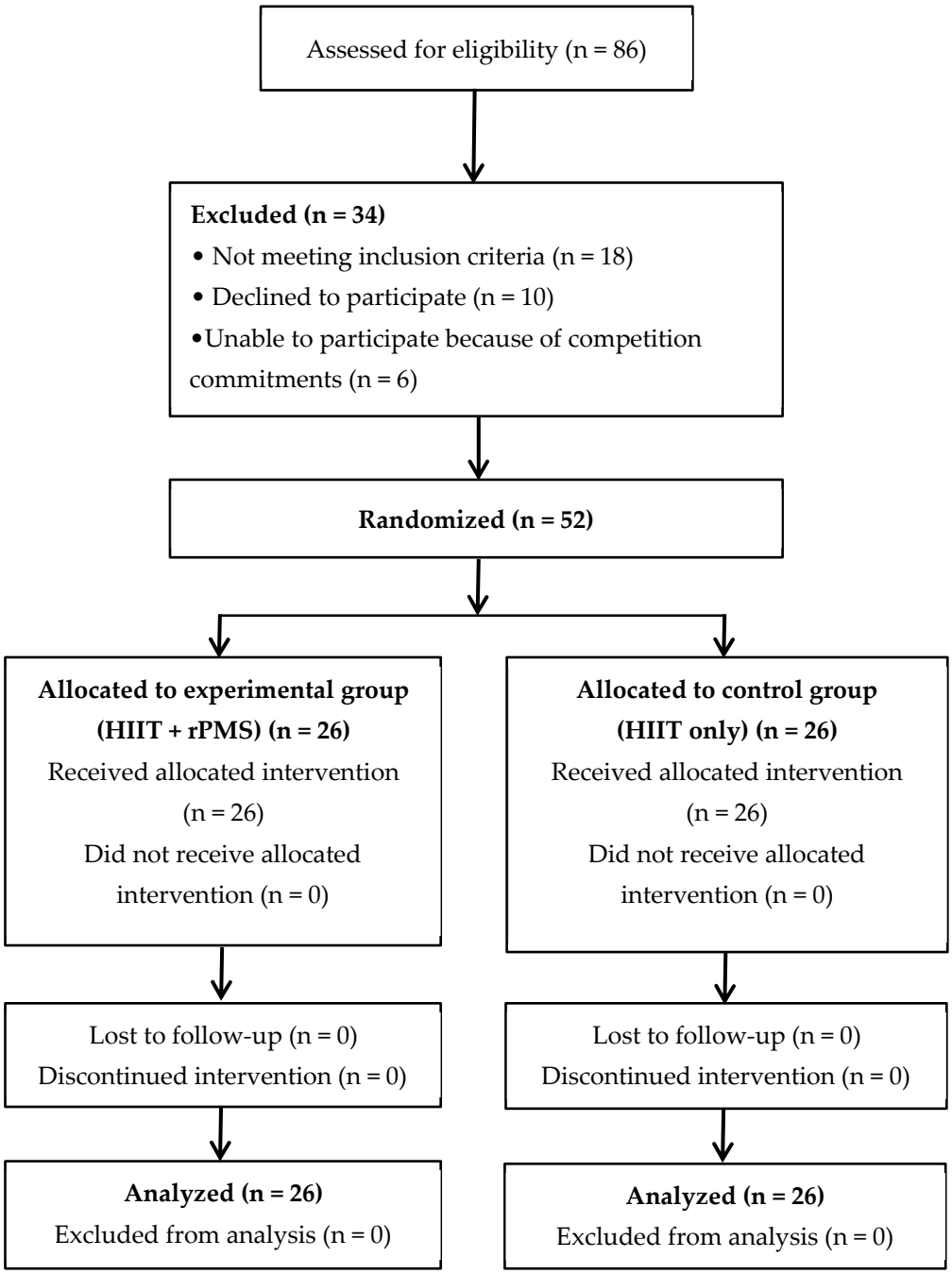


Figure 1. CONSORT flow diagram of participant recruitment, randomization, follow up, and analysis.

No adverse events were reported in either group throughout the study (0/26 per group). Events were monitored during supervised sessions through health-status checks, observation of symptoms of exercise intolerance, and checks of stimulation tolerance and adverse responses, as described in Sections 2.6 and 2.8.

3.2. Baseline Characteristics

The baseline demographic, anthropometric, and resting physiological characteristics of the participants are presented in Table 1. The experimental and control groups were comparable at baseline. No statistically significant between group differences were observed in age, body mass index, percentage body fat, muscle mass, resting respiratory rate, resting heart rate, systolic blood pressure, diastolic blood pressure, or peripheral oxygen saturation ($p > 0.05$).

Table 1. Baseline demographic, anthropometric, and physiological characteristics of the participants.

Variable	HIIT + rPMS Group (n = 26)	HIIT-Only Group (n = 26)	*p*-Value
Age (years) Mean (SD)	19.77 (1.27)	19.88 (1.18)	0.734 [b]
Body mass index (kg/m^2) Mean (SD)	20.57 (1.03)	20.49 (0.96)	0.793 [a]
Body fat (%) Mean (SD)	15.35 (0.58)	15.30 (0.65)	0.771 [a]
Muscle mass (%) Mean (SD)	41.97 (1.58)	41.74 (1.34)	0.567 [a]
Resting respiratory rate (breaths/min) Mean (SD)	19.00 (0.85)	19.35 (0.85)	0.124 [b]
Resting heart rate (beats/min) Mean (SD)	67.12 (2.96)	67.77 (2.78)	0.415 [a]
Systolic blood pressure (mmHg) Mean (SD)	118.62 (3.69)	118.08 (3.92)	0.612 [a]
Diastolic blood pressure (mmHg) Mean (SD)	76.35 (4.52)	74.62 (4.49)	0.172 [a]
Peripheral oxygen saturation (%) Mean (SD)	98.00 (0.75)	98.15 (0.67)	0.448 [b]

Data are presented as mean (SD); [a] Independent-samples *t*-test; [b] Mann–Whitney U test.

3.3. Physical Performance Outcomes

Changes in physical performance outcomes from baseline to week 6 are presented in Table 2. The prespecified primary analysis compared individual change scores (week 6 minus baseline) between groups using independent samples *t*-tests or Welch's *t*-test, as

appropriate. Post hoc baseline-adjusted and nonparametric sensitivity analyses are summarized in Section 3.5.

Table 2. Changes in physical performance outcomes from baseline to week 6 in the HIIT + rPMS and HIIT-only groups.

Outcome	HIIT + rPMS (n = 26)			HIIT-Only (n = 26)			Between-Group Difference in Change, Δ (95% CI)	t (df)	*p*-Value	Hedges' g
	Baseline	Week 6	Change, Δ	Baseline	Week 6	Change, Δ				
Relative quadriceps strength [1] (kg·kg^{-1} body mass)	2.07 (0.12)	2.37 (0.11)	0.31 (0.11)	2.03 (0.13)	2.18 (0.13)	0.15 (0.12)	0.16 (0.09 to 0.22)	4.936 (50)	<0.001	1.35
Relative hamstring strength (kg·kg^{-1} body mass)	0.70 (0.06)	1.01 (0.13)	0.31 (0.16)	0.71 (0.07)	0.99 (0.13)	0.28 (0.15)	0.03 (−0.05 to 0.12)	0.731 (50)	0.468	0.20
Fixed-load knee-extension repetitions-to-failure (repetitions)	19.50 (1.63)	24.20 (1.70)	4.73 (1.95)	20.27 (1.31)	22.88 (1.40)	2.62 (1.39)	2.12 (1.17 to 3.06)	4.506 (45.15) [2]	<0.001	1.23
Estimated VO_2max (mL·kg^{-1}·min^{-1})	49.60 (2.33)	54.12 (1.99)	4.52 (3.14)	50.57 (1.85)	53.56 (1.56)	2.99(2.28)	1.53 (0.00 to 3.06)	2.010 (50)	0.0498 [3]	0.55

Data are presented as mean (SD). Δ = week 6 − baseline. Between group difference = ΔHIIT + rPMS − ΔHIIT only; [1] Primary outcome; [2] Welch's *t*-test due to unequal variances; [3] Nominal unadjusted *p*-value reported to four decimal places. The fixed-load knee-extension repetitions-to-failure test used the same absolute load, equal to 70% of baseline estimated 1RM, at both baseline and week 6. CI, confidence interval; HIIT, high intensity interval training; rPMS, repetitive peripheral magnetic stimulation; VO_2max, maximal oxygen uptake (estimated using the Wattbike maximal ramp test).

3.3.1. Relative Quadriceps Strength (Primary Outcome)

Relative quadriceps strength, the prespecified primary outcome, increased in both groups over the six-week intervention period. In the HIIT + rPMS group, relative quadriceps strength increased from 2.07 ± 0.12 kg·kg^{-1} body mass at baseline to 2.37 ± 0.11 kg·kg^{-1} at week 6, corresponding to a mean change of 0.31 ± 0.11 kg·kg^{-1}. In the HIIT-only group, relative quadriceps strength increased from 2.03 ± 0.13 to 2.18 ± 0.13 kg·kg^{-1}, corresponding to a mean change of 0.15 ± 0.12 kg·kg^{-1}.

The improvement was significantly greater in the HIIT + rPMS group than in the HIIT-only group. The between-group difference in change was 0.16 kg·kg^{-1} body mass (95% CI, 0.09 to 0.22), t(50) = 4.94, $p < 0.001$. The standardized between-group effect was large (Hedges' g = 1.35).

3.3.2. Relative Hamstring Strength

Relative hamstring strength increased over the intervention period in both groups. In the HIIT + rPMS group, the mean value increased from 0.70 ± 0.06 to 1.01 ± 0.13 kg·kg^{-1} body mass, representing a mean change of 0.31 ± 0.16 kg·kg^{-1}. In the HIIT-only group, relative hamstring strength increased from 0.71 ± 0.07 to 0.99 ± 0.13 kg·kg^{-1}, with a mean change of 0.28 ± 0.15 kg·kg^{-1}.

The between group difference in change was not statistically significant (mean difference, 0.03 kg·kg^{-1}; 95% CI, −0.05 to 0.12), t(50) = 0.73, p = 0.468, Hedges' g = 0.20. Thus, the data did not provide evidence of an additional rPMS effect on relative hamstring strength beyond HIIT alone.

3.3.3. Fixed-Load Knee-Extension Repetitions-to-Failure Performance

Fixed-load knee-extension repetitions-to-failure performance improved in both groups and showed a greater increase in the HIIT + rPMS group. Participants receiving HIIT + rPMS increased from 19.50 ± 1.63 repetitions at baseline to 24.20 ± 1.70 repetitions at week 6, corresponding to a mean increase of 4.73 ± 1.95 repetitions. Participants receiving HIIT alone increased from 20.27 ± 1.31 to 22.88 ± 1.40 repetitions, corresponding to a mean increase of 2.62 ± 1.39 repetitions. Because the same absolute load derived from 70% of baseline estimated 1RM was retained at week 6, this outcome should be interpreted as fixed-load performance rather than endurance assessed at an identical relative intensity.

Because the assumption of equal variances for the change scores was not satisfied, the between group comparison used Welch's independent samples t-test. The mean between group difference in change was 2.12 repetitions (95% CI, 1.17 to 3.06), t(45.15) = 4.51, p < 0.001, with Hedges' g = 1.23. The larger increase in repetitions may partly reflect the greater improvement in knee-extension strength and should not be interpreted as an independent muscular endurance adaptation.

3.3.4. Estimated Maximal Oxygen Uptake

Estimated VO_2max increased over six weeks in both intervention groups. In the HIIT + rPMS group, estimated VO_2max increased from 49.60 ± 2.33 to 54.12 ± 1.99 mL·kg^{-1}·min^{-1}, representing a mean increase of 4.52 ± 3.14 mL·kg^{-1}·min^{-1}. In the HIIT-only group, estimated VO_2max increased from 50.57 ± 1.85 to 53.56 ± 1.56 mL·kg^{-1}·min^{-1}, corresponding to a mean increase of 2.99 ± 2.28 mL·kg^{-1}·min^{-1}.

The prespecified change score comparison yielded a mean between group difference of 1.53 mL·kg^{-1}·min^{-1} (95% CI, approximately 0.00 to 3.06), t(50) = 2.01, with a nominal p-value of 0.0498 and Hedges' g = 0.55. Because estimated VO_2max was a secondary outcome and the result was immediately adjacent to the conventional threshold, it was treated cautiously. Post hoc sensitivity analyses did not support a robust between group effect (baseline-adjusted ANCOVA p = 0.270; Mann–Whitney U p = 0.082); accordingly, the estimated VO_2max finding was considered inconclusive rather than evidence of an additional aerobic effect of rPMS.

3.4. Blood Chemistry Outcomes

Serum IGF-1 concentrations before and after the intervention are presented in Table 3. IL-6 was a prespecified secondary outcome, but its quantitative values were not used for inferential interpretation after analytical verification identified the limitations described in Section 2.7.5.

Table 3. Serum IGF-1 concentrations at baseline and after the 6-week intervention.

Outcome	HIIT + rPMS (n = 26)			HIIT-Only (n = 26)			Between-Group Difference in Change, Δ (95% CI)	t (df)	*p*-Value	Hedges' g
	Baseline	Week 6	Change, Δ	Baseline	Week 6	Change, Δ				
IGF-1 (ng/mL)	226.96 (10.49)	238.31 (10.98)	11.35 (7.56)	231.92 (14.23)	240.27 (12.23)	8.35 (8.87)	3.00 (−1.59 to 7.59)	1.313 (50)	0.195	0.36

Data are presented as mean (SD). Δ = week 6 − baseline. Between-group difference = ΔHIIT + rPMS − ΔHIIT only. CI, confidence interval; HIIT, high-intensity interval training; rPMS, repetitive peripheral magnetic stimulation; IGF-1, insulin-like growth factor-1.

3.4.1. Insulin-like Growth Factor-1

Serum IGF-1 concentrations increased over the six-week intervention period in both groups. In the HIIT + rPMS group, mean IGF-1 increased from 226.96 ± 10.49 ng/mL at baseline to 238.31 ± 10.98 ng/mL at week 6, corresponding to an increase of 11.35 ± 7.56 ng/mL. In the HIIT-only group, serum IGF-1 increased from 231.92 ± 14.23 to 240.27 ± 12.23 ng/mL, representing a mean increase of 8.35 ± 8.87 ng/mL.

The difference in change between groups was 3.00 ng/mL (95% CI, −1.59 to 7.59), t(50) = 1.31, p = 0.195, with Hedges' g = 0.36. Therefore, the addition of rPMS did not demonstrate a detectable additional effect on circulating IGF-1 beyond the response associated with HIIT alone.

3.4.2. IL-6 Assay Documentation and Interpretation

IL-6 was a prespecified secondary outcome and was measured at baseline and following the six-week intervention. During revision, the available laboratory documentation for the IL-6 assay was re-examined in greater detail. This review showed that the reported concentration values were below the lowest calibration standard of the stated assay, with several values also below the manufacturer-reported minimal detectable dose. In addition, baseline and week-6 samples had been analyzed on different plates/batches, and the original assay lot identifier, raw optical-density data, 4PL curve output, and concentration-calculation records were not available for independent re-evaluation.

Because these limitations did not allow sufficiently reliable quantitative interpretation of the IL-6 results, IL-6 was not included in the inferential statistical analyses presented in the revised manuscript. Importantly, IL-6 remains identified as a prespecified secondary outcome and as a biomarker that was measured during the study; the decision not to include it in the inferential analyses should therefore not be interpreted as removal of the outcome from the study. No conclusions regarding systemic inflammation, recovery, physiological responses, or the effect of the intervention were drawn from the IL-6 measurements.

3.5. Post Hoc Sensitivity Analyses

Baseline-adjusted ANCOVA sensitivity analyses supported the robustness of the primary quadriceps strength finding (adjusted between group difference, +0.174 $kg \cdot kg^{-1}$; 95% CI, 0.119 to 0.230; $p < 0.001$). Relative hamstring strength remained null (+0.018 $kg \cdot kg^{-1}$; 95% CI, −0.056 to 0.093; $p = 0.620$). The adjusted difference for fixed-load knee-extension repetitions-to-failure performance was +1.63 repetitions (95% CI, 0.79 to 2.47; $p < 0.001$), whereas estimated VO_2max was not supported (+0.57 $mL \cdot kg^{-1} \cdot min^{-1}$; 95% CI, −0.46 to 1.61; $p = 0.270$) and IGF-1 remained null (+1.59 ng/mL; 95% CI, −2.68 to 5.85; p =

0.459). Nonparametric Mann–Whitney U sensitivity analyses of change scores were consistent for quadriceps strength ($p < 0.001$), hamstring strength ($p = 0.458$), fixed-load repetitions-to-failure performance ($p < 0.001$), and IGF-1 ($p = 0.354$), while estimated VO_2max did not reach the conventional threshold ($p = 0.082$). IL-6 was not included in these sensitivity analyses because the available assay documentation did not support sufficiently reliable quantitative interpretation. These analyses were exploratory and were added post hoc during revision; they neither replace the prespecified comparisons nor independently confirm secondary-outcome benefits.

4. Discussion

The present randomized controlled trial evaluated the effect of adding active rPMS immediately after repeated sprint HIIT in trained male collegiate football and futsal athletes. The prespecified primary finding was a greater improvement in relative quadriceps strength with HIIT + rPMS than with HIIT alone (between-group difference in change, 0.16 kg·kg^{-1}; 95% CI, 0.09 to 0.22; $p < 0.001$; Hedges' g = 1.35), and this finding remained robust in baseline-adjusted sensitivity analysis. Fixed-load knee-extension repetitions-to-failure performance also increased more in the combined group, although this outcome was tested using the same absolute load at week 6 and may partly reflect the greater strength gain. No additional effect was supported for relative hamstring strength or serum IGF-1.

The nominal change-score result for estimated VO_2max ($p = 0.0498$) was not robust to baseline-adjusted or nonparametric sensitivity analyses and is therefore considered inconclusive. Quantitative IL-6 inference was withdrawn because the retained assay documentation did not support reliable re-verification of the reported concentrations. These revisions narrow the interpretation of the trial to the outcomes that can be supported by the available design and measurement evidence. The ANCOVA and nonparametric analyses were exploratory post hoc checks, and disagreement across analyses should not be resolved by selecting the most favorable result.

Because the trial did not include a sham-rPMS condition, the observed between-group differences cannot be attributed exclusively to the physiological effects of magnetic stimulation. Participants knew their allocation and the experimental group received additional therapist-administered treatment time; expectancy, contextual effects, additional therapist contact, and participant effort may therefore have contributed. The findings should be interpreted as the effect of adding active rPMS under the present study conditions rather than as proof of a mechanism-specific rPMS effect.

4.1. Effects on Relative Quadriceps Strength: Primary Outcome

Relative quadriceps strength increased more in the HIIT + rPMS group than in the HIIT-only group, and the primary finding remained statistically robust in baseline-adjusted sensitivity analysis. Because this outcome was prespecified in the ethics-approved protocol and formed the basis of the sample size calculation, it provides the clearest evidence of a between group difference in this trial. However, the magnitude of the standardized effect should not be interpreted as evidence of a specific physiological mechanism.

The direction of the finding is consistent with prior evidence that neuromuscular magnetic stimulation can evoke peripheral contractions and has been associated with quadriceps strength gains in healthy adults [17]. Peripheral magnetic stimulation studies have also reported induced movement and changes in cortical or spinal excitability in healthy participants [16,46,47]. Evidence from neuromuscular electrical stimulation [48–50] provides only indirect contextual support and should not be considered equivalent evidence for rPMS.

One hypothesis is that post-exercise magnetic stimulation provided supplementary peripheral muscle activation after voluntary high-intensity exercise. However, electromyographic activity, voluntary activation, motor unit recruitment, muscle architecture, muscle morphology, local circulation, and recovery physiology were not measured. The present data therefore cannot identify the neural, structural, metabolic, or recovery mechanism underlying the observed strength difference.

Lower-limb strength is an important component of health-related physical fitness and functional capacity [5]. Nevertheless, the direct evidence from this trial applies to trained male collegiate athletes, not to the general young-adult population. The quadriceps result may justify the further study of adjunctive neuromuscular technologies in comparable training settings, but it does not establish disease prevention or population-level health promotion benefit.

The magnitude of the primary effect was large and warrants cautious interpretation. The analysis dataset was re-audited and the reported primary statistics were reproducible, but standardized effects from a modest, homogeneous, single-center sample may be imprecise. The outcome was also estimated from a submaximal repetition test rather than a direct maximal force measure, and the absence of sham control leaves expectancy and performance effects unresolved. Independent sham-controlled replication is therefore required.

4.2. Effects on Relative Hamstring Strength

Relative hamstring strength increased in both groups, but the between-group difference was not statistically significant and remained null in baseline-adjusted sensitivity analysis. Thus, the additional between-group effect observed for knee-extension strength was not reproduced for knee-flexion strength.

The present measurements cannot determine why knee-extension and knee-flexion outcomes differed. Differences in anatomy, applicator field distribution, measurement specificity, baseline adaptation, or sampling variability are possible explanations, but none was directly tested. The rectus femoris served as a reproducible reference site for quadriceps region applicator placement, and muscle-specific recruitment of the adjacent vastus muscles was not measured. Hamstring-region stimulation was not accompanied by an additional knee-flexion strength benefit; this mismatch further limits a selective quadriceps mechanistic interpretation.

Accordingly, the differential findings should be described as outcome-specific observations rather than evidence of a 'muscle-specific' rPMS mechanism. They reinforce the need for direct mechanistic measurements and sham control before attributing the pattern to differential physiological responsiveness.

4.3. Effects on Fixed-Load Knee-Extension Repetitions-to-Failure Performance

Fixed-load knee-extension repetitions-to-failure performance increased more in the HIIT + rPMS group than in the HIIT-only group. The between-group difference in change was 2.12 repetitions (95% CI, 1.17 to 3.06; $p < 0.001$), and the direction of the finding remained evident in baseline-adjusted and nonparametric sensitivity analyses. This secondary outcome remains exploratory because comparisons were not adjusted for multiplicity and the trial was not separately powered for secondary outcomes; consistency in post hoc analyses does not remove these limitations.

However, the same absolute load, calculated as 70% of baseline estimated 1RM, was used again at week 6. Because the HIIT + rPMS group also demonstrated larger knee-extension strength gain, the retained load represented a lower relative intensity at follow up in that group. The larger increase in repetitions may therefore partly reflect the

concurrent strength improvement and should not be interpreted as an independent muscular endurance adaptation.

This distinction also limits broader health-related interpretation. Repetitions-to-failure performance at a fixed external load is relevant to muscular task capacity, but the present trial did not assess habitual physical activity, daily life fatigue, long-term physical function, or participation behavior. The outcome therefore supports further investigation in training contexts rather than direct extrapolation to preventive health or population-level outcomes.

4.4. Effects on Estimated Maximal Oxygen Uptake

Estimated VO_2max increased over six weeks in both intervention groups, consistent with evidence that HIIT improves cardiorespiratory fitness in athletic and physically active populations [9–13,51,52]. Cardiorespiratory fitness is an important health-related fitness attribute [6], but the present participants were already trained athletes and the outcome was estimated from the Wattbike protocol rather than measured directly by respiratory gas exchange.

The prespecified change-score analysis produced a nominal between group p-value of 0.0498. However, no multiplicity adjustment was prespecified for secondary outcomes, a simple Bonferroni threshold across the five prespecified secondary outcomes would be $\alpha = 0.01$, and the estimated VO_2max result was not robust to baseline-adjusted ANCOVA ($p = 0.270$) or nonparametric sensitivity analysis ($p = 0.082$). The finding is therefore considered inconclusive rather than evidence of an additional aerobic effect of rPMS.

This conservative interpretation is also physiologically appropriate because maximal aerobic capacity reflects integrated cardiovascular, pulmonary, vascular, and skeletal-muscle function, whereas rPMS was applied locally to selected lower-limb regions. In addition, the cited Wattbike validation study used a different test protocol from the maximal incremental protocol applied here [36].

The principal aerobic observation is therefore that structured HIIT was accompanied by improved estimated cardiorespiratory fitness in both groups. Any independent contribution of rPMS to aerobic capacity remains unestablished and should be tested with direct respiratory-gas analysis in adequately powered trials.

4.5. Effects on Circulating IGF-1

Serum IGF-1 increased over the intervention period in both groups, but the between-group difference in change was not statistically significant and remained null in baseline-adjusted sensitivity analysis. This result is compatible with evidence that exercise can influence circulating IGF-1, with considerable heterogeneity according to exercise modality, duration, participant characteristics, and sampling conditions [22,23,53–55].

The similar change in both groups is therefore more consistent with the common training exposure than with an additional systemic endocrine effect attributable to the add-on intervention. Circulating IGF-1 should not be interpreted as a direct surrogate for local muscular anabolic signaling because systemic hormonal concentrations do not necessarily correspond proportionally with local tissue signaling or strength adaptation [23].

Post-intervention blood was collected 24–48 h after the final intervention session, using the same timing conditions and 16:00–18:00 h collection window in both groups. Even with this standardization, endocrine concentrations may vary according to circadian rhythm, nutritional state, preceding exercise, and recovery status [22,53–55]. The IGF-1 result should therefore be viewed as a circulating systemic measure rather than a direct mechanistic explanation for the strength findings.

The null between-group IGF-1 finding also demonstrates that the observed functional differences were not accompanied by a detectable differential response in this selected circulating marker. No broader endocrine or preventive-health conclusion should be inferred.

4.6. Analytical Considerations for IL-6

IL-6 was prespecified as a secondary circulating marker; however, retrospective re-examination of the retained assay documentation identified analytical limitations that precluded reliable quantitative interpretation. The reported values were below the stated calibration range of the assay, several were below the manufacturer-reported minimal detectable dose, baseline and week-6 samples were analyzed on different plates/batches, and the original lot identifier and raw OD/4PL concentration-calculation records were unavailable for re-verification.

Accordingly, the original IL-6 effect size, *p*-value, and mechanistic interpretations were withdrawn. The revised manuscript does not use IL-6 to support an anti-inflammatory, recovery-related, physiological-strain, or intervention-effect claim. This approach was considered more appropriate than attempting to address the problem statistically because the primary concern was analytical verifiability rather than baseline adjustment.

4.7. Integrated Interpretation of HIIT and rPMS

The overall pattern of results does not indicate uniform enhancement of HIIT adaptations. The clearest supported difference was the prespecified quadriceps-strength outcome. Fixed-load knee-extension repetitions-to-failure performance also differed between groups, but its interpretation is partly strength-dependent. No additional effect was supported for hamstring strength or IGF-1, the estimated VO_2max result was inconclusive, and quantitative IL-6 inference was withdrawn because of analytical limitations.

The study therefore supports an outcome-specific add-on effect under the present conditions rather than a generalized or mechanism-specific rPMS effect. The absence of a sham condition prevents the separation of active magnetic stimulation from expectancy, contextual effects, additional treatment contact, and participant effort.

The potential public-health relevance of these findings is indirect. Muscular strength and cardiorespiratory fitness are components of health-related physical fitness [2–6], but the participants were trained male collegiate athletes. The trial does not establish effectiveness, feasibility, accessibility, affordability, scalability, or preventive-health benefit in females, sedentary individuals, non-athletes, or the broader young-adult population.

Exercise remains the core intervention. Active rPMS should be viewed as an investigational adjunct to structured training, not as a replacement for regular physical activity or evidence-based aerobic and resistance exercise. Broader health-promotion implications require separate evaluation in more diverse populations and real-world settings.

4.8. Practical Implications and Potential Public Health Relevance

The direct applicability of the present findings is primarily to trained male collegiate team sport athletes participating in supervised exercise. Their potential public-health relevance is indirect and derives from the health-related fitness attributes evaluated. The present trial does not establish rPMS as an effective health-promotion intervention for the general young-adult population.

For practitioners working with comparable athletic populations, active rPMS may warrant further evaluation as an adjunct to an established exercise program when the aim is to investigate selected lower-limb performance outcomes without adding more externally performed high-impact exercise volume. However, the absence of sham control means that the present study cannot isolate a specific physiological magnetic stimulation effect, and exercise should remain the primary intervention.

For health-promotion planners and policy makers, these findings are preliminary rather than implementation-ready. Before any consideration of university or community health-promotion use, future studies should establish effectiveness in non-athletic and more diverse populations and evaluate feasibility, acceptability, cost effectiveness, equipment and staffing requirements, adherence, and equity of access.

For public health researchers, the study raises a broader question about whether adjunctive technologies can meaningfully support health-related fitness within evidence-based exercise programs. The current trial provides no basis for population-wide implementation, and broader public-health claims should await evidence from appropriately designed effectiveness and implementation studies.

4.9. Strengths and Limitations

Several features strengthen the study, including randomized allocation, an identical HIIT program in both groups, prospective specification of the primary and secondary outcomes and original statistical plan in the ethics-approved protocol, blinded outcome assessment and masked statistical coding, high intervention adherence, and complete follow up. Re-audit of the individual level analysis dataset reproduced the reported descriptive statistics and primary change-score findings, and post hoc baseline-adjusted and nonparametric analyses were added to assess robustness without replacing the prespecified analysis.

Important limitations remain. The trial did not include a sham-rPMS condition; participants and the intervention provider knew treatment allocation, and the experimental group received approximately 30 min of additional therapist contact after each HIIT session. Expectancy, contextual effects, additional treatment contact, and participant effort therefore cannot be excluded, particularly for effort-dependent strength and repetitions-to-failure tests. The sample included only trained male collegiate football and futsal athletes from a single institution, limiting external validity. The six-week duration also precludes conclusions about persistence of effects.

The primary strength outcome was estimated from a submaximal repetition test rather than direct maximal-force measurement. The fixed-load repetitions-to-failure outcome used the same absolute load at week 6 and may partly reflect the greater gain in knee-extension strength rather than an independent endurance adaptation. Estimated VO_2max was not directly measured using respiratory gas exchange and was not robust to sensitivity analyses. Direct measures of neuromuscular activation, muscle architecture, morphology, local circulation, oxygenation, and recovery physiology were unavailable; therefore, proposed mechanisms remain hypothetical. Recruitment of individual vastus muscles was not measured. Hamstring-region stimulation was not accompanied by an additional improvement in hamstring strength, and the differing strength outcomes cannot be attributed to a demonstrated muscle-specific stimulation effect.

IL-6 was prespecified as a secondary outcome, but assay-documentation review identified analytical limitations that precluded reliable quantitative interpretation: reported values were below the stated calibration range, several were below the manufacturer-reported minimal detectable dose, baseline and week-6 samples were analyzed in different batches, and the original lot identifier and raw OD/4PL concentration-calculation records were unavailable. IL-6 was therefore not used to

support physiological, inflammatory, recovery, or intervention effect conclusions. Serum IGF-1 likewise represents a circulating systemic marker rather than direct local muscle signaling [22,23,53–55].

Multiple secondary outcomes were evaluated without formal multiplicity adjustment and the study was not powered separately for those outcomes; secondary *p*-values are therefore nominal and should be interpreted as exploratory. This limitation is especially relevant to the original estimated VO_2max *p*-value of 0.0498, which did not meet a simple Bonferroni threshold of $\alpha = 0.01$ and was not robust to sensitivity analyses. Finally, the trial was retrospectively rather than prospectively registered. Although all outcomes and the original statistical analysis plan were specified in the ethics-approved protocol before recruitment and data collection, prospective public registration would have provided stronger independently time-stamped documentation. The additional ANCOVA and nonparametric analyses were post hoc sensitivity analyses added during revision in response to reviewer concerns.

Session-level stimulation and training-load records were unavailable for verification and aggregation during revision, so actual stimulation intensity, frequency, RPE, and running speed could not be summarized. This limits intervention reproducibility and comparisons of individual exposure and training load between groups. The reported ranges describe the prescribed protocol, and similar attendance and heart rate do not establish equivalent total external training load.

4.10. Future Research

Future studies should replicate the primary quadriceps-strength finding in larger, multicenter, sham-controlled trials with matched treatment time and participant contact. Samples should include females, non-athletes, different levels of baseline physical activity, and broader age groups. Direct maximal-strength measures and prespecified procedures for blinding expectations should be considered.

If muscular endurance is a target outcome, future studies should distinguish fixed-load task performance from endurance assessed at a constant relative intensity. Recalibrating the follow-up load to the participant's current 1RM, or reporting both fixed-load and relative-load tests, would help separate endurance adaptation from concurrent strength gain. Longer follow-up should assess whether any functional differences persist.

Research in university and community settings should evaluate effectiveness, feasibility, accessibility, acceptability, adherence, cost-effectiveness, staff requirements, and equity of access before any population-level health-promotion role is considered. Such studies should also include habitual physical activity, physical function, quality of life, and other outcomes relevant to real world health promotion.

Mechanistic studies should examine rPMS frequency, intensity, duty cycle, treatment duration, target region, field distribution, and timing together with direct measurements of electromyographic activation, voluntary activation, muscle morphology, local circulation, and oxygenation. Direct respiratory gas analysis should be used to clarify aerobic outcomes. Future biomarker studies should use analytically validated assays, paired baseline and follow-up samples analyzed within the same batch where feasible, complete lot/plate documentation, retained raw OD and standard-curve outputs, and a prespecified plan for values below the quantifiable range.

Ultimately, future research should determine for whom, under what conditions, and at what cost adjunctive neuromuscular technologies provide meaningful benefits beyond established exercise. This evidence is required before any broader preventive health or population-based health-promotion role can be defined.

5. Conclusions

Six weeks of repeated sprint HIIT with post-exercise active rPMS was associated with a greater improvement in relative quadriceps strength than HIIT alone in trained male collegiate football and futsal athletes. Fixed-load knee-extension repetitions-to-failure performance also improved more in the combined group, although this finding may partly reflect the greater gain in knee-extension strength because the same absolute test load was retained at week 6. No additional effect was supported for hamstring strength or serum IGF-1, and the estimated VO_2max finding was not robust to sensitivity analyses and is therefore considered inconclusive. Because the study did not include a sham-rPMS condition, the observed between group differences cannot be attributed exclusively to the physiological effects of magnetic stimulation. From a public health perspective, the potential relevance of these findings is indirect, as muscular strength and muscular fitness are important components of health-related physical fitness. However, the present findings were obtained in a specific population of trained male collegiate athletes and do not establish the effectiveness of rPMS as a health-promotion intervention in the broader young-adult population. Further sham-controlled studies in more diverse populations are warranted to determine whether rPMS may have a meaningful role as an adjunct to structured exercise beyond athletic training settings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijerph23111380/s1.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and was approved by the Human Research Ethics Committee of the Uttaradit Rajabhat University (protocol no. 075/2568, 30 December 2025).

Informed Consent Statement: All participants provided written informed consent to participate in this study.

Data Availability Statement: De-identified individual-level baseline and week-6 data for all measured study outcomes, together with baseline participant characteristics and explanatory notes, are provided in Supplementary File S1. IL-6 values are retained for transparency, explicitly flagged as not quantitatively validated, and excluded from inferential conclusions.

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Abbreviations

The following abbreviations are used in this manuscript:

CERT	Consensus on Exercise Reporting Template
CRP	C-reactive protein
HIIT	high-intensity interval training
HRmax	maximal heart rate
IGF-1	insulin-like growth factor-1
IL-6	interleukin-6
%MSO	maximum stimulator output
1RM	one-repetition maximum
rPMS	repetitive peripheral magnetic stimulation
RPE	rating of perceived exertion
TIDieR	Template for Intervention Description and Replication
TNF-α	tumor necrosis factor-alpha
VO_2max	maximal oxygen uptake

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