https://doi.org/10.47183/mes.2025-367

EFFECT OF RHYTHMIC PERIPHERAL MAGNETIC STIMULATION ON THE FUNCTIONAL CAPABILITIES OF THE MUSCULOSKELETAL SYSTEM OF MALE ATHLETES

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Introduction. Previous research has demonstrated the high efficacy of peripheral magnetic stimulation (PMS) in the postoperative period of athletes for increasing strength and muscle tissue hypertrophy. Scientific and experimental substantiation for the use of PMS within the medical and biological support system for elite sports to improve the functional capabilities of the musculoskeletal system (MSS) in healthy athletes represents a relevant research task.

Objective. Study of the effect of rhythmic PMS on the functional capabilities of MSS in male athletes.

Materials and methods. The study was conducted at the Yug-Sport Rehabilitation and Recovery Center for Athletes in Kislovodsk (Russia). In total, 38 highly qualified male athletes were involved, who were divided into three groups: experimental group 1 (EG1) — 15 individuals, experimental group 2 (EG2) — 8 individuals, and the control group (CG) — 15 individuals. PMS was administered using a BTL-6000 Super Inductive System high-intensity magnetotherapy device, following two protocols for modulation and stimulation frequency. In the athletes, the following parameters were assessed: electrophysiological studies (electroneuromyography), rheovasography, and dynamometry of the lower limbs. These assessments were conducted before the intervention, after the first session, and after a course of eight PMS treatment sessions. In the control group, PMS was not applied. All parameters in this group were measured before and after the training camp period.

Results. The application of PMS to the posterior aspect of the left and right thigh at an intensity above the motor threshold (25–80%) and a frequency modulation of 1–150 Hz (EG1) contributed to a decrease in latency parameters and an increase in motor conduction velocity, as well as the M response amplitude and area upon stimulation of the peroneal nerve. The application of PMS to the same area and at the same intensity, but with a frequency modulation of 1–50 Hz (EG2), increased the M response amplitude and area. An increase in peripheral hemodynamics in the vessels of the lower limbs and in the strength parameters of the hip flexor and extensor muscles was revealed, along with an improvement in intermuscular coordination.

Conclusions. The application of PMS in highly qualified athletes contributes to an increase in the functional capabilities of MSS, manifested in improved parameters of neuromuscular transmission, peripheral hemodynamics, and strength capabilities.

Keywords: athletes; functional capacity; musculoskeletal system; neuromuscular system; peripheral magnetic stimulation; physiotherapy; electroneuromyography; hemodynamics; muscle strength

For citation: Koryagina Y.V., Kushnareva J.V., Nopin S.V., Abutalimova S.M., Mitin I.N. Effect of rhythmic peripheral magnetic stimulation on the functional capabilities of the musculoskeletal system of male athletes. *Extreme Medicine.* 2026;28(1):88–94. https://doi.org/10.47183/mes.2025-367

Funding: the study was conducted in accordance with contract No. 31V/CSM/23 dated 07.07.2023, for the execution of a component of applied research work on the topic: “Development and Scientific-Experimental Substantiation of the Application of Peripheral Magnetic Stimulation in the Medical-Biological Support System of Elite Sports for the Recovery and Improvement of the Functional State of the Neuromuscular Apparatus in Athletes” (code: “Magnet-23”).

Compliance with the ethical principles: the study was conducted in accordance with the ethical principles for medical research involving human subjects outlined in the 2013 Helsinki Declaration. The study was approved by the Local Ethical Committee for the Review of Biomedical Research at the North Caucasian Federal Research and Clinical Center of the FMBA of Russia (Minutes No. 2, of 30.06.2023). All participants provided written informed consent to participate in the study, as well as permission for the processing of their personal data.

Potential conflict of interest: the authors declare no conflict of interest.

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Received: 4 Aug. 2025 **Revised:** 6 Oct. 2025 **Accepted:** 31 Oct. 2025 **Online first:** 17 Dec. 2025

УДК 615.8

ВЛИЯНИЕ ПРИМЕНЕНИЯ РИТМИЧЕСКОЙ ПЕРИФЕРИЧЕСКОЙ МАГНИТНОЙ СТИМУЛЯЦИИ НА ФУНКЦИОНАЛЬНЫЕ ВОЗМОЖНОСТИ ОПОРНО-ДВИГАТЕЛЬНОГО АППАРАТА СПОРТСМЕНОВ-МУЖЧИН

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Введение. Исследования, проведенные специалистами, показали высокую эффективность применения периферической магнитной стимуляции (ПМС) в послеоперационном периоде для повышения силы и гипертрофии мышечной ткани у спортсменов. Актуальным является научно-экспериментальное обоснование применения ПМС в системе медико-биологического обеспечения спорта высших достижений для улучшения функциональных возможностей опорно-двигательного аппарата (ОДА) здоровых спортсменов.

Цель. Изучение влияния применения ритмической ПМС на функциональные возможности ОДА спортсменов-мужчин.
Материалы и методы. Исследование проведено на базе реабилитационно-восстановительного центра для спортсменов ФГБУ «Юг Спорт» в г. Кисловодске. В нем приняли участие 38 спортсменов-мужчин высокой квалификации. Спортсмены были разделены на три группы: опытную группу 1 (ОГ1) — 15 чел., опытную группу 2 (ОГ2) — 8 чел. и контрольную (КГ) — 15 чел. ПМС проводили с помощью системы высокоинтенсивной магнитотерапии BTL-6000 Super Inductive System по двум разным протоколам модуляции и частоты воздействий. До применения, после первого сеанса и после курса из 8 процедур ПМС у спортсменов определялись показатели электронейромиографии, реовазографии и динамометрии нижних конечностей. В контрольной группе спортсменов ПМС не применяли, все показатели исследовали до и после учебно-тренировочных сборов.
Результаты. Применение ПМС на область задней поверхности левого и правого бедра с интенсивностью выше порога моторного ответа (25–80%) и модуляцией частоты 1–150 Гц (ОГ 1) способствовало снижению показателей латентности и увеличению параметров скорости моторного проведения, амплитуды и площади М-ответов при стимуляции малоберцового нерва. Применение ПМС на ту же область и с той же интенсивностью с модуляцией частоты 1–50 Гц (ОГ2) увеличивало показатели амплитуды и площади М-ответов. Выявлено увеличение периферической гемодинамики в сосудах нижних конечностей и параметров силы мышц-сгибателей и разгибателей бедра, улучшение межмышечной координации работы мышц.
Выводы. Применение ПМС у спортсменов высокой квалификации способствует увеличению функциональных возможностей ОДА: параметров нервно-мышечной передачи, периферической гемодинамики и силовых возможностей.

Ключевые слова: спортсмены; функциональные возможности; опорно-двигательный аппарат; нервно-мышечный аппарат; периферическая магнитная стимуляция; физиотерапия; электронейромиография; гемодинамика; сила мышц

Для цитирования: Корягина Ю.В., Кушнарева Ю.В., Нопин С.В., Абуталимова С.М., Митин И.Н. Влияние применения ритмической периферической магнитной стимуляции на функциональные возможности опорно-двигательного аппарата спортсменов-мужчин. *Медицина экстремальных ситуаций*. 2026;28(1):88–94. https://doi.org/10.47183/mes.2025-367

Финансирование: исследование проведено в соответствии с контрактом № 31В/ЦСМ/23 от 07.06.2023 на выполнение составной части прикладной научно-исследовательской работы по теме: «Разработка и научно-экспериментальное обоснование применения периферической магнитной стимуляции в системе медико-биологического обеспечения спорта высших достижений для восстановления и улучшения функционального состояния нейромышечного аппарата спортсменов» (шифр: «Магнит-23»).

Соответствие принципам этики: исследование проводилось в соответствии с этическими принципами медицинских исследований с участием человека, изложенными в Хельсинкской декларации 2013 г. Исследование было одобрено локальным этическим комитетом по экспертизе биомедицинских исследований ФГБУ СКФНКЦ ФМБА России (протокол № 2 от 30.06.2023). Все участники подписали информированное согласие на участие в исследовании, а также разрешение на обработку персональных данных.

Потенциальный конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

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Статья поступила: 04.08.2025 **После доработки:** 06.10.2025 **Принята к публикации:** 31.10.2025 **Online first:** 17.12.2025

INTRODUCTION

Magnetic stimulation is a highly effective treatment method widely used in clinical practice for the therapy and rehabilitation of patients with pathologies of the central and peripheral nervous systems, musculoskeletal system (MSS), and urological diseases [1–3]. In recent years, an increasing number of studies have been published investigating the effects of transcranial and peripheral rhythmic magnetic field exposure on the functional state of organs and systems in athletes [4, 5]. Research results have demonstrated the high efficacy of using peripheral magnetic stimulation (PMS) in the postoperative period to enhance strength and muscle tissue hypertrophy in athletes [6]. Data indicating increased muscle strength performance following a course of PMS have been published [7, 8]. Furthermore, by regulating the frequency characteristics of the magnetic field, it is possible not only to increase strength parameters but also to potentiate the aerobic capacity of the muscular system in athletes [9].

Therefore, scientific and experimental substantiation for the application of PMS within the medical and biological support system of elite sports to enhance the functional capabilities of the MSS in healthy athletes appears a highly relevant research task. In this article, we aim to study the effect of rhythmic PMS on the functional capabilities of MSS in male athletes.

MATERIALS AND METHODS

The study was conducted at the rehabilitation and recovery center for Russian national team athletes, located on the premises of the Yug-Sport center (Kislovodsk, Russia). The study involved 38 highly qualified male athletes engaged in athletics, baseball, cross-country skiing, short track speed skating, kettlebell lifting, and badminton, with a median age of 22 [19; 25] years. The athletes were divided into three groups: experimental group 1 (EG1) — 15 individuals, experimental group 2 (EG2) — 8 individuals, and the control group (CG) — 15 individuals:

- in EG1, the pre-set protocol (A-1012) “Pre-Rehabilitation Preparation” of the device was applied (see Table 1);
- in EG2, the pre-set protocol (A-0012) “Muscle Strengthening” of the device was applied;
- in the CG, PMS was not applied; all parameters were assessed before and after the training camp period.

The inclusion criteria for the study were highly qualified athletes undergoing intensive training loads. The exclusion criteria were refusal to participate in the study, acute illnesses and injuries, presence of contraindications to PMS (general contraindications to physiotherapy, arterial hypotension, clinically significant endocrinopathies (especially hyperthyroidism), bleeding tendency, hemorrhagic diathesis, presence of an implanted pacemaker).

PMS was performed using a BTL-6000 Super Inductive System high-intensity magnetotherapy device, specifically the BTL-6000 Super Inductive System Elite version (BTL Industries Ltd., the UK). The treatment session was conducted with the participant in a prone position, with the center of the applicator positioned at the minimal distance from the skin surface. The stimulation area targeted the posterior aspect of the left and right thigh (corresponding to the projection of the *m. biceps femoris* long head and *m. semimembranosus*). The stimulation intensity was set individually above the motor threshold (25–80%). The total number of sessions was 8, conducted daily.

Before and after the first session, as well as after the course of eight PMS sessions, the following parameters were recorded:

- motor response parameters using stimulation electroneuromyography (ENMG) by a four-channel Neuro-MVP complex (Neurosoft, Russia);
- peripheral hemodynamics via rheovasography (RVG) using a Valent rheography device;
- strength parameters of the thigh muscles via dynamometry using a robotic CON-TREX LP complex (Physiomed Elektromedizin AG).

A movement template (bilateral: extension/flexion, sitting position) was used during the measurement.

Statistical data processing was performed using the Statistica 13.0 software. Standard descriptive statistics measures were calculated (medians (M_e) with upper (Q_1) and lower (Q_3) quartiles). Comparison of parameters was carried out using non-parametric tests: Wilcoxon test for analyzing data dynamics in dependent groups, Dunn's test for assessing differences between two independent groups, Kruskal–Wallis test for comparisons between three independent groups.

RESULTS

During the study, when comparing the parameters of the neuromuscular apparatus (NMA) based on ENMG data before PMS application in athletes of EG1, EG2, and CG using the Kruskal–Wallis and Dunn tests, statistically significant differences were found only for the duration and latency of the M response, which were higher in the athletes of the CG ($p < 0.05$).

The conducted analysis of the dynamics of motor response parameters during PMS in athletes of EG1 showed a statistically significant increase in:

- motor conduction velocity at the stimulation point "fibular head" on the right side after the PMS course (dynamics: pre-PMS 49.3 [47.7; 50.5] m/s, after the first session 50.3 [48.3; 51.4] m/s, after the PMS course 50 [48.7; 52] m/s ($p < 0.03$));
- motor conduction velocity at the stimulation point "popliteal fossa" on the left ($p < 0.02$);
- M-wave amplitude at the stimulation points "fibular head" ($p < 0.05$) and "popliteal fossa" on the left ($p < 0.03$);
- a decrease in latency at the stimulation point "tarsus" on the left ($p < 0.02$) (see Table 2).

A trend toward an increase in the M-wave area was noted at all stimulation points, both on the right and left sides.

The conducted analysis of the results of PMS application in athletes of EG2 showed a statistically significant increase in:

Table 1. Peripheral magnetic stimulation protocol parameters

PMS modes	Groups	
	EG1	**EG2**
Frequency modulation, Hz	1–150	1–50
Sequence, frequency (Hz), and duration (s) of frequency modulation sections	1. Variable (150 Hz), 30 s 2. No modulation (0 Hz), 30 s 3. No modulation (150 Hz), 15 s 4. Variable (1 Hz), 45 s 5. No modulation (150 Hz), 15 s 6. No modulation (1 Hz), 45 s 7. Trapezoidal (25–45 Hz), 240 s 8. No modulation (1 Hz), 60 s 9. Variable (50 Hz), 30 s 10. Variable (1 Hz), 30 s	1. Variable (15–50 Hz), 30 s 2. No modulation (1 Hz), 30 s 3. Trapezoidal (1–15 Hz), 120 s 4. No modulation (1 Hz), 60 s 5. Trapezoidal (15–30 Hz), 120 s 6. No modulation (1 Hz), 60 s 7. Trapezoidal (30–40 Hz), 120 s 8. No modulation (1 Hz), 60 s 9. Trapezoidal (40–50 Hz), 120 s 10. No modulation (1 Hz), 60 s
Procedure duration	10 min per zone	13 min per zone

Table compiled by the authors based on original data

Note: PMS — peripheral magnetic stimulation; EG1 — experimental group 1; EG2 — experimental group 2.

Table 2. **Parameters of the motor response from the *m. extensor digitorum brevis* (by the left *n. peroneus*) in athletes of experimental group 1 during peripheral magnetic stimulation, *n* = 15**

Parameters	Normal value	Before the 1st session	PMS	
			After the 1st session	After the course
Stimulation point "Tarsus"				
Terminal latency, ms	–	3.7 [3.5; 3.9]	3.6 [3.2; 3.9]†	3.5 [3.1; 4.3]†
Amplitude, mV	>3	8.5 [5.2; 10.4]	7.9 [5.6; 10.1]	8.4 [7.3; 11.7]
Duration, ms	–	5.95 [5.55; 6.35]	5.9 [5.5; 6.45]	5.82 [5.65; 6.7]
Area, mV × ms	–	22.4 [15.6; 32]	23.1 [19.6; 27.9]	26.9 [22.8; 33.7]
Residual latency, ms	<3	2.37 [2.01; 2.57]	2.27 [1.74; 2.51]	1.99 [1.79; 2.77]**
Stimulation point "Fibular head"				
Terminal latency, ms	–	11 [10.2;11.4]	10.8 [10; 11.1]	10.8 [9.9; 11.1]
Amplitude, mV	>3	7.5 [6; 10.4]	8.3 [5.1; 9.9]	7.9 [7.1; 11]*
Duration, ms	–	6.42 [5.9; 7.1]	6.38 [6.15; 7.05]	6.45 [5.9; 6.9]
Area, mV × ms	–	25.2 [19.9; 31.8]	23.8 [19.6; 32.7]	27.8 [21.5; 33.6]
Velocity, m/s	>40	48.8 [46.7; 50.7]	50 [48.3; 51.7]	49.6 [47.7; 51.3]
Stimulation point "Popliteal fossa"				
Terminal latency, ms	–	12.8 [12.5; 13.5]	12.7 [12; 13.2]*	12.7 [11.9; 12.9]
Amplitude, mV	>3	7.9 [6.2; 10.4]	8 [5.8; 10.2]	8.4 [7; 11.8]**
Duration, ms	–	6.7 [5.83; 7.11]	6.45 [5.97; 7.4]	6.5 [5.86; 7.57]
Area, mV × ms	–	27.7 [19.5; 33.7]	24.5 [19.2; 32.5]	28.6 [22.4; 37.5]
Velocity, m/s	>40	51.4 [48.3; 55.6]	52.6 [48.8; 55.6]	56.4 [51.2; 58.9]**

Table compiled by the authors based on original data

Note: PMS — peripheral magnetic stimulation; data are presented as median with lower and upper quartiles M_e [Q_1; Q_3]; *n* — number of athletes in the group; *p* — statistically significant differences from the parameter before the 1st session; * — $p < 0.05$; † — $p < 0.03$; ** — $p < 0.02$; "–" — data not available.

- M-wave amplitude at the stimulation points "tarsus" ($p < 0.03$), "fibular head" ($p < 0.04$), and "popliteal fossa" ($p < 0.04$) on the right side (Fig. 1A);
- M-wave area at the stimulation points "tarsus" ($p < 0.03$), "fibular head" ($p < 0.01$), and "popliteal fossa" ($p < 0.03$) on the right side (Fig. 1B).

A similar increase in the parameters of M response amplitude and area were observed in athletes of EG2 on the left side at all stimulation points. In the CG, a decrease in motor conduction velocity was observed at the stimulation point "popliteal fossa" on the left side (before the training camp — 54 [51.2; 57.8] m/s, after — 48.1 [44.7; 52.8] m/s; $p < 0.02$).

The comparison of RVG parameters before PMS application in athletes of EG1, EG2, and CG revealed statistically significant differences only in the elasticity modulus (EM) parameters, which were higher in the CG ($p < 0.04$). The analysis of lower limb hemodynamic parameters in athletes of EG1 showed a statistically significant increase after the first session in the "left foot" segment for the following parameters:

- rheographic index 1.4 [0.97; 1.71] conv. units ($p < 0.05$) compared to pre-PMS values of 1.13 [0.93; 1.29] conv. units and post-course PMS values of 1.32 [1.07; 1.49] conv. units;
- propagation time of rheographic waves pre-PMS 0.3 [0.28; 0.3] s; after the first session 0.32 [0.3; 0.32] s ($p < 0.006$); post-course 0.3 [0.29; 0.31] s.

In the "right foot" segment, the duration of maximum systolic vessel filling increased: pre-PMS 0.13 [0.115; 0.142] s; after the first session 0.142 [0.132; 0.154] s ($p < 0.05$); post-course 0.119 [0.107; 0.15] s.

In the "left shin" segment, after the first session, the propagation time of rheographic waves increased to 0.28 [0.26; 0.29] s ($p < 0.05$) against the background of pre-PMS values of 0.27 [0.26; 0.28] s and post-therapy course values of 0.27 [0.26; 0.29] s.

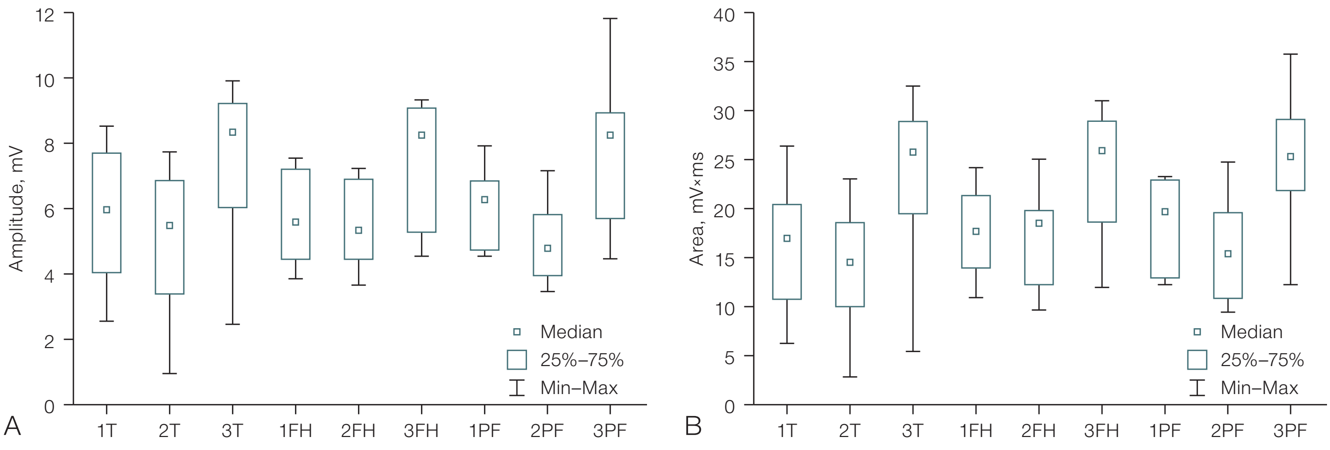

Figure prepared by the authors based on original data

Fig. 1. Dynamics of amplitude (A) and area (B) of the M response at the stimulation points “tarsus”, “fibular head”, and “popliteal fossa” (*n. peroneus*) in athletes of experimental group 2 during peripheral magnetic stimulation, *n* = 8: *n* — number of athletes in the group; T — tarsus; FH — fibular head; PF — popliteal fossa; 1 — before the 1st session; 2 — after the 1st session; 3 — after a course of peripheral magnetic stimulation

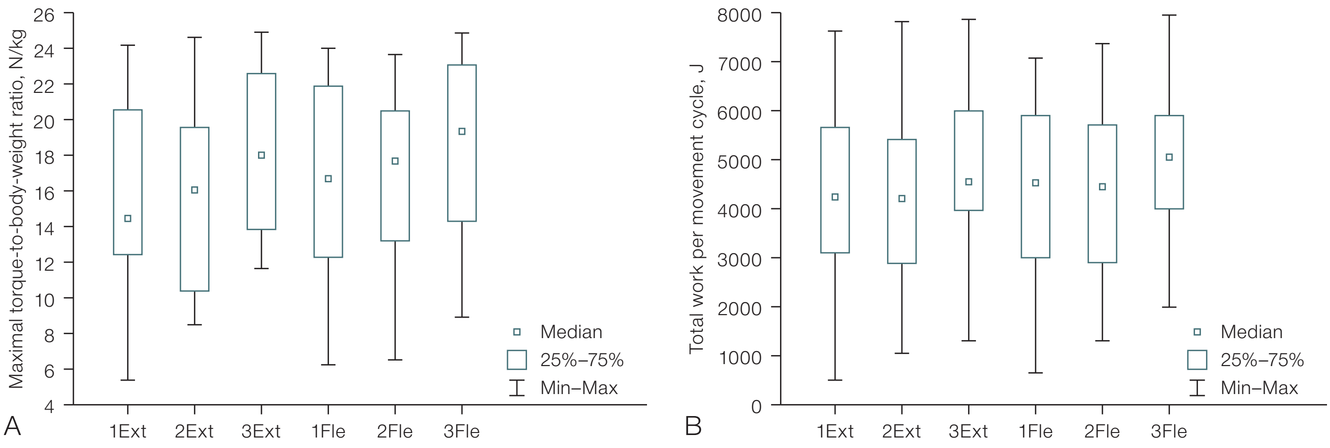

Figure prepared by the authors based on original data

Fig. 2. Dynamics of the mean maximal torque-to-body-weight ratio (A) and total work per movement cycle (B) in athletes of experimental group 1, *n* = 15: *n* — number of athletes in the group; Ext — extensor muscles; Fle — flexor muscles; 1 — before the 1st session; 2 — after the 1st session; 3 — after a course of peripheral magnetic stimulation

In the “right shin” segment, the diastolic index was higher both after the first session and after the entire course (pre-PMS — 0.43 [0.31; 0.46] conv. units; after the first session — 0.52 [0.44; 0.61] conv. units, $p < 0.04$; after the course — 0.5 [0.36; 0.59] conv. units, $p < 0.04$).

After the full PMS course, the blood flow asymmetry coefficient in the feet decreased threefold (pre-PMS — 34 [12; 56]; after the 1st session — 13 [7; 27]; after the course — 11 [4; 24], $p < 0.03$). In the CG athletes, the diastolic index decreased statistically significantly in the “left foot” segment (pre-training camp — 0.47 [0.39; 0.53] conv. units and post-training camp — 0.38 [0.32; 0.44] conv. units, $p < 0.02$) and the “right foot” segment (pre-training camp — 0.46 [0.41; 0.56] conv. units and post-training camp — 0.38 [0.36; 0.45] conv. units, $p < 0.05$).

The comparison of dynamometry parameters in athletes of EG1 and CG before the application of PMS revealed no statistically significant differences. The analysis of the dynamics of thigh muscle strength in men of EG1 showed a statistically significant increase in the strength parameters of the hip extensor and flexor muscles after completing the entire course. Specifically, for the extensor muscles, the following parameters increased:

- maximum torque strength, in newtons (N): pre-PMS — 1475 [1277; 1714] N; after the first session — 1442.5 [1034; 1629] N; after the course — 1610 [1277; 2018] N, $p < 0.05$;
- mean maximal torque-to-body-weight ratio, N: pre-PMS — 14.45 [12.4; 20.52] N; after the first session — 16.01 [10.39; 19.53] N; after the course — 17.97 [13.84; 22.56] N, $p < 0.03$ (Fig. 2A).

In flexor muscles, a statistically significant increase in the following parameters was observed:

- mean maximal power per movement cycle, N: before PMS — 128.3 [91; 163] N; after the first session — 116.2 [83.2; 170.9] N; after the course — 140.1 [117.1; 175.5] N; $p < 0.04$;

- mean work per cycle (per movement direction), normalized to body weight, N: before PMS — 226 [150.5; 293] N; after the first session — 221.95 [144.7; 284.3] N; after the course — 252.2 [199.6; 294.2] N; $p < 0.05$;
- total work per movement cycle, N: before PMS — 4519.1 [3010.4; 5860.6] N; after the first session — 4438.7 [2894.6; 5686.2] N; after the course — 5044.5 [3992.8; 5883.6] N; $p < 0.05$ (Fig. 2B).

Additionally, after both the single session and the full PMS course, athletes in EG1 showed optimization of extensor and flexor muscle strength. This was reflected in a decrease in the ratio of this parameter (before PMS — 109.6 [101; 123.6]%; after the first session — 105.15 [94.6; 107.7]%; $p < 0.05$; after the course — 103.5 [99.3; 112.2]%; $p < 0.04$). The analysis of dynamometry parameters of the thigh muscles in the CG revealed no statistically significant differences.

DISCUSSION

The application of PMS in clinical practice is widely documented in the scientific literature, particularly in the treatment of myofascial pain syndrome, other MSS disorders, patients with peripheral neuropathic pain, acute and chronic back pain, post-stroke spasticity, paresis, plegia, dysphagia [10–14]. In sports practice, the use of rhythmic PMS is most frequently reported in studies focusing on methods to enhance athlete performance. For instance, applying rhythmic PMS in athletes during isokinetic exercises revealed an increase in muscle aerobic capacity, attributed to higher oxygen uptake at the aerobic and anaerobic thresholds. Additionally, an improvement in muscle strength parameters was observed without an increase in muscle mass [9].

Our study has found that a course of eight PMS treatment sessions applied to the posterior surface of both left and right thighs — using intensities above the motor response threshold (25–80 %) and frequency modulation of 1–150 Hz — led to:

- a reduction in latency values;
- an increase in motor conduction velocity;
- higher amplitude and area of M responses during peroneal nerve stimulation.

A PMS course applied to the same region at the same intensity, but with a frequency modulation of 1–50 Hz, resulted in increased amplitude and area of M responses. These changes indicated the attainment of potentially greater NMA capabilities in improvement of intramuscular coordination mechanisms, activation and synchronization of motor units. This, in turn, contributed to a greater expression of strength capabilities. Dynamometry assessments revealed that athletes exhibited a statistically significant increase in all measured strength parameters of both hip flexor and extensor muscles. Additionally, intermuscular coordination of their activity improved.

The results obtained complement previously published data demonstrating that 10 sessions of PMS applied to the *m. gastrocnemius* during its voluntary contraction in healthy men led to a greater increase in maximal torque (muscle force) and an enhancement of H reflex (Hoffmann's reflex) amplitude [15]. The authors suggest that one mechanism underlying the improvement in strength parameters is an increase in reflex excitability of the corresponding spinal motor neuron pool. The recorded higher strength values result from additional activation of high threshold (fast) motor units [15–17].

Current research identifies enhanced microcirculation in muscle tissue as one of the key mechanisms underlying increased muscle strength. This improvement creates optimal conditions for altering the concentration of potassium, sodium, and calcium ions across semipermeable cell membranes, thereby facilitating depolarization processes and the generation of action potentials [16]. Our study has shown that PMS application enhanced blood flow in athletes. Overall, a review of scientific literature suggests that the applied PMS modulation and frequency parameters contribute to the activation of specific physiological processes, including enhanced metabolic reactions, modulation of neuroplasticity, improved cellular permeability. Collectively, these effects improve the functional state of MSS in athletes.

CONCLUSION

Our study of the effects of rhythmic PMS on the functional capabilities of MSS in male athletes demonstrated that its application with pre-set modulation and frequency parameters leads to statistically significant improvements in neuromuscular transmission parameters, peripheral hemodynamics, and strength capabilities. Therefore, this method can be recommended for inclusion in the biomedical support of athletes to enhance the functional state of MSS and increase strength capabilities.

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Authors' contributions. All authors confirm that their authorship complies with the ICMJE criteria. The main contribution is distributed as follows: Yulia V. Koryagina — supervision during planning and conducting the study, critical analysis of the draft manuscript, making comments and corrections, critical analysis of the work for scientific novelty; Julia V. Kushnareva — collection of experimental data on the PMS use in athletes and source tables preparation; Sergey V. Nopin — data interpretation, study design, final approval of the manuscript; Sabina M. Abutalimova — manuscript drafting; Igor N. Mitin — collection of experimental data on the PMS use in athletes.

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