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Research Article

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Comparison of Single- and Doublex-Coil rPMS Configurations in Physiotherapy: Perception and Field Distribution in Commonly Treated Areas

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Abstract

Background: Repetitive Peripheral Magnetic Stimulation (rPMS) is an established treatment for various musculoskeletal and neurological conditions. Despite its long-term use, rPMS technology in physiotherapy has seen little innovation, with the single-coil configuration remaining standard. Inspired by advances in transcranial stimulation, novel double-coil setups allowing adjustable angulation are now being introduced in physiotherapy and may offer improved targeting of common treatment areas.

Methods: A review of selected 5,390 treatment records identified the four most commonly treated body areas and standard rPMS protocols. Based on this, 28 healthy volunteers assessed perceived intensity, comfort, penetration depth, and field homogeneity of single- and double-coil configurations. These results were compared with COMSOL simulations evaluating magnetic field distribution across various double-coil angles and in comparison to the conventional single-coil setup.

Results: Application of single- and double-coil configurations to commonly treated areas - knee, lower back, shoulder, and hip - revealed notable differences in subjective therapy perception. Patients consistently rated the double-coil setup as more homogeneous and comfortable. Perceived intensity and penetration depth varied with coil angle: at 90° (knee), the double-coil was rated ~30% higher, while at 160° (lower back), the single-coil was perceived as more intense. COMSOL simulations confirmed that smaller coil angles in the double-coil configuration significantly enhance energy delivery, particularly at 4-5 cm depth.

Conclusions: These experimental findings suggest that both the conventional single-coil and the novel double-coil configurations hold potential for physiotherapy applications. While the single-coil setup delivers higher intensity in superficial, anatomically flat regions, the angled dual-coil configuration generates a broader, more uniform field in planar areas and enables deeper, more focused stimulation in curved anatomical regions such as large joints.

Keywords: Magnetic coil; Double coil; Single coil; Super inductive system DuoI; 3D applicator; Magnetic energy; Comsol Multiphysics

Introduction

Repetitive Peripheral Magnetic Stimulation (rPMS), regarded as a modern successor to traditional electrotherapy, has gained increasing attention in recent years due to its enhanced therapeutic efficacy, greater patient

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Vrbová B, et al., J Ortho Sports Med 2025
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comfort, and minimal side effects [1]. This non-invasive technique utilizes time-varying magnetic fields to induce electric currents in peripheral tissues. In contrast to classical electrical stimulation, rPMS generate substantially higher peak magnetic field strengths, allowing for more effective neuromuscular activation while reducing stimulation-induced discomfort. The ability of magnetic fields to penetrate high-resistance tissues, such as skin and subcutaneous fat, helps to bypass cutaneous nociceptors and thus minimizes pain during treatment [2,3]. As a result, rPMS is emerging as a valuable tool in neurological and orthopedic rehabilitation, with promising applications in post-stroke motor recovery, reduction of spasticity, and pain management [4].

Despite more than three decades of rPMS use in physiotherapy, the design of stimulation applicators has remained largely uniform, with minimal exploration of multi-coil configurations or the use of mutually tilted coils. Current rPMS therapy typically relies on static stimulation delivered by a single, large coil positioned over the treatment area. From a technological perspective, however, this approach may be considered suboptimal. The high voltages and currents required to achieve effective magnetic nerve stimulation can result in significant thermal stress and overheating of the coil. This raises the question of whether a multi-coil design, optimized for specific anatomical regions, might provide a more efficient alternative. Rather than relying on a single source, deep tissue stimulation could instead result from the cumulative effect of overlapping magnetic fields generated by multiple coils. Improved control over magnetic field distribution may enhance stimulation efficacy while maintaining or even reducing energy consumption [5].

Innovations in coil design within the field of Transcranial Magnetic Stimulation (TMS) have increasingly focused on incorporating multi-coil arrays and adjustable angulation to improve targeting precision and magnetic field penetration. In addition to the traditional single-coil approach, figure-8 coils and double-cone coils have been introduced. The double-cone coil consists of two coils positioned at an angle between 95° and 120°, a configuration that, according to existing evidence, enables deeper field penetration and thus facilitates stimulation of subcortical brain structures [6-8]. However, this increased depth of stimulation with double-cone coils has been associated with higher energy delivery, which can lead to increased patient discomfort [6].

In the field of physiotherapy and rehabilitation, similar research is virtually nonexistent. Goetz et al. have suggested the potential of novel coil geometries for use in rPMS; however, significant innovation in this area has yet to be translated into clinical practice [9]. Nevertheless physiotherapy and rehabilitation represent disciplines that demand adaptable technologies capable of addressing a wide range of indications and anatomical regions, where treatment must be tailored as precisely as possible to the specific body area and condition of each patient. The shape of the treated area, the depth of the target tissue, and the overall anatomical complexity can vary significantly between different body regions and among individual patients, making the established single-coil approach potentially insufficient for effective targeting in all cases.

A novel double-coil applicator, capable of mutual tilting between coils, offers the first solution of its kind for adapting to different body areas. This study aims to compare the double-coil configuration with a conventional single-coil approach in treating the four most commonly targeted areas, based on subjective patient perception and theoretically calculated values of delivered magnetic energy. Impact of coil geometry on performance across commonly treated body regions, through a combination of clinical data analysis, volunteer-based assessments, and finite element simulations using COMSOL Multiphysics.

Materials and Methods

Analysis of treatment logs

Out of a total of 7,932 device logs collected from multiple rehabilitation facilities, 5,390 therapy setting records were included for analysis. Records were excluded if they were incomplete, lacked information on the treatment area, or involved prematurely terminated therapy sessions. A list of the most frequently treated body regions was compiled, and the subsequent phase of the study- Experimental Procedure and Subjective Evaluation, described below- was applied to the four most common areas: knee, lower back, shoulder, and hip. Additionally, the most frequently used protocols were identified for each region. A detailed analysis of these records is provided in the Results section. The device logs did not contain any personally identifiable or sensitive data that would require patient consent for processing.

Experimental procedure and subjective evaluation

Adult healthy volunteers willing to participate were included in an experiment comparing the subjective intensity of stimulation using single-coil (Focused Field) and double-coil (3D) applicators, both part of the Super Inductive System Duo (BTL Industries, Ltd.). Exclusion criteria included pregnancy; the presence of implanted devices such as cardiac pacemakers, defibrillators, neurostimulators, electronic or metallic implants (including intrauterine devices containing metal); drug delivery pumps; or any history, pain or existing medical condition affecting the treated region. Individuals with a history of seizures, severe or life-threatening medical conditions, pulmonary or renal insufficiency, cardiac disorders, fever, malignant tumors, or decompensated hemorrhagic, coagulation, or cardiovascular disorders were also excluded from the study. The experiment was conducted

Vrbová B, et al., J Ortho Sports Med 2025
DOI:10.26502/josm.511500214

in accordance with the ethical principles outlined in the Declaration of Helsinki and its subsequent amendments. All participants were informed about the nature and purpose of the study and provided written informed consent prior to inclusion.

Prior to the initiation of treatment, the participant was instructed to assume a supine, prone, or seated position, depending on the anatomical region targeted for therapy.

For knee, shoulder, and hip treatments, a single-coil applicator was used on one limb and a double-coil applicator on the contralateral limb (Figure 1-3). For the lower back, each coil configuration was applied sequentially (Figure 4). The treatment order was randomly assigned using a coin toss, such that half of the participants received the single-coil applicator first, while the other half received the double-coil applicator first. Prior to the main stimulation, a preliminary pulse train- referred to as the targeting mode- was applied to the patient. This phase allowed for observation of the patient's physiological response and collection of subjective feedback to ensure accurate positioning of the applicator. During the stimulation phase, both applicators were used at the same intensity for each participant. The same factory-preset therapeutic protocol was applied for both coil configurations.

A 0 to 10 scale, where 0 represented the lowest and 10 the highest perceived value, was used in this study to evaluate subjective perceptions of stimulation intensity, depth of penetration, comfort, and homogeneity. Participants continuously assessed these parameters during the stimulation sessions (Figure 1).

Given the pilot nature of the study, a sample size of 30 participants was selected. Data processing and subsequent statistical analysis were conducted using a custom script

Figure 1: Experimental setup for comparing subjective perceptions during knee stimulation using single-coil (left limb) and double-coil (right limb) configurations.

Figure 2: Experimental setup for comparing subjective perceptions during shoulder stimulation using single-coil (left limb) and double-coil (right limb) configurations.

Figure 3: Experimental setup for comparing subjective perceptions during hip stimulation using single-coil (left limb) and double-coil (right limb) configurations.

Figure 4: Experimental setups for comparing subjective perceptions during low back stimulation using single-coil (left) and double-coil (right) configurations.

Vrbová B, et al., J Ortho Sports Med 2025
DOI:10.26502/josm.511500214

developed in the MATLAB environment. Since the Shapiro–Wilk test indicated a deviation from normal distribution, the results are presented as medians with interquartile ranges (IQR). Comparative analysis between the single- and double-coil configurations was performed using the non-parametric Mann–Whitney U test. A p-value of less than 0.05 was considered statistically significant.

Theoretical modeling and simulation

For the purpose of theoretical calculation of the magnetic energy delivered by the single-coil and double-coil rPMS configurations with varying mutual tilt angles, a simplified finite element model was constructed. The model consisted of an array of spherical volumes with a radius of 1 mm, spaced 6.7 mm apart. The coil models were based on the characteristics of commercially available rPMS applicators (Super Inductive System Duo, BTL Industries, Ltd.), as illustrated in Figure 5. The coil geometry in the model was explicitly modified to accurately reflect the physical configuration of the actual coils. To simplify the simulation, other components of the applicator were excluded, as they do not significantly influence the simulation results.

Figure 5: Single-coil (left) and double-coil (right) configurations, which served as the basis for the simulation models. Courtesy of BTL Industries, Ltd. Used with permission.

While the single-coil configuration was applied perpendicularly to the spherical array without any tilt, the double-coil configuration was simulated with progressive angular adjustments between the coils, ranging from 140° to 90°. The total magnetic energy absorbed by individual spheres located at depths from 1 cm to 5 cm, in 1 cm increments, was calculated using the following formula:

$$W = \iiint W_m dV = \iiint \left(\frac{1}{2} B \cdot H\right) dV$$

where W_m is the magnetic energy density, B is the magnetic flux density (in tesla) and H is the magnetic field strength (in A/m), and dV represents the differential volume element.

The complete simulation setup implemented in the COMSOL Multiphysics environment is presented in Figure 6.

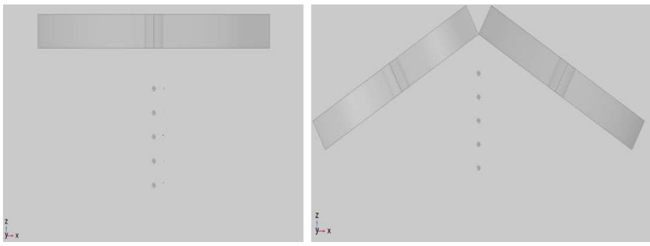
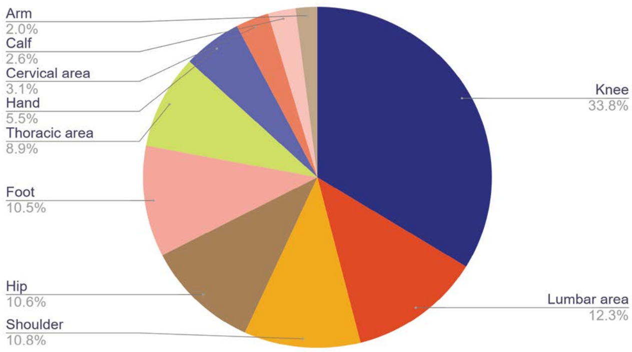


Figure 6: Geometry of the spherical volumes array and location of stimulation coils for single (left) and double (right) coil configurations.

Results

Analysis of treatment logs

The knee is the most frequently treated area, followed by the lumbar region, shoulder, and hip. The distribution of treated anatomical regions is illustrated in the pie chart presented in Figure 7. Table 1 summarizes the treatment protocols used for the four most commonly treated areas, along with their respective frequencies. Notably, three of these four regions-namely the knee, shoulder, and hip- are large joints that are commonly affected by arthrosis and other conditions requiring analgesic protocols.



FiguFigure 1re 7: Pie chart illustrating the distribution of individual body areas treated using rPMS.

Experimental procedure and subjective evaluation

Of the 30 volunteers recruited, 28 completed the experimental therapy (mean age 33.32 ± 4.64 years; 11 men and 17 women). One participant withdrew due to anterior cruciate ligament (ACL) reconstruction of the left knee, and another due to acute low back pain. Overall, the therapies were well tolerated, with no reports of adverse effects or significant discomfort. The results of the subjective assessments regarding the perception of sensations during stimulation with single and double coil configurations are summarized in Table 2.

The results demonstrate that subjective perceptions of specific indicators vary significantly across treatment areas. For the knee, stimulation using the double-coil configuration yielded statistically significant improvements in perceived

Table 1: The four most frequently treated anatomical regions using rPMS and the corresponding frequencies of applied treatment protocols.

Knee	1624
Arthrosis	423
Analgesia - chronic	219
Analgesia - acute	178
Gonalgia - chronic	158
Circulation and trophic improvement - chronic	115
Healing enhancement - acute	113
Healing enhancement - chronic	95
Tendinopathy	68
Distortion - subacute	52
Swelling reduction	48
Gonalgia - acute	45
Muscle regeneration	39
Other	71
Lumbar area	590
Lumbosacral syndrome - chronic	151
Analgesia - acute	111
Analgesia - chronic	104
Lumbosacral syndrome - acute	81
Myalgia - chronic	67
Muscle relaxation	45
Other	31
Shoulder	520
Analgesia - chronic	137
Tendinopathy	93
Bursitis - acute	68
Arthrosis - chronic	65
Calcification - extraarticular	48
Impingement syndrome	42
Circulation and trophic improvement - chronic	37
Other	30
Hip	511
Arthrosis - chronic	142
Analgesia - acute	93
Calcification - extraarticular	58
Impingement syndrome	55
Muscle relaxation	49
Analgesia - chronic	45
Healing enhancement - acute	42
Other	27

Table 2: Summary of the results reflecting participants' subjective perceptions during the actual therapy sessions. The values are presented as median (interquartile range). P-values less than 0.05 were considered statistically significant.

	Single coil	**Double coil**	**% Δ**	**Mann-Whitney U test (P < 0.05)**
Knee				
Intensity	4 (1)	7 (2)	30.95% (9.82%)	<0.001
Comfort	6.5 (2.25)	8 (2.25)	11.11% (19.05%)	0.13
Penetration depth	5 (2)	7 (1.25)	33.33% (22.32%)	<0.001
Homogeneity	6 (2)	9 (3)	33.33% (33.73%)	<0.001
Low back				
Intensity	6 (1)	4 (1)	-50.00% (55.00%)	<0.001
Comfort	5.5 (3)	7.5 (3)	26.79% (18.33%)	<0.001
Penetration depth	7 (2)	6 (1)	-7.14% (34.17%)	0.294
Homogeneity	7 (2)	8 (3.25)	13.39% (13.89%)	0.019
Shoulder				
Intensity	5.5 (1)	6 (1)	14.29% (32.14%)	0.029
Comfort	6 (1)	8 (2)	22.22% (19.49%)	<0.001
Penetration depth	7 (1)	7 (1)	12.50% (16.67%)	0.009
Homogeneity	6 (0.25)	9 (0.25)	33.33% (8.33%)	<0.001
Hip				
Intensity	6 (4)	9 (6)	18.33% (28.57%)	0.024
Comfort	4 (1)	8 (2)	35.42% (13.84%)	<0.001
Penetration depth	4 (1)	6.5 (1)	14.29% (25.89%)	0.004
Homogeneity	4 (1.25)	9.5 (1)	41.43% (17.50%)	<0.001

%Δ: Percentage change calculated as the average of individual participants' reported percentage differences

Vrbová B, et al., J Ortho Sports Med 2025
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intensity, depth of penetration, and field homogeneity, without a reduction in participant-reported comfort compared to the single-coil configuration. For parameters showing statistical significance, percentage differences exceeded 30%. These outcomes are depicted in the box plot in Figure 8.

In the case of the lumbar region, single-coil stimulation was perceived as more intense, with differences reaching up to 50%. However, comfort ratings and perceived field homogeneity favored the double-coil setup, both with statistically significant differences. Although the single coil was associated with greater perceived depth of penetration, this difference did not reach statistical significance. These findings are illustrated in the box plot presented in Figure 9.

During stimulation of both the shoulder and hip regions, all evaluated parameters favored the double-coil configuration, with statistically significant differences observed in comparison to the single-coil setup. The most pronounced improvements were reported in perceived field homogeneity, followed by treatment comfort. In contrast, perceived intensity and penetration depth showed only modest differences between the two configurations, particularly when compared to the more substantial effects noted during knee stimulation (Figure 10,11).

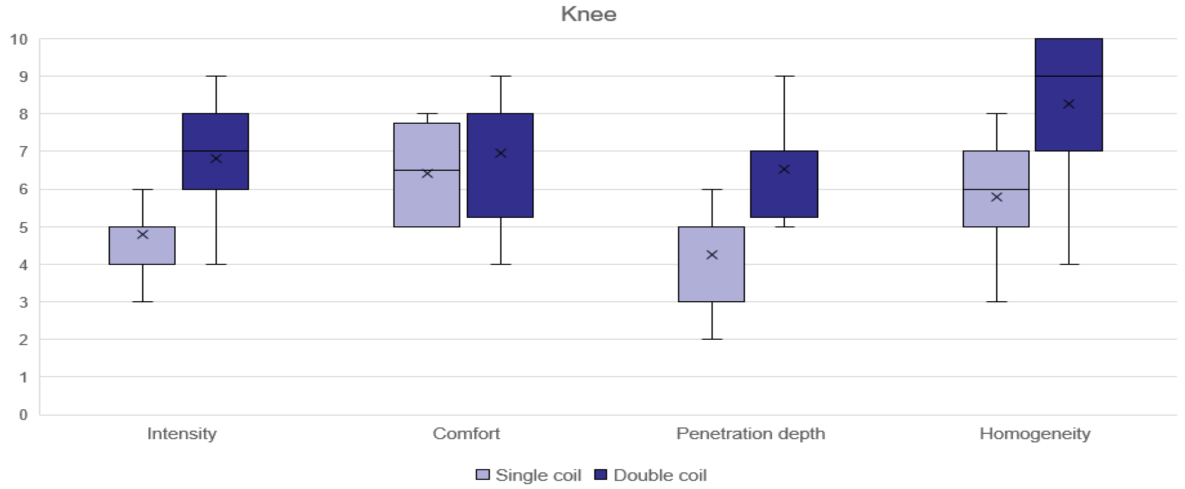

Figure 8: Box plots illustrating the distribution of measured values for intensity, depth of penetration, field homogeneity, and comfort during knee stimulation with single-coil and double-coil configurations. Boxes represent the interquartile range (IQR), with the horizontal line indicating the median and the cross mark denoting the mean value. Whiskers extend to the minimum and maximum values.

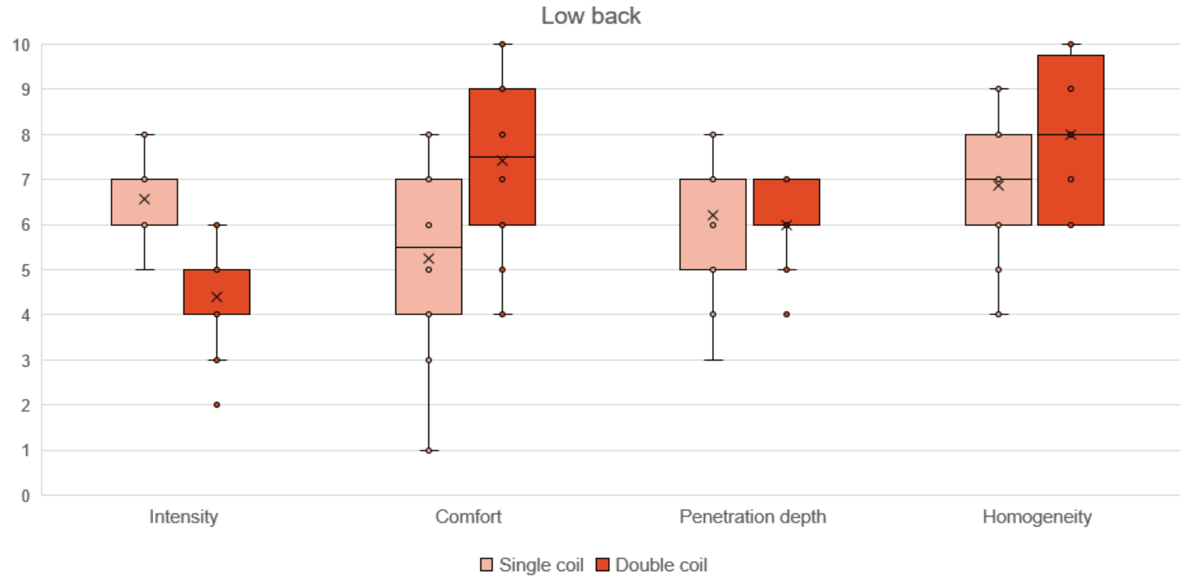

Figure 9: Box plots illustrating the distribution of measured values for intensity, depth of penetration, field homogeneity, and comfort during low back stimulation with single-coil and double-coil configurations. Boxes represent the interquartile range (IQR), with the horizontal line indicating the median and the cross mark denoting the mean value. Whiskers extend to the minimum and maximum values.

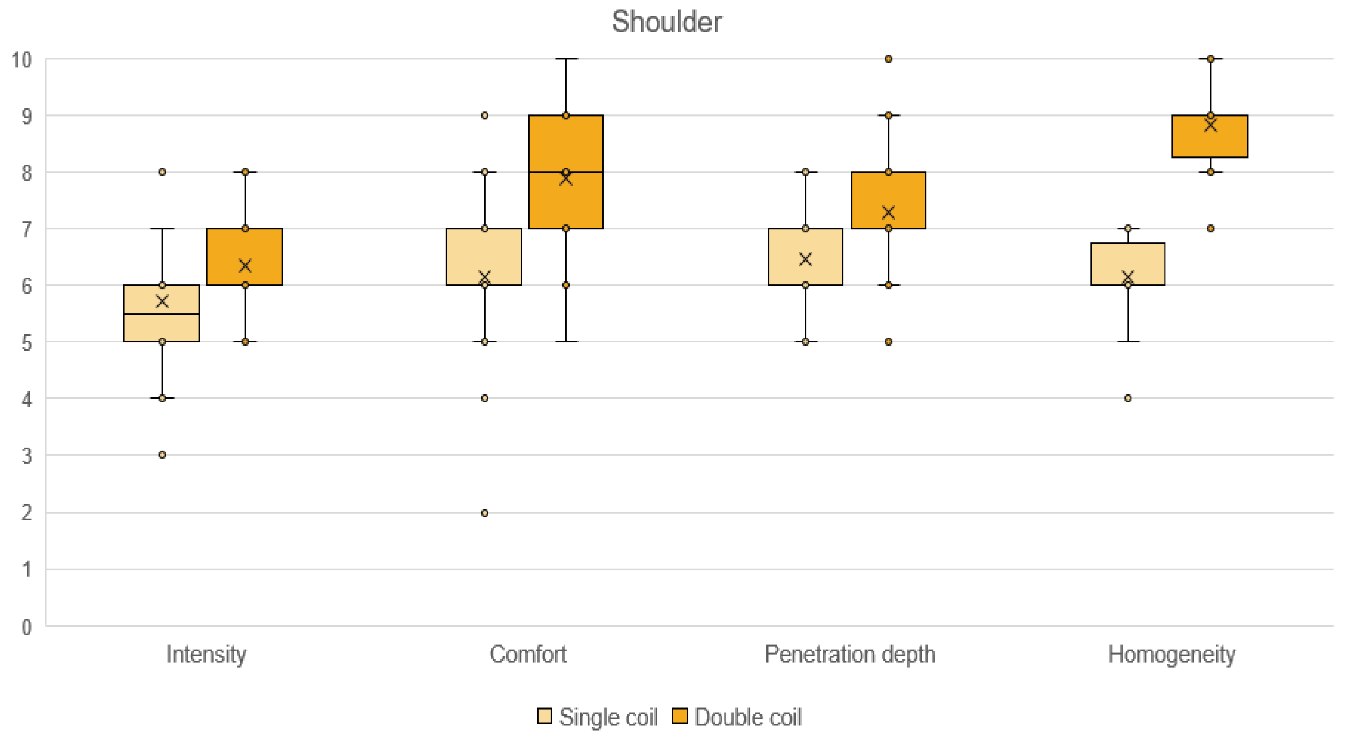

Figure 10: Box plots illustrating the distribution of measured values for intensity, depth of penetration, field homogeneity, and comfort during shoulder stimulation with single-coil and double-coil configurations. Boxes represent the interquartile range (IQR), with the horizontal line indicating the median and the cross mark denoting the mean value. Whiskers extend to the minimum and maximum values.

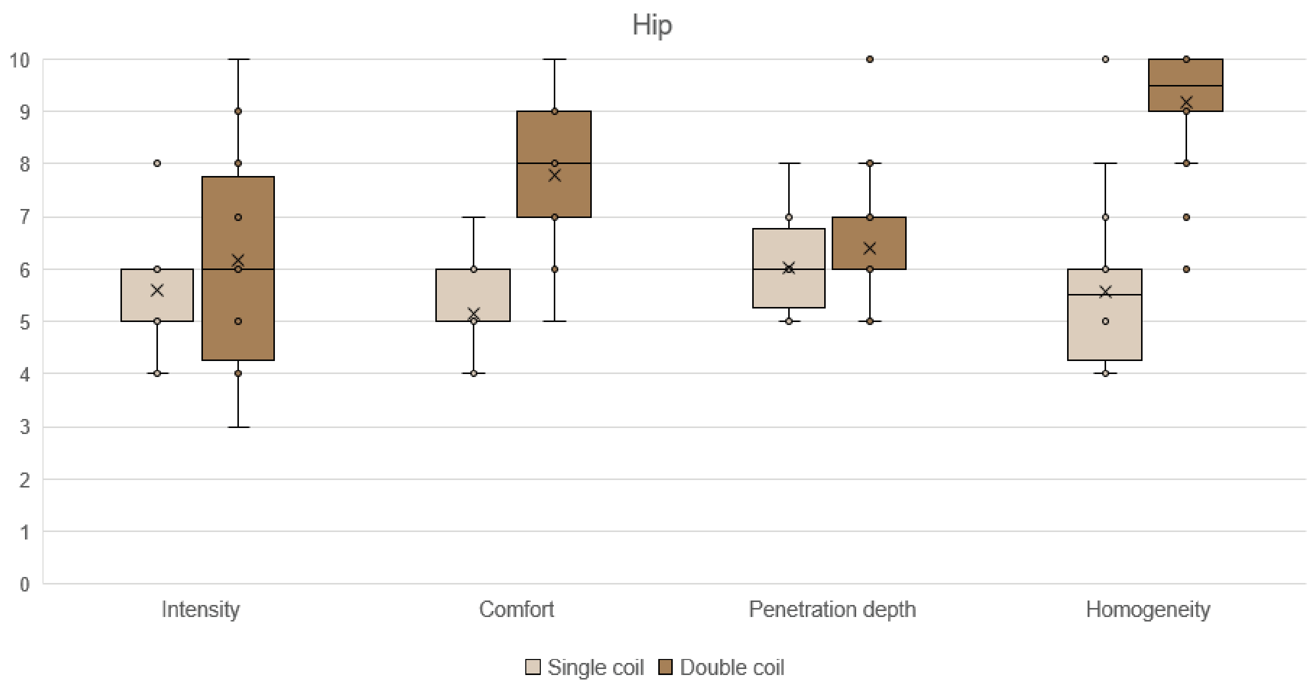

Figure 11: Box plots illustrating the distribution of measured values for intensity, depth of penetration, field homogeneity, and comfort during hip stimulation with single-coil and double-coil configurations. Boxes represent the interquartile range (IQR), with the horizontal line indicating the median and the cross mark denoting the mean value. Whiskers extend to the minimum and maximum values.

Vrbová B, et al., J Ortho Sports Med 2025
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Theoretical modeling and simulation

The results of the COMSOL simulation are numerically presented in Table 3. These results demonstrate that the angle between the coils in the double-coil configuration significantly influences the magnetic energy absorbed in the modeled tissue. While the single-coil setup generates higher magnetic energy at all depths compared to the double-coil configuration with a 140° inter-coil angle, the situation changes markedly at smaller angles. At 120° and particularly at 90°, the double-coil configuration delivers significantly higher energies beyond a depth of 3 cm. At 90°, the double-coil setup already exceeds the single-coil energy by nearly 57% at a depth of 2 cm, with the difference increasing to 247% at 4 cm.

Table 3: Magnetic energy (in joules) absorbed by the modeled tissue following stimulation using either a single-coil configuration or a double-coil setup with varying inter-coil angles. The results highlight the influence of coil geometry on energy delivery at different tissue depths.

Depth	Single coil	Double coil 140°	%Δ	Double coil 120°	%Δ	Double coil 90°	%Δ
1 cm	3.50E-04	1.64E-04	-53.14%	2.19E-04	-37.43%	3.31E-04	-5.43%
2 cm	1.85E-04	9.43E-05	-48.97%	1.46E-04	-21.00%	2.90E-04	56.93%
3 cm	6.82E-05	4.96E-05	-27.27%	8.39E-05	23.02%	2.00E-04	193.26%
4 cm	3.31E-05	2.49E-05	-24.77%	4.38E-05	32.33%	1.15E-04	247.43%
5 cm	1.69E-05	1.22E-05	-27.81%	2.16E-05	27.81%	5.80E-05	243.20%

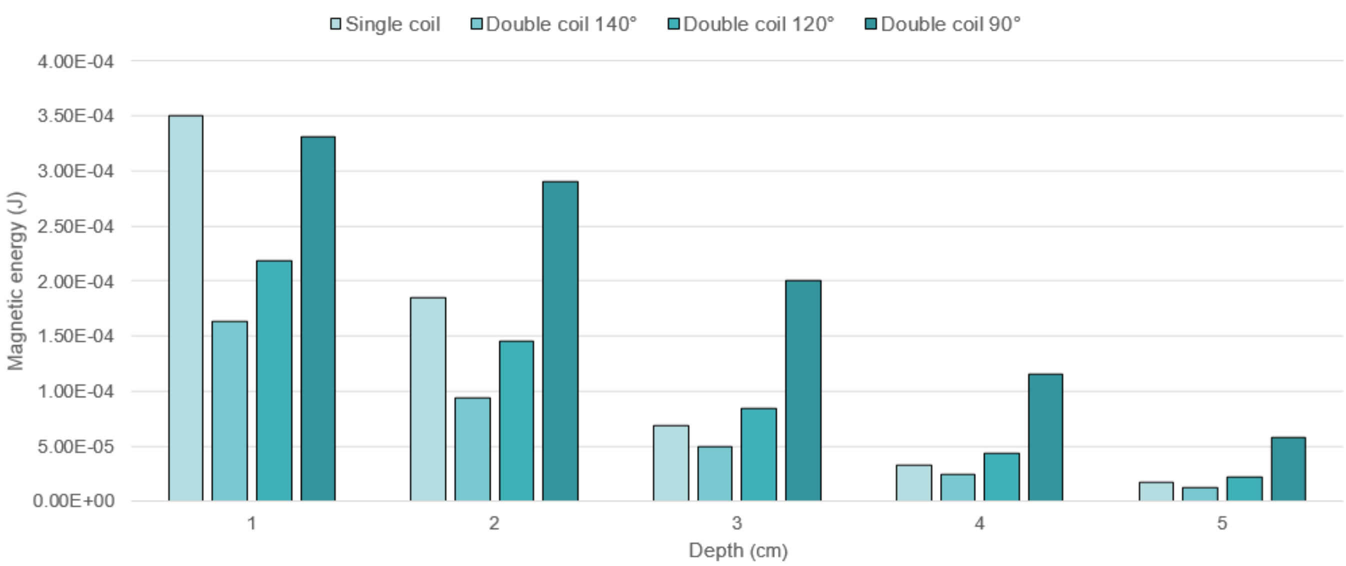

Figure 12: Bar graph comparing COMSOL simulation results for individual coil configurations at specified tissue depths.

Based on the bar chart illustrating the delivered magnetic energy at various tissue depths for different coil configurations (Figure 12), it is evident that the double coil 90° configuration delivers a comparable amount of energy at a depth of 5 cm as the single coil does at 3 cm. This observation suggests that the double coil 90° is capable of reaching significantly deeper tissue layers with equivalent energy output. Specifically, this represents a 67% increase in penetration depth, indicating a substantial advantage in reaching deeper targets while maintaining therapeutic intensity.

Discussion

This study provides a comprehensive analysis of the potential of a novel double-coil rPMS configuration with an adjustable inter-coil angle for stimulating commonly treated anatomical regions. Log data analysis indicated that large joints, such as the knee and hip, may benefit from bilateral stimulation- a capability inherently offered by the double-coil design. This was confirmed through a subjective evaluation in healthy volunteers, where all assessed parameters (intensity, comfort, depth, and homogeneity) favored the double-coil

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Vrbová B, et al., J Ortho Sports Med 2025
DOI:10.26502/josm.511500214

setup for the knee, shoulder, and hip, though with varying magnitudes of difference. In contrast, during lower back stimulation, the single-coil configuration was perceived as more intense, while the double-coil maintained superior comfort and homogeneity.

These findings were further supported by COMSOL Multiphysics simulations, which demonstrated that decreasing the angle between the coils significantly increased magnetic field intensity at greater tissue depths. The underlying mechanism lies in the dual-source nature of the double-coil setup. Unlike the single-coil, where field strength rapidly diminishes with depth, the opposing fields of the double-coil overlap and accumulate in deeper layers, enhancing total energy delivery. Additionally, the double-coil produces a broader and more uniform field, contributing to a more homogeneous stimulation experience.

This deeper, more even stimulation is particularly beneficial for targeting large joints and deeper structures such as the cruciate ligaments and articular cartilage in the knee. Such improvements in field targeting could enhance the therapeutic potential of rPMS in treating osteoarthritis and connective tissue-related pain syndromes. Variations in perceived stimulation across large joints may be attributed to differences in tissue depth, anatomical curvature, and the slightly larger inter-coil angles used [10,11]. In the case of the knee, it is generally necessary to set the double-coil applicator at a mutual angle of 90° for nearly all patients. However, for the shoulder and hip regions, the angle can vary between 90° and 120°, depending on the patient's body composition.

The more intense perception of single-coil stimulation in the lower back is likely due to the flat surface necessitating a wide angle between the double-coil setup. This explanation is supported by COMSOL simulation results, which demonstrated higher magnetic energy at all monitored depths for the single-coil configuration- even at a mutual double-coil angle of 140°. However, the use of the double-coil setup cannot be considered entirely unsuitable for this region. Volunteers reported greater comfort and a more homogeneous treatment experience with the double-coil stimulation, which may be attributed to the broader area being stimulated at a lower intensity. This configuration may be particularly appropriate for conditions that do not require precise targeting of a specific muscle, but rather benefit from the activation of multiple muscle groups to promote general muscle relaxation [12]. Furthermore, the double-coil setup may be better suited for individuals who are extremely thin or sensitive and who may not tolerate single-coil stimulation well [13,14].

Comparing the findings of the present study with existing literature is challenging due to the lack of similarly comprehensive analyses. Nonetheless, studies involving both TMS and rPMS have reported that tilting the coils to conform to the anatomical characteristics of the treated area can enhance the effectiveness of deep stimulation [6-9]. Despite these parallels, a direct comparison is not feasible due to differences in methodologies and coil configurations across studies.

A certain limitation of this study lies in the simplicity of the proposed spherical model, which, due to its anatomical abstraction, does not represent any specific tissue type and is therefore unsuitable for assessing absolute magnetic energy values. However, for the purpose of relative comparisons between different rPMS coil configurations at varying depths, it remains acceptable- though its applicability to specific anatomical structures is inherently limited. While the results of both the experimental and simulation components are largely consistent and support the potential utility of the novel double-coil configuration in physiotherapy, its therapeutic efficacy must be validated through future clinical studies focused on specific indications. These studies should particularly target large joints and deeper tissue structures, where the benefits of the double-coil design appear most promising.

Although this study does not provide direct clinical evidence, it highlights the theoretical potential of the adjustable double-coil setup and suggests a valuable direction for future innovation in rPMS technology within physiotherapy.

Conclusions

These experimental and simulation findings indicate that both the conventional single-coil and the novel adjustable double-coil configurations have potential applications in physiotherapy. The single-coil setup is particularly effective for delivering high-intensity, focused stimulation to superficial tissues over anatomically flat areas. In contrast, the double-coil design, by allowing coil angulation, generates a broader and more uniform magnetic field over planar regions. This results in less focal but more comfortable and homogeneous stimulation, which may be advantageous for generalized muscle activation or in sensitive patients. Moreover, by narrowing the inter-coil angle, the double-coil configuration can achieve greater field strength at deeper tissue levels, making it especially suitable for stimulating irregular anatomical structures like large joints that require multi-directional and deeper targeting. These characteristics position the double-coil setup as a versatile and promising tool for advancing rPMS-based physiotherapeutic interventions, particularly in managing conditions involving deep or complex musculoskeletal structures.

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