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Original Article

Orthopaedics Section

Single versus Double-coil Repetitive Peripheral Magnetic Stimulation Targeting Knee Cartilage and Ligaments: A Finite Element Analysis

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ABSTRACT

Introduction: Despite the growing use of repetitive Peripheral Magnetic Stimulation (rPMS) in non-invasive rehabilitation over the past three decades, stimulation applicator designs have seen minimal innovation. A multi-coil approach with independently adjustable tilt and angle could broaden the possibilities of stimulation in physiotherapeutic practice.

Aim: To theoretically compare the effects of single and double-coil configurations on a simplified model of knee tissue.

Materials and Methods: The present in-silico Finite Element Modelling (FEM) study was conducted using COMSOL multiphysics, without the involvement of human or animal participants and therefore without the need for ethical clearance. The development and simulations of both configurations were carried out at the Research Centre in Prague, Czech Republic. A simplified knee cartilage model was created to assess total magnetic energy, and a cylindrical ligament model was used to evaluate energy distribution with depth. Model outputs were deterministic and were analysed descriptively without statistical testing.

Results: In the cartilage model, the double-coil configuration produced up to 20% greater total magnetic energy compared to the single coil. In the ligament model, the single coil delivered higher energy superficially (≤3 cm), whereas the double-coil generated 45-121% greater energy at deeper layers (3-8 cm).

Conclusion: The study theoretically indicated the potential application of the novel double-coil configuration in physiotherapy. Its enhanced energy delivery may be beneficial for conditions such as osteoarthritis and ligament injuries, particularly when deeper tissue targeting is required. Further clinical studies are warranted to confirm these findings.

Keywords: Anterior cruciate ligament, Articular cartilage, Knee joint, Osteoarthritis, Posterior cruciate ligament

INTRODUCTION

The use of electricity for pain relief dates back to at least 1000 BCE, when ancient Egyptians and later the Greeks and Romans employed electric discharges from fish such as the Torpedo or Electric Ray to alleviate pain. The systematic development of electrotherapeutic technologies began in the 18th and 19th centuries [1]. Initially, static electrical currents were utilised, followed by the discovery and application of direct currents generated through chemical means. Subsequent advancements led to the intermittent and alternating application of electric currents, culminating in the therapeutic use of high-frequency currents [1]. The 19th century, in particular, is often regarded as the “golden age” of electrotherapy, during which electrical stimulation was widely employed in the treatment of various conditions, including dental, neurological, psychiatric, and gynaecological disorders [1].

Despite its historical popularity, electrotherapy presents several notable limitations, including stimulation-associated discomfort, limited force generation, electrochemical degradation at the electrode-tissue interface, and restricted current penetration into deeper muscle layers due to preferential conduction through superficial tissues [2]. To address these challenges, PMS was introduced in 1982 by researchers at the University of Sheffield. Unlike earlier technologies, this magnetic stimulator featured a substantially higher peak magnetic field strength, enabling more effective stimulation of human peripheral nerves [3]. In addition, PMS can circumvent stimulation-induced pain, as the magnetic field is capable of penetrating high resistance tissues, thereby minimising activation of cutaneous nociceptors [4].

The principle of operation of rPMS relies on the induction of electric currents within underlying tissues, generated by rapidly changing magnetic fields [5,6]. These induced currents facilitate muscle contractions by primarily stimulating peripheral nerves. This neural activation results in increased local blood flow and enhanced muscle perfusion, which may support tissue healing and promote muscle recovery [6]. Moreover, the repetitive nature of rPMS has the potential to induce long-term potentiation within the central nervous system, thereby enhancing motor learning and functional performance [7]. In addition to its neuromuscular effects, rPMS can modulate pain pathways and stimulate the release of endogenous analgesic substances, contributing to a reduction in pain perception and improvements in quality of life. These combined effects are particularly valuable in rehabilitation, as they address both muscular function and the neural mechanisms underlying motor control [6].

A primary limitation of magnetic nerve stimulation is the requirement for high voltages and currents, necessitating the use of large coils and, consequently, bulky devices. These systems often exhibit suboptimal energy efficiency, and in the context of rPMS which has gained increasing popularity in recent years, overheating of stimulation coils can be a significant issue [8,9]. To enhance the efficiency of nerve stimulation, application-specific optimisation of coil design has become increasingly important. Precise control of the magnetic field distribution may enable more effective therapy without increasing energy consumption [8].

Despite the rising prominence of rPMS in non-invasive rehabilitation over the past three decades, the design of stimulation applicators for physiotherapeutic use has seen limited innovation. Current devices typically rely on static configurations using one or two circular coils, with no provisions for tilting or anatomical adaptation to the treatment area [2,10]. Research on various coil configurations for Transcranial Magnetic Stimulation (TMS) has demonstrated that tilting coils at specific angles can enhance depth-spread characteristics while maintaining a significantly reduced spatial footprint [10]. Goetz SM et al., demonstrated that optimised coil designs for use in rPMS can produce a force recruitment curve with a slope more than two and a half times steeper than that achieved with standard circular coils [2]. Although these promising findings exist, a commercially available rPMS approach that incorporates multiple coils, which can be tilted and angled relative to one another, has not yet been introduced for physiotherapy rehabilitation. The recently developed double-coil applicator concept represents the first commercially available solution of its kind and holds particular promise for the treatment of large joints, where the ability to distribute the magnetic field across multiple angles and directions may offer significant therapeutic advantages.

The present study is the first to simulate and compare the electromagnetic fields generated by single and double-coil applicators in an artificial knee joint model. It is built on the previous research, which demonstrated that a 90° double-coil configuration produces a markedly stronger effect at greater depths compared to the single-coil approach [11]. This was confirmed not only by simulations but also by subjective perception reported by volunteers. The present study therefore focuses specifically on the knee joint, which is expected to benefit most from the 90° double-coil configuration. The computational approach included two simulations: one compared magnetic energy within the articular cartilage, and the other assessed cumulative energy in a ligament placed at varying depths. This theoretical comparison of a novel two-sided stimulation method with the conventional single-coil approach provides an initial indication of its potential and highlights the respective advantages of both configurations in the treatment of large joints.

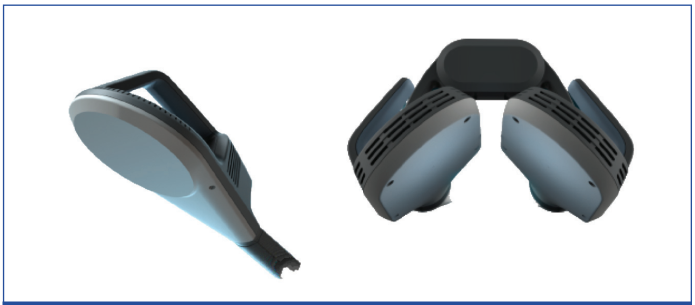
MATERIALS AND METHODS

The present in-silico FEM study, i.e., a simulation based analysis, was carried out at the Research Centre in Prague, Czech Republic, between January and June 2025. As no human or animal participants were involved, it does not fall into a conventional observational study category and no approval from an Ethics Committee was required. The study was based entirely on mathematical calculations and theoretical simulations performed in COMSOL Multiphysics [12].

As this was a simulation based analysis with deterministic outputs, conventional elements such as inclusion and exclusion criteria, sample size calculation, or power analysis were not applicable. The number of computational runs represents the ‘sample size’, and results were analysed descriptively without statistical testing.

Study Procedure

Two simplified FEMs were developed for the simulations: one representing the knee joint, and the other representing a ligament positioned at different depths. Identical single and double-coil applicator configurations were applied to both FEMs to compare the distribution of magnetic energy. Applied coil configurations were corresponding to commercially available rPMS applicators included in the Super Inductive System Duo (BTL Industries, Ltd.,): a single-coil configuration (focused field applicator) and a double-coil configuration {3D applicator}. The coil geometry in the model was explicitly modified to accurately reflect the physical configuration of the actual coils. To simplify the simulation, non conductive and non magnetic components of the applicator such as the handle, external plastic housing in contact with the skin, and cooling elements designed to prevent overheating were excluded. These parts do not contribute to electromagnetic field generation and therefore do not affect the simulated magnetic performance. The single-coil configuration was applied from only one side of the FEM, whereas in the double-coil setup two coils were applied in parallel under a mutual angle of 90°. The spatial arrangement of both coil configurations is presented in [Table/Fig-1,2].



[Table/Fig-1]: 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.

[Table/Fig-2]: Illustrative animations of electromagnetic fields generated by single-coil (left) and double-coil (right) configurations. Courtesy of BTL Industries, Ltd., Used with permission.

The Alternating Current /Direct Current (AC/DC) magnetic fields interface in COMSOL multiphysics was used to determine the magnetic energy density within the FEM. This was achieved by performing a volume integral of the computed energy density, originally expressed in units of J/m³, to obtain the magnetic energy in Joules (J). The magnetic energy density was calculated using the following equation:

$$W_m = \frac{1}{2} B \cdot H \quad [13]$$

Where B is the magnetic flux density (in T) and H is the magnetic field strength (in A/m).

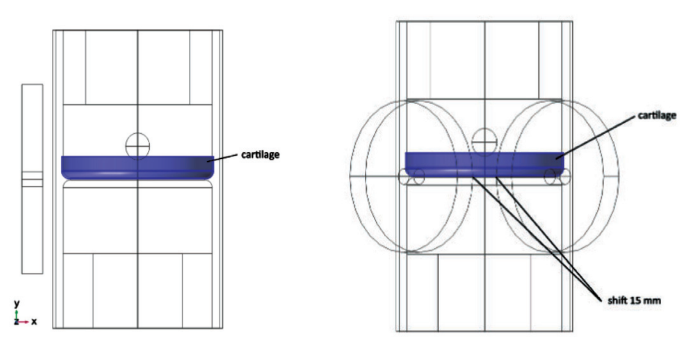
The magnetic energy was then obtained by integrating the magnetic energy density over the cartilage or ligament volume of the FEM, as expressed by:

$$W = \iiint W_m \, dV = \iiint (\tfrac{1}{2} B \cdot H) dV \quad [13]$$

Where, W_m is the magnetic energy density, and dV represents the differential volume element.

Cartilage model: To enable theoretical calculation of the magnetic energy accumulated within knee cartilage, a simplified in-silico model was developed [Table/Fig-3]. Articular cartilage was represented as a ring-shaped structure with a diameter of 102 mm and uniform thickness of 1 mm, based on published anatomical data and prior modeling studies [14-16]. The selected diameter (~10.2 cm) corresponds to a cartilage surface area of ~81.7 cm², which closely matches the reported total femoral cartilage surface area of 78.0±10.3 cm² in healthy individuals [15]. The reduced cartilage thickness of 1 mm reflects the degenerative thinning typically observed in osteoarthritic joints, allowing for a clinically relevant approximation of pathological cartilage conditions [16].

Each tissue type within the model was assigned an appropriate dielectric parameter as electrical conductivity and relative permittivity, as summarised in [Table/Fig-4]. Tissue dielectric properties were obtained from the IT’IS Foundation database (https://itis.swiss), which provides frequency-dependent values based on Gabriel C seminal compilation [17]. The FEM was meshed using tetrahedral elements with extremely fine mesh size.

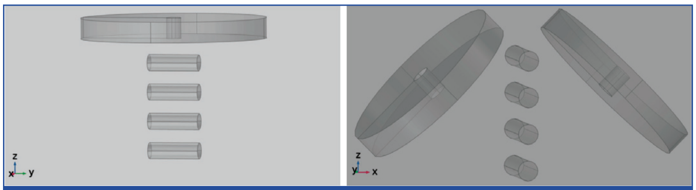


[Table/Fig-3]: Geometry of the simplified knee joint model and location of stimulation coils for single (left) and double (right) coil configurations.

Materials	Electrical conductivity (S/m)	Relative permittivity (-)
Skin	2.01e-4	1.13e+3
Bone / patella	2.03e-2	1.05e+3
Muscle	3.35e-1	7.38e+4
Cartilage / meniscus	1.75e-1	7.66e+3
Ligament / tendon	3.85e-1	2.63e+4

[Table/Fig-4]: Electrical conductivity of tissues used in the Finite Element Model (FEM) of simplified knee joint model.

Ligament model: The ligament model was developed based on the anatomical characteristics of the Anterior Cruciate Ligament (ACL), which has an average length of approximately 35 mm and a diameter of 11 mm, as reported in the literature [18]. To simplify the geometry, the ligament was modeled as a cylinder with these dimensions. This cylindrical model was subsequently positioned at distances ranging from 1 cm to 8 cm from the coil models, in 1 cm increments [Table/Fig-5].



[Table/Fig-5]: Geometry of the simplified ligament model and location of stimulation coils for single (left) and double (right) coil configurations.

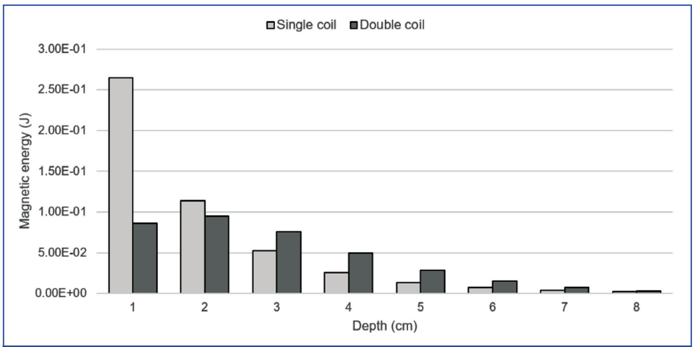
RESULTS

The single-coil configuration generated 0.124 J of magnetic energy within the cartilage volume, while the double-coil configuration produced 0.151 J representing a 20.2% increase in magnetic energy.

Simulation results for the ligament model positioned at varying depths are presented in [Table/Fig-6,7]. While the single-coil configuration demonstrated higher magnetic energy at superficial depths (1-2 cm), the double-coil setup produced greater energy deposition from 3 cm onward. Magnetic energy in the single-coil configuration declined sharply with increasing depth, whereas in the double-coil configuration, energy initially increased between 1 cm and 2 cm and then decreased more gradually.

Depth	Single coil	Double-coil	%Δ*
1 cm	0.265	0.086	-67.37%
2 cm	0.114	0.095	-16.67%
3 cm	0.052	0.076	44.76%
4 cm	0.026	0.05	95.31%
5 cm	0.013	0.029	120.61%
6 cm	0.007	0.015	114.08%
7 cm	0.004	0.007	87.56%
8 cm	0.002	0.003	49.78%

[Table/Fig-6]: Simulated magnetic energy values in the ligament model at depths ranging from 1 to 8 cm for single and double-coil rPMS configurations.
* %Δ: Percentage difference between single and double-coil configurations



[Table/Fig-7]: Bar graph illustrating the magnetic energy distribution for single and double-coil rPMS configurations at depths of 1 to 8 cm, based on COMSOL Multiphysics simulation of a ligament model.

DISCUSSION

The simulation theoretically compared the effects of single and double-coil rPMS stimulation on two commonly targeted knee tissues: cartilage and ligaments. The observed 20.2% increase in magnetic energy in cartilage with the double-coil setup aligns with the finding that magnetic energy is significantly higher under this configuration at depths ranging from 3 to 8 cm. Given that articular cartilage is typically located at a depth of approximately 3 cm, the enhanced energy delivery from the double-coil configuration is well justified [19].

This increased depth of penetration offers potential therapeutic advantages in treating cartilage-related conditions such as osteoarthritis - the most prevalent joint disease. In overweight individuals, who are at elevated risk for osteoarthritis, targeting the cartilage can be more challenging due to the additional subcutaneous fat layer, which places the cartilage even deeper [20]. The opposing placement of two coils allows their magnetic fields to converge, enhancing the cumulative energy delivered to deeper tissues [21]. This approach may be particularly beneficial for patients with greater tissue depth, where deeper stimulation is essential.

When it comes to ligament treatment, the ACL and Posterior Cruciate Ligament (PCL) are most commonly involved. These ligaments are typically located at depths of approximately 2.5 to 5 cm [22,23]. In athletes, who are at increased risk of ligament injuries, the ligaments may be positioned toward the deeper end of this range due to greater muscle mass. In such cases, the improved depth penetration offered by the double-coil configuration is again justified and may play a critical role in achieving more effective therapeutic outcomes [20,24].

Finding direct support for the present study's findings in existing literature is challenging, given the lack of prior applications of a double-coil rPMS setup in physiotherapy. However, related research provides indirect validation. For instance, Bagherzadeh H et al., demonstrated in a TMS study that tilting multiple coils could enhance the depth of stimulation, suggesting potential for deeper therapeutic targeting [10]. In the context of rPMS, Goetz SM et al., conducted a theoretical investigation into a slightly tilted multi-coil design and similarly reported improved performance compared to the traditional single-coil configuration [2]. While direct comparison is limited due to differences in coil design and methodological approaches, these studies collectively support the potential advantages of novel multi-coil configurations, including the double-coil approach proposed here.

The mechanism of action of single and double-coil configurations - illustrated in simplified form in [Table/Fig-2] supports the study's conclusions. In the case of the standard single-coil applicator, energy penetrates the tissue from a single source, typically oriented perpendicularly to the treated area. As a result, the energy density decreases progressively with increasing distance from the applicator surface, leading to higher exposure in superficial tissues and a gradual attenuation toward deeper layers

[8]. The novel dual-coil applicator, in contrast, delivers energy from two sources that can be tilted at variable angles. The angle between the coils determines the resulting field distribution: when positioned at 180°, the effect resembles the application of two separate single-coil stimulators, whereas a 90° configuration produces overlapping fields. According to the present simulations, this overlap occurs predominantly at greater depths, leading to cumulative field intensity and enhanced magnetic energy delivery in deeper tissues. This, in turn, results in different levels of energy delivery at varying tissue depths when the two approaches are compared [11].

Although the conclusions presented are theoretical, the innovative nature of the present study in the field of rPMS - an area that has seen limited technological advancement in recent decades should not be overlooked. The novel double-coil tPMS configuration demonstrated promising potential for improving magnetic field penetration into deeper knee tissues, which may be especially beneficial for patient groups such as individuals with obesity or athletes with greater muscle mass.

Limitation(s)

The conclusions of the current study must be interpreted in light of its theoretical nature and inherent limitations. To achieve the primary objective of comparing the effects of single and double-coil rPMS configurations - highly simplified FEMs were utilized. Although these models do not accurately replicate the complex anatomical structures of the knee, they are considered sufficient for assessing relative differences in magnetic field distribution. However, to obtain accurate absolute field values, the use of anatomically detailed models derived from MRI data would be necessary. It is also important to underscore that the current findings are based solely on theoretical simulations; any clinical implications must be validated through future clinical trials. A valuable next step would be to compare these theoretical predictions with clinical outcomes in patients undergoing treatment for knee osteoarthritis or ACL/PCL-related conditions using single and double-coil rPMS approaches.

CONCLUSION(S)

The present study presents a novel theoretical comparison between single and double-coil rPMS configurations, highlighting the potential advantages of the double-coil setup in delivering more effective stimulation to deeper knee structures such as cartilage and ligaments. While the findings are preliminary and based on simplified models, they provide a compelling foundation for future research and clinical exploration. The enhanced energy delivery associated with the double-coil configuration could offer meaningful benefits in the treatment of conditions like osteoarthritis and ligament injuries, particularly in patient populations where deeper tissue targeting is essential. Future studies should focus on validating these results in anatomically accurate models and through well-designed clinical trials to fully assess the therapeutic potential of this innovative approach.

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