http://www.jourmag.org/index.php/jma

Journal of Magnetism and Its Applications

Received February14th 2026 received in revised April 6th 2026 accepted May15th 2026

Research articles

Magnetic Nanoparticles in Biomedical Rehabilitation: Emerging Applications in Physiotherapy and Targeted Therapeutics

Elena V. Petrova
Department of Solid-State Physics, Lomonosov Moscow State University, Moscow, Russian Federation

Article info
Keywords:
magnetic nanoparticles,
biomedical rehabilitation,
physiotherapy,
targeted drug delivery,
tissue engineering,
regenerative medicine,
magnetic hyperthermia,
superparamagnetic iron oxide

Abstract
Magnetic nanoparticles have emerged as multifunctional materials for biomedical imaging, targeted drug delivery, controlled therapeutic release, magnetic hyperthermia, cell guidance, tissue engineering, and regenerative medicine. Superparamagnetic iron oxide nanoparticles are particularly important because their magnetic behavior can be remotely controlled while their surfaces can be modified with polymers, antibodies, peptides, growth factors, drugs, nucleic acids, and biomimetic molecules. These characteristics have generated interest in their possible integration with biomedical rehabilitation and physiotherapy, especially for bone healing, peripheral nerve repair, skeletal-muscle regeneration, cartilage restoration, tendon recovery, localized pain management, and the delivery of anti-inflammatory or regenerative agents.
This review examines the physicochemical design of magnetic nanoparticles, their interaction with external magnetic fields, and their emerging roles in rehabilitation-oriented medicine. Magnetic scaffolds may provide mechanical and biochemical cues that support osteogenesis, angiogenesis, axonal growth, myoblast alignment, and stem-cell differentiation. Magnetic targeting may also concentrate therapeutic agents or magnetically labelled cells at injured tissues while reducing systemic exposure. Alternating magnetic fields can produce localized heating for hyperthermia or temperature-triggered drug release, whereas static or low-frequency fields may generate mechanical forces within magnetically responsive biomaterials. Nevertheless, most applications directly related to physiotherapy remain at laboratory or animal-study stages. Established clinical uses of iron-oxide nanoparticles in medicine do not yet demonstrate that magnetic nanoparticle treatments are effective replacements for exercise therapy, manual therapy, electrotherapy, rehabilitation training, or conventional pharmacological management. Translation requires standardized characterization, realistic dosing, long-term toxicity assessment, controlled clinical trials, rehabilitation-specific outcome measures, and interdisciplinary collaboration. Magnetic nanoparticles are therefore best understood as potential adjunctive platforms that may increase the precision and biological responsiveness of future rehabilitation interventions.

Introduction

Biomedical rehabilitation aims to restore mobility, strength, coordination, independence, and quality of life following injury, surgery, neurological disease, musculoskeletal degeneration, or prolonged immobility. Conventional rehabilitation combines therapeutic exercise, manual techniques, physical agents, assistive devices, education, pain management, and task-specific functional training. Although these methods are effective for many conditions, rehabilitation outcomes may be limited when tissues possess poor intrinsic regenerative capacity, extensive fibrosis, impaired vascularization, chronic inflammation, denervation, or large structural defects. nNanomedicine offers a possible means of modifying the biological environment in which rehabilitation occurs. Instead of relying only on externally applied mechanical or electrical stimulation, nanomaterials may deliver drugs, growth factors, genes, cells, heat, or mechanical forces directly to injured tissues. Magnetic nanoparticles are especially attractive because they can respond to externally applied magnetic fields without requiring direct physical contact with the target tissue. Their surfaces can also be engineered to carry therapeutic molecules or interact with specific cells and extracellular-matrix components. The most extensively investigated biomedical magnetic particles are superparamagnetic iron oxide nanoparticles, commonly abbreviated as SPIONs. These particles usually contain magnetite, Fe_3O_4, or maghemite, γ-Fe_2O_3. When their dimensions are sufficiently small, they display strong magnetization in an applied field but retain little permanent magnetization after the field is removed. This behavior can reduce persistent particle aggregation and permits remote guidance, imaging, heating, separation, or mechanical stimulation. Surface coatings such as dextran, polyethylene glycol, chitosan, silica, lipids, proteins, and biodegradable polymers are used to improve colloidal stability and provide sites for drug or ligand attachment. Magnetic nanoparticle technology must be distinguished from ordinary permanent-magnet products, pulsed electromagnetic-field therapy, repetitive transcranial magnetic stimulation, and other magnetic modalities already discussed in rehabilitation medicine. In magnetic nanomedicine, particles are introduced into a drug carrier, scaffold, cell population, implant, or tissue and subsequently manipulated or activated through a magnetic field. Thus, both a nanomaterial component and an appropriately controlled magnetic-field system are required. Some iron-oxide products already possess clinical or regulatory precedents. Ferumoxytol is an iron-oxide nanoparticle approved as an intravenous iron-replacement product, although its use as an MRI contrast agent is generally off-label. The Magtrace system contains carboxydextran-coated superparamagnetic iron oxide particles and is approved by the United States Food and Drug Administration for magnetic localization of sentinel lymph nodes in breast-cancer surgery. These examples demonstrate that appropriately manufactured iron-oxide formulations can enter clinical practice, but neither product is approved as a musculoskeletal or neurological rehabilitation treatment.

Design, Properties, and Biological Functionalization of Magnetic Nanoparticles

The biomedical behavior of magnetic nanoparticles depends on their core composition, diameter, shape, surface coating, charge, magnetic moment, aggregation state, and interaction with proteins and immune cells. Iron oxides are generally preferred over metallic cobalt or nickel particles because iron can enter normal metabolic pathways, whereas free cobalt and nickel ions may produce greater toxicological concerns. However, biocompatibility cannot be assumed merely because the core contains iron. Toxicity depends on dose, coating, degradation rate, impurities, tissue distribution, administration route, and patient characteristics. Particle size affects circulation, cellular uptake, magnetic response, renal clearance, and recognition by the mononuclear phagocyte system. Very small particles may display weak magnetic moments and rapid clearance, whereas larger or aggregated particles may accumulate in the liver, spleen, lungs, or other organs. Hydrodynamic diameter is normally greater than core diameter because it includes the coating, hydration layer, and adsorbed biomolecules. After entering a biological fluid, nanoparticles become covered by proteins, lipids, and other molecules, forming a biomolecular corona. This corona can change the apparent

surface identity of the nanoparticle and influence cellular uptake, immune recognition, aggregation, and targeting. A ligand attached to a nanoparticle may therefore behave differently in blood than it does in a purified laboratory solution. Successful biomedical design requires evaluation in physiologically relevant media rather than only in water. Surface coatings prevent oxidation and agglomeration while allowing therapeutic functionalization. Polyethylene glycol can reduce non-specific protein adsorption and extend circulation, although immune responses against polyethylene glycol have been reported in some contexts. Dextran and carboxydextran provide hydrophilic stabilization, while chitosan offers biodegradability and reactive amino groups. Poly(lactic-co-glycolic acid) can form drug-loaded magnetic carriers with controlled degradation. Therapeutic molecules may be attached covalently, adsorbed electrostatically, encapsulated within a polymer shell, or trapped in a porous coating. Covalent attachment offers stability but may reduce drug release unless a cleavable linker is incorporated. Non-covalent loading is simpler but may produce premature leakage. Stimuli-responsive bonds can be designed to release their payload in response to acidic pH, enzymes, reducing conditions, heat, or magnetic-field exposure. Active targeting involves attaching a molecule that recognizes a receptor expressed by target cells. Antibodies, peptides, aptamers, folic acid, transferrin, carbohydrates, and extracellular-matrix-binding sequences have all been investigated. In rehabilitation-oriented applications, possible targets include activated macrophages, inflamed synovium, osteoclasts, osteoblasts, damaged vascular endothelium, Schwann cells, neuronal receptors, or proteins exposed within injured muscle and tendon. Magnetic targeting adds a physical localization mechanism. A magnetic-field gradient exerts force on the nanoparticles and may increase their retention near an injury. The magnitude of this force depends on nanoparticle magnetization, field strength, field gradient, tissue depth, blood flow, and the distance between the magnet and target. Deep tissues are harder to target because magnetic-field gradients decline with distance. Implantable magnetic devices or specially designed electromagnets may overcome some of this limitation but increase procedural complexity. Nanoparticles should be characterized through transmission electron microscopy, dynamic light scattering, X-ray diffraction, Fourier-transform infrared spectroscopy, thermogravimetric analysis, zeta-potential measurement, and magnetic testing. Drug-loading efficiency, release kinetics, sterility, endotoxin level, colloidal stability, protein binding, hemocompatibility, and degradation must also be measured before in vivo investigation. For rehabilitation applications, the nanoparticle cannot be evaluated independently of the physical intervention. Magnetic-field intensity, gradient, frequency, waveform, exposure duration, coil geometry, treatment interval, and tissue temperature should be reported. Without these parameters, experiments cannot be reproduced or translated into clinical protocols.

Magnetic Nanoparticles in Physiotherapy and Regenerative Rehabilitation

Bone regeneration and fracture rehabilitation

Bone healing requires inflammation, vascularization, recruitment of progenitor cells, extracellular-matrix deposition, mineralization, and mechanical remodelling. Physiotherapy supports this process through protected loading, progressive weight bearing, muscle activation, mobility restoration, and functional training. Magnetic nanoparticles could potentially improve the biological repair environment in which these rehabilitation activities occur. Iron-oxide nanoparticles have been incorporated into collagen, chitosan, hydroxyapatite, bioactive glass, polylactic acid, and other scaffold materials. Magnetic scaffolds can support cell adhesion while responding to externally applied fields. Laboratory studies suggest that these materials may influence osteoblast proliferation, mesenchymal-stem-cell differentiation, angiogenic activity, and the expression of osteogenic markers. In one animal investigation, a superparamagnetic nanofibrous scaffold containing iron oxide and hydroxyapatite accelerated bone formation in a rabbit defect model when combined with an external static magnetic field. Although this supports biological feasibility, an animal bone-defect experiment does not establish effectiveness in human fracture rehabilitation. Differences in field exposure, scaffold implantation, loading, immune response, and healing rate must be considered. Magnetic scaffolds may also serve as localized carriers for antibiotics, anti-inflammatory agents, bone morphogenetic proteins, vascular endothelial growth factor, or osteoporosis drugs. Controlled release could be beneficial after complex fractures, bone infection, spinal fusion, joint replacement, or tumour-related reconstruction. A localized system might reduce the systemic exposure associated with high-dose medication. A future rehabilitation protocol could combine a surgically implanted magnetic scaffold with controlled magnetic stimulation and progressive mechanical loading. The magnetic component might support early cellular organization, while physiotherapy would provide the mechanical signals required for later remodelling. Such integration remains experimental and requires careful investigation of whether magnetic stimulation and mechanical loading have additive, synergistic, or opposing effects.

Peripheral nerve regeneration and neurological rehabilitation

Peripheral nerve injuries can cause weakness, sensory loss, neuropathic pain, impaired coordination, and long-term disability. Rehabilitation includes range-of-motion exercises, sensory re-education, strengthening, splinting, functional training, pain control, and prevention of contracture. Biological recovery is often limited by slow axonal growth, scar formation, misdirection of regenerating fibres, and insufficient neurotrophic support. Magnetic nanoparticles have been proposed as tools for directing neuronal growth and organizing cells within nerve-guidance conduits. Cells can internalize appropriately coated nanoparticles and subsequently respond to magnetic forces. Controlled magnetic gradients may encourage orientation of neuronal or glial cells and could potentially direct axonal extension across a damaged region. Current evidence is predominantly experimental, and the magnitude of force must remain low enough to avoid cellular injury. Nanoparticle-loaded nerve conduits may also provide sustained delivery of nerve growth factor, brain-derived neurotrophic factor, glial-cell-line-derived neurotrophic factor, or anti-inflammatory drugs. Growth factors delivered in soluble form are often degraded rapidly and may diffuse away from the injury. Nanoparticle encapsulation can protect the molecule and provide a more controlled release profile. Magnetically labelled stem cells or Schwann cells could potentially be guided toward a nerve lesion. Magnetic tracking may also enable clinicians to monitor cell distribution using magnetic-resonance-based techniques. Nevertheless, labelling must not alter differentiation, migration, viability, electrophysiological function, or therapeutic activity. Central-nervous-system applications are more challenging because of the blood–brain barrier, complex neural circuitry, and the potential consequences of inflammation. Magnetic nanoparticles are being investigated for drug delivery, cell tracking, and regenerative hydrogels in stroke and spinal-cord injury, but these approaches are not established neurological rehabilitation treatments. Rehabilitation remains essential for motor learning and neuroplastic adaptation even when a biological regenerative intervention is used.

Skeletal-muscle regeneration

Severe trauma, tumour resection, infection, and compartment injuries can produce volumetric muscle loss in which the defect exceeds the natural regenerative capacity of skeletal muscle. Conventional rehabilitation may improve the performance of remaining muscle but cannot fully replace a large volume of lost contractile tissue. Skeletal muscle contains highly aligned fibres. A regenerative scaffold should therefore provide directional cues that support myoblast alignment, fusion, vascularization, innervation, and force transmission. Magnetic nanoparticles can be incorporated into collagen or hydrogel systems and aligned by a static magnetic field after injection. A 2025 study described an injectable hydrogel containing magnetic collagen bundles that developed an anisotropic structure under a low-intensity static magnetic field. The material demonstrated muscle-like mechanical characteristics and encouraging biocompatibility in experimental testing. Such research illustrates how magnetic fields might organize an injectable biomaterial after delivery without extensive open surgery. However, it remains an experimental regenerative platform rather than a clinical physiotherapy intervention. Magnetic nanoparticles may also generate small mechanical forces that stimulate mechanosensitive pathways in myoblasts or stem cells. These forces could potentially complement exercise-induced mechanical signals, particularly during early healing when active loading is restricted. The biological response is likely to depend on force amplitude, frequency, cell type, and stage of differentiation. In future volumetric-muscle-loss management, a magnetic scaffold could provide structural support during early regeneration, while electrical stimulation and progressive resistance exercise promote maturation and functional integration. Meaningful translation will require demonstration of restored contractile force, fatigue resistance, innervation, gait, and daily function rather than histological improvement alone.

Cartilage, tendon, and ligament repair

Articular cartilage possesses limited intrinsic healing capacity because it is avascular and contains relatively few cells. Magnetic nanoparticles can be incorporated into hydrogels containing chondrocytes, stem cells, growth factors, or anti-inflammatory agents. Magnetic fields may help position cells, organize scaffold architecture, or trigger local release.

For osteoarthritis, magnetically targeted carriers could potentially deliver corticosteroids, disease-modifying molecules, small interfering RNA, or regenerative factors to the synovium or cartilage surface. The purpose would be to maintain a therapeutic concentration within the joint while reducing systemic exposure. Challenges include rapid clearance from the joint, nanoparticle uptake by synovial macrophages, cartilage penetration, and repeated joint movement. Tendon and ligament repair requires aligned collagen deposition and gradual mechanical loading. Magnetically responsive fibres could provide orientation cues during scaffold formation. However, the interaction between magnetic stimulation and the high mechanical forces experienced by tendons remains insufficiently studied.

Targeted Therapeutics, Hyperthermia, and Theranostic Applications

Magnetic drug targeting attempts to concentrate a therapeutic agent at a selected anatomical site through an external field gradient. The nanoparticle acts as a carrier, while the magnetic field improves localization. This approach may reduce systemic toxicity, permit lower total doses, or prolong local exposure. Possible rehabilitation-related targets include inflamed joints, painful musculoskeletal lesions, postoperative tissue, injured nerves, infected bone, fibrotic muscle, and vascularly compromised wounds. Carried agents could include analgesics, non-steroidal anti-inflammatory drugs, corticosteroids, antibiotics, antioxidants, neurotrophic factors, angiogenic molecules, or nucleic-acid therapies. The effectiveness of magnetic targeting is constrained by blood flow and tissue depth. A nanoparticle travelling through a large vessel may pass the target before sufficient magnetic force can retain it. Targeting superficial joints or surgically accessible tissues may therefore be more practical than targeting deep spinal or pelvic structures. Local injection can overcome some limitations of systemic targeting. Magnetic particles may be injected into a joint, scaffold, tumour, or surgical site and retained using an external field. Local delivery reduces the distance the particle must travel but introduces procedural risks such as leakage, uneven distribution, inflammation, or tissue damage. Magnetic nanoparticles can also support triggered drug release. Under an alternating magnetic field, iron-oxide particles dissipate heat through magnetic relaxation and hysteretic processes. The heat can soften a thermoresponsive polymer, break a temperature-sensitive bond, or increase diffusion of an encapsulated drug. Mild heating may provide on-demand release without producing the higher temperatures required for tissue destruction. At higher temperatures, the same principle is used for magnetic hyperthermia. Nanoparticles are introduced into or concentrated within a tumour and activated by an alternating magnetic field. The resulting heat can injure tumour cells or increase their sensitivity to radiotherapy and chemotherapy. Magnetic hyperthermia has progressed further clinically than magnetic regenerative rehabilitation. A systematic review of clinical glioma studies included reports on 227 patients, but most evidence came from pilot, non-randomized, or retrospective investigations. The findings were encouraging in some primary glioblastoma settings but less consistent for recurrent disease, illustrating the need for cautious interpretation. Hyperthermia may have indirect relevance to rehabilitation because successful tumour control can preserve neurological or musculoskeletal function and reduce the disability associated with radical surgery. Nevertheless, hyperthermia is an oncological treatment rather than a physiotherapy technique. Rehabilitation professionals would contribute to the management of mobility, fatigue, weakness, balance, cognition, pain, and participation before and after treatment. Theranostic systems combine therapy and diagnosis within the same nanoparticle. An iron-oxide carrier may support magnetic imaging, drug delivery, and field-triggered heating. This combination could allow treatment localization, monitoring of particle distribution, and adjustment of field exposure. Such systems are attractive for personalized medicine but involve complex manufacturing and regulatory evaluation. Magnetically labelled cells provide another theranostic strategy. Stem cells, immune cells, or regenerative cells can be labelled, guided, and tracked. Yet the imaging signal may persist after the labelled cell dies because macrophages can take up the particles. Imaging cannot therefore be assumed to represent living therapeutic cells unless viability is confirmed through additional methods.

Safety, Biodistribution, Dosimetry, and Clinical Monitoring

The safety of magnetic nanoparticles is influenced by composition, crystallinity, surface coating, dose, route of administration, degradation, and duration of retention. Iron-oxide particles may eventually enter normal iron-processing pathways, but rapid degradation can release reactive iron and contribute to oxidative stress. Persistent particles may remain in macrophages or organs for extended periods. Potential adverse effects include inflammation, complement activation, hypersensitivity, oxidative injury, membrane damage, altered mitochondrial function, coagulation changes, and interference with immune-cell activity. These effects may be absent at one concentration and significant at another. Results obtained in a single cell line cannot establish systemic safety. Intravenously administered particles are commonly recognized by circulating proteins and cleared by macrophages in the liver and spleen. Surface modification can extend circulation, but it may not eliminate immune recognition. Patients with iron-overload disorders, severe allergies, impaired iron metabolism, or certain inflammatory conditions may require additional caution. Regulatory documents for clinically used iron-oxide systems illustrate relevant risks. Ferumoxytol is administered as an iron-replacement drug and carries warnings related to hypersensitivity. Magtrace is contraindicated in patients with hypersensitivity to iron oxide or dextran compounds and in certain patients with iron overload or relevant metal implants. It can also produce skin discoloration and affect subsequent MRI interpretation. Magnetic-field safety must be assessed separately from nanoparticle toxicity. Static fields, gradient fields, and alternating fields have different biological and physical effects. Alternating fields may cause unintended tissue heating, peripheral nerve stimulation, or interference with implants. Patients with pacemakers, neurostimulators, cochlear implants, metal fragments, or other implanted devices may face additional risks. For magnetic hyperthermia, heating performance is commonly described using specific absorption rate. However, values measured in water may not represent heating inside tissue because particle aggregation, viscosity, protein adsorption, and cellular internalization affect magnetic relaxation. Temperature must therefore be measured at multiple locations during treatment. In rehabilitation-oriented studies, functional safety is also important. A material may appear non-toxic under microscopy while impairing muscle contractility, nerve conduction, joint lubrication, tendon strength, sensation, or motor coordination. Safety evaluation should include electrophysiology, muscle-force testing, gait analysis, pain behaviour, inflammatory biomarkers, organ histology, and long-term degradation. Outcome selection should reflect the International Classification of Functioning, Disability and Health. Laboratory studies frequently report cell proliferation or marker expression, but rehabilitation requires evidence at the levels of body function, activity, and participation. Appropriate outcomes include strength, range of motion, walking speed, dexterity, balance, fatigue, pain, independence, work participation, and quality of life.

Translational Challenges and Future Directions

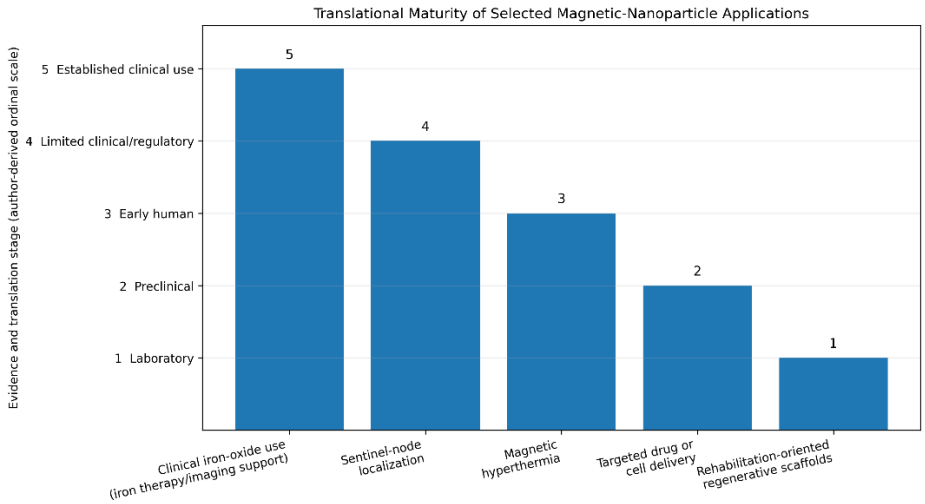
The most important limitation is the distance between experimental promise and clinical rehabilitation evidence. Magnetic nanoparticles have established medical precedents, but applications for bone, nerve, cartilage, tendon, and skeletal-muscle rehabilitation remain mainly preclinical. Positive cell-culture findings do not guarantee functional tissue regeneration in humans. Manufacturing reproducibility is another challenge. Small changes in size, coating, crystal phase, surface charge, or aggregation can alter biodistribution and magnetic response. Clinical products require validated manufacturing processes, sterile preparation, endotoxin control, batch consistency, stability testing, and clearly defined release criteria. Dose should be expressed in a manner that permits comparison across studies. Researchers may report nanoparticle mass, iron concentration, particle number, drug dose, scaffold weight, or dose per body mass. These measurements are not interchangeable. Studies should report core composition, total iron, hydrodynamic size, coating mass, active-drug loading, administration volume, and local tissue concentration. Rehabilitation trials will require comparison with meaningful standards of care. A magnetic scaffold should not be tested only against an untreated control when patients normally receive surgery, exercise, bracing, analgesia, electrical stimulation, or other rehabilitation. Trials should determine whether the nanoparticle intervention provides additional benefit beyond a complete rehabilitation programme. Treatment protocols should also investigate timing. Biological interventions may be most effective during a limited phase of inflammation, cell migration, tissue formation, or remodelling. Exercise loading introduced too early may damage fragile regenerative tissue, while loading introduced too late may permit fibrosis or disuse. Magnetic stimulation schedules should therefore be coordinated with rehabilitation progression. Interdisciplinary teams will be essential. Materials scientists must define particle properties; pharmacologists must evaluate release and metabolism; surgeons must establish delivery procedures; radiologists must monitor distribution; toxicologists must examine safety; and physiotherapists must design functional rehabilitation protocols and outcome measures. Low-resource health systems require technologies that are affordable, robust, and maintainable. For countries such as Pakistan, potential priorities include low-cost iron-oxide production, locally manufactured magnetic scaffolds, infection-resistant bone-repair systems, and portable field-generating devices. However, cost reduction must not bypass toxicological,

ethical, or regulatory requirements.

Singh and Sohail (2026) examined medical negligence in Malaysian hospitals through a qualitative thematic analysis of medico-legal court cases. Their study explored organisational and governance-related factors contributing to healthcare failures, including communication problems, documentation weaknesses, and inadequate risk management systems. The findings emphasized the importance of strengthening healthcare governance and adopting system-based approaches to improve patient safety.

Qazi and Sohail (2026) investigated the factors influencing investors' intention to participate in socially responsible investing among Pakistan Stock Exchange investors. The study focused on attitude, subjective norms, and perceived behavioral control as key determinants of investment intention. The results indicated that investors' positive attitudes significantly influence their willingness to engage in socially responsible investment practices.

Mousumi and Sohail (2026) studied the relationship between service quality, customer engagement, and customer loyalty in the Malaysian telecommunications sector. Their research highlighted that effective service quality dimensions, including reliability, responsiveness, and customer support, contribute to stronger customer relationships. The study suggested that improving service quality can enhance customer engagement and promote long-term loyalty.



This figure is a qualitative synthesis of the cited literature and regulatory evidence. Scores indicate translational stage, not comparative safety or clinical efficacy.

Summary

Magnetic nanoparticles provide a versatile platform for remotely controlled drug delivery, cellular guidance, regenerative scaffolding, diagnostic imaging, and localized heating. Their surface chemistry can be modified to carry therapeutic agents, recognize biological targets, or become incorporated into hydrogels, fibres, implants, and cell populations. In biomedical rehabilitation, the most promising experimental applications involve bone regeneration, peripheral nerve repair, skeletal-muscle alignment, cartilage restoration, tendon healing, and targeted delivery of anti-inflammatory or regenerative molecules. Magnetic scaffolds may create physical and biochemical conditions that support tissue formation, while physiotherapy provides the functional loading required for maturation and reintegration. The technology should not be regarded as a replacement for therapeutic exercise, manual therapy, neurorehabilitation, or established medical treatment. Most rehabilitation-oriented uses remain at laboratory or animal-study stages. Clinical precedents for iron-oxide nanoparticles demonstrate manufacturing and regulatory feasibility, but they do not prove efficacy for musculoskeletal or neurological recovery. Future translation requires standardized material characterization, controlled magnetic-field exposure, realistic dosing, long-term safety monitoring, functional outcome measurement, and well-designed clinical trials. The greatest potential lies in combined approaches in which magnetic nanotechnology improves the biological environment while rehabilitation restores movement, strength, coordination, and participation.

References

[1] Pankhurst, Q. A., Connolly, J., Jones, S. K., and Dobson, J. "Applications of Magnetic Nanoparticles in Biomedicine." *Journal of Physics D: Applied Physics*, 36, R167–R181, 2003. doi:10.1088/0022-3727/36/13/201.

[2] Laurent, S., Forge, D., Port, M., Roch, A., Robic, C., Vander Elst, L., and Muller, R. N. "Magnetic Iron Oxide Nanoparticles: Synthesis, Stabilization, Vectorization, Physicochemical Characterizations, and Biological Applications." *Chemical Reviews*, 108(6), 2064–2110, 2008. doi:10.1021/cr068445e.

[3] Ulbrich, K., Holá, K., Šubr, V., Bakandritsos, A., Tuček, J., and Zbořil, R. "Targeted Drug Delivery with Polymers and Magnetic Nanoparticles: Covalent and Noncovalent Approaches, Release Control, and Clinical Studies." *Chemical Reviews*, 116(9), 5338–5431, 2016. doi:10.1021/acs.chemrev.5b00589.

[4] Vangijzegem, T., Lecomte, V., Ternad, I., Van Leuven, L., Muller, R. N., Stanicki, D., and Laurent, S. "Superparamagnetic Iron Oxide Nanoparticles: From Fundamentals to State-of-the-Art Innovative Applications for Cancer Therapy." *Pharmaceutics*, 15(1), 236, 2023. doi:10.3390/pharmaceutics15010236.

[5] Dasari, A., Xue, J., and Deb, S. "Magnetic Nanoparticles in Bone Tissue Engineering." *Nanomaterials*, 12(5), 757, 2022. doi:10.3390/nano12050757.

[6] Sadeghzadeh, H., Dianat-Moghadam, H., Del Bakhshayesh, A. R., Mohammadnejad, D., and Mehdipour, A. "A Review on the Effect of Nanocomposite Scaffolds Reinforced with Magnetic Nanoparticles in Osteogenesis and Healing of Bone Injuries." *Stem Cell Research & Therapy*, 14, 194, 2023. doi:10.1186/s13287-023-03426-0.

[7] Poggetti, A., Battistini, P., Parchi, P. D., Novelli, M., Raffa, S., Cecchini, M., Nucci, A. M., and Lisanti, M. "How to Direct the Neuronal Growth Process in Peripheral Nerve Regeneration: Future Strategies for Nanosurfaces Scaffold and Magnetic Nanoparticles." *Surgical Technology International*, 30, 458–461, 2017.

[8] Escobar, A., Reis, R. L., and Oliveira, J. M. "Nanoparticles for Neurotrophic Factor Delivery in Nerve Guidance Conduits for Peripheral Nerve Repair." *Nanomedicine*, 17(7), 477–494, 2022. doi:10.2217/nnm-2021-0413.

[9] Rossi, A., Bassi, G., Cunha, C., Baldisserri, C., Ravaglia, N., Gardini, D., et al. "Magnetically Induced Anisotropic Structure in an Injectable Hydrogel for Skeletal Muscle Regeneration." *Journal of Colloid and Interface Science*, 678, 334–345, 2025. doi:10.1016/j.jcis.2024.09.121.

[10] Meng, J., Xiao, B., Zhang, Y., Liu, J., Xue, H., Lei, J., et al. "Super-Paramagnetic Responsive Nanofibrous Scaffolds under Static Magnetic Field Enhance Osteogenesis for Bone Repair in Vivo." *Scientific Reports*, 3, 2655, 2013. doi:10.1038/srep02655.
[11] Maier-Hauff, K., Ulrich, F., Nestler, D., Niehoff, H., Wust, P., Thiesen, B., et al. "Efficacy and Safety of Intratumoral Thermotherapy Using Magnetic Iron-Oxide Nanoparticles Combined with External Beam Radiotherapy on Patients with Recurrent Glioblastoma Multiforme." *Journal of Neuro-Oncology*, 103, 317–324, 2011.
[12] Shirvalilou, S., Khoei, S., Khoee, S., and Raoufi, N. J. "Magnetic Hyperthermia as an Adjuvant Cancer Therapy in Combination with Radiotherapy versus Radiotherapy Alone for Recurrent/Progressive Glioblastoma: A Systematic Review." *Journal of Neuro-Oncology*, 2021.
[13]Qazi, M. A., & Sohail, N. (2026). Factors influencing the intention to engage in socially responsible investing. *Journal of Economic Innovation and Development, 1*(1), 21–30. https://doi.org/10.65072/jeid.v1i1.3
[14]Mousumi, A., & Sohail, N. (2026). Service quality, engagement, and loyalty in Malaysian telecom. *International Journal of Business and Social Science Studies, 6*(1). https://ijbsss.com/index.php/IJBSSS/index
[15]Singh, H. S. J., & Sohail, N. (2026). Medical negligence in Malaysian hospitals: A qualitative thematic analysis of organisational and governance failures. *Journal of Innovation and Research in Technology, 3*(2). https://doi.org/10.66857/jirt.v3i2.38