

ISSN: 2637-8078



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Submission:  May 19, 2025

Published:  May 28, 2025

Volume 7 - Issue 3

How to cite this article: Nan Wang, Shaohui Jiang, Yunwei Zhang, Yawen Song, Hong Chen, Feilin Wang and Jingyu Li*. Application of Transcranial Magnetic Stimulation in Urological Surgery: From Neuromodulation to Pelvic Floor Functional Reconstruction. Significances Bioeng Biosci. 7(3). SBB. 000663. 2025. DOI: [10.31031/SBB.2025.07.000663](https://doi.org/10.31031/SBB.2025.07.000663)

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Application of Transcranial Magnetic Stimulation in Urological Surgery: From Neuromodulation to Pelvic Floor Functional Reconstruction

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Abstract

Benign Prostatic Hyperplasia (BPH) and prostate cancer are common urological diseases in elderly men. Transurethral Resection of the Prostate (TURP) and Laparoscopic Radical Prostatectomy (LRP) are the standard treatments. However, the incidence of Postoperative Transient Urinary Incontinence (POUI) is as high as 30%-49%, with 15% to 20% progressing to persistent urinary incontinence [1]. This complication not only increases healthcare costs, but also severely impacts the quality of life through multiple dimensions, including skin infections, psychological obstacle and social avoidance. Traditional rehabilitation methods have significant limitations. The therapeutic effect of Pelvic Floor Muscle Training (PFMT) relies on patient compliance; biofeedback therapy requires specialized equipment support and has a limited popularity rate; pharmacotherapy is only effective for some symptomatic urinary incontinence; and invasive surgeries carry risks like postoperative avoiding dysfunction. These approaches fail to overcome the challenges of prolonged recovery times and interindividual variability in outcomes [2]. Transcranial Magnetic Stimulation (TMS), as a noninvasive brain stimulation technique, offers a novel strategy for urological functional reconstruction. By modulating the excitability of cortical-spinal-peripheral neural pathway via time-varying magnetic fields, TMS has the advantages of precise targeting, multiparameter regulation, and non-invasive safety. Recent studies demonstrate that TMS combined with conventional therapies significantly shortens urinary incontinence recovery time, improves urodynamic parameters and quality-of-life scores. These findings suggest that TMS is expected to break through the existing treatment paradigm through the regulation of the "central-peripheral" dual pathways and open up a new path for pelvic floor function reconstruction [3].

Keywords: Postoperative Transient Urinary Incontinence (POUI); Transcranial Magnetic Stimulation (TMS); Pelvic Floor Muscle Training (PFMT); Stress; Magnetic fields

Introduction

The biological basis of neuromodulation: From electromagnetic induction to synaptic plasticity

The core principle of Transcranial Magnetic Stimulation (TMS) is based on Faraday's law of electromagnetic induction. High-frequency pulsed currents in a scalp-positioned coil generate time-varying magnetic fields that penetrate the skull, inducing reverse eddy currents in the cerebral cortex. When these currents exceed neuronal excitation thresholds, localized depolarization occurs, generating action potentials, conducting along axons, and ultimately

regulating peripheral neuromuscular activity via corticospinal tracts [4]. This process not only achieves precise intervention in the central nervous system, but also provides support for neuromodulation for pelvic floor dysfunction through synaptic plasticity regulation. Neural plasticity, as the core mechanism by which the nervous system adapts to environmental changes, plays a pivotal role in the therapeutic effects of Transcranial Magnetic Stimulation (TMS). Synaptic plasticity, one of its primary manifestations, is predominantly mediated through two mechanisms: Long-Term Potentiation (LTP) and Long-Term Depression (LTD). LTP involves sustained enhancement of synaptic transmission efficacy following high-frequency neural activity, whereas LTD reflects synaptic weakening induced by low-frequency activity [5]. TMS parameter design leverages these plasticity mechanisms: high-frequency repetitive TMS (>5Hz) enhances neuronal excitability in target regions by inducing LTP-like effects, while low-frequency stimulation (<1Hz) reduces pathological hyperexcitability through LTD-like effects. This bidirectional modulation enables TMS to achieve personalized interventions tailored to distinct pathological mechanisms.

Frequency-specific regulation: From basic research to clinical translation

The stimulation frequency of Transcranial Magnetic Stimulation (TMS) is a critical parameter determining its neuromodulation direction. High-frequency stimulation* (typically 10-20 Hz) promotes Long-Term Potentiation (LTP)-like effects, significantly enhancing neuronal excitability and synaptic connection strength in target regions. In pelvic floor rehabilitation field, this effect has dual significance: high-frequency repetitive TMS (rTMS) not only strengthens the corticospinal drive from the primary motor cortex (M1) to pelvic floor muscles, improving muscle strength and coordination, but also activates spinal pathways to facilitate neural circuit reorganization. Preclinical studies demonstrate that high-frequency stimulation of the M1 region in rats with suprasacral spinal cord injury significantly increases pelvic floor Motor Evoked Potential (MEP) amplitudes and partially restores micturition function. Low-frequency stimulation (<1Hz) exerts unique therapeutic advantages in urgency urinary incontinence by inducing Long-Term Depression (LTD)-like effects to reduce neuronal excitability. Such patients often exhibit central sensitization associated with bladder overactivity. Low-frequency TMS may disrupt the “bladder-central” vicious feedback loop by suppressing abnormal hyperactivity in the Dorsolateral Prefrontal Cortex (DLPFC) or insula. Notably, frequency selection is not absolute: emerging Theta Burst Stimulation (TBS) patterns, mimicking natural brainwave rhythms, achieve efficient neuromodulation at lower stimulation intensities, offering a novel approach for clinical applications [6].

Urinary incontinence subtypes and parameter personalization: From mechanistic heterogeneity to protocol customization

The distinct pathophysiological mechanisms of Stress Urinary Incontinence (SUI) and Urgency Urinary Incontinence (UUI)

necessitate precise alignment of Transcranial Magnetic Stimulation (TMS) protocols. In SUI, characterized by pelvic floor muscle laxity and urethral sphincter dysfunction, therapeutic strategies focus on enhancing excitability of corticospinal-peripheral neural pathways. Based on this, high-frequency repetitive TMS (rTMS, 10-20Hz) targeting the M1 region or paracentral lobule is the preferred approach. Functional MRI (fMRI) studies demonstrate that such stimulation significantly increases cerebral blood flow in pelvic floor muscle representation areas and shortens Motor Evoked Potential (MEP) latency, objectively reflecting improved neural conduction efficiency. For UUI, treatment prioritizes suppression of aberrant neural signaling associated with bladder overactivity. Low-frequency TMS (1Hz) applied to the Dorsolateral Prefrontal Cortex (DLPFC) may alleviate urinary urgency by regulating connectivity between emotional centers and bladder control networks. Notably, some studies, attempting to use bilateral DLPFC stimulation, has shown promise in improving subjective urgency scores and lowering bladder sensory thresholds for objective efficacy [7]. However, current parameter selection lacks robust large-scale RCT evidence, underscoring the need for future development of personalized stimulation protocols based on urodynamic parameters.

Precision targeting techniques: From anatomical navigation to functional guidance

The therapeutic efficacy of Transcranial Magnetic Stimulation (TMS) is highly dependent on targeting precision, for which modern neuro navigation technology provides revolutionary solutions. Anatomical navigation systems based on structural Magnetic Resonance Imaging (sMRI) achieve millimeter-level targeting accuracy through individualized scalp fiducial markers, ensuring precise alignment of the stimulation coil with the M1 region or paracentral lobule. More advanced protocols integrate functional MRI (fMRI) data to achieve activity-guided targeting, such as identifying Blood Oxygen Level-Dependent (BOLD) signal hotspots in the M1 region during pelvic floor muscle activation in Stress Urinary Incontinence (SUI) patients, thereby significantly improving stimulation specificity. Electrophysiological guidance provides the possibility of real-time feedback regulation. Monitoring Motor Evoked Potentials (MEPs) can not only verify corticospinal tract integrity but also facilitate individualized threshold determination through stimulus intensity adjustment. In spinal cord injury patients, combining TMS with Electromyography (EMG) to record pelvic floor MEPs allows quantitative assessment of preserved corticofugal innervation, providing an objective basis for parameter optimization [8]. Notably, the emerging TMS-Electroencephalography (TMS-EEG) technology records post-stimulation electroencephalographic responses to monitor real-time changes in neural network excitability, laying the foundation for the development of closed-loop neuromodulation systems.

Neuroanatomical basis for urological applications: From cortical regulation to peripheral effects

The applicability of Transcranial Magnetic Stimulation (TMS) in urology stems from its direct neuromodulation capacity on pelvic floor neural pathways. Anatomical studies demonstrate that

the pelvic floor musculature receives dual innervation: “somatic nerves” originate from the ventral horn of the sacral spinal cord (S2-S4), while “autonomic nerves” arise from the thoracolumbar sympathetic trunk and pelvic splanchnic nerves. TMS enhances corticospinal tract drive to sacral motor neurons by activating pyramidal neurons in the M1 region, thereby directly improving pelvic muscle contractile force. Furthermore, stimulation of the paracentral lobule may influence coordination between bladder storage and voiding phases by regulating connectivity between micturition centers and cortical regions. Animal studies have further elucidated the neuroprotective effects of TMS. In rat spinal cord transection models, high-frequency TMS intervention can promote synaptic regeneration of injured ventral horn motor neurons and restore bladder-sphincter synergic function. This effect may correlate with upregulated expression of Brain-Derived Neurotrophic Factor (BDNF), suggesting that TMS not only exerts acute neuromodulation effects but may also achieve long-term therapeutic efficacy through enhancing neural plasticity [9].

Clinical Application Progress of TMS in Urology

Accelerated recovery for post-prostatectomy urinary incontinence

Post-prostatectomy urinary incontinence is a common complication in urological surgery, significantly impacting patients' quality of life postoperatively. Recently, Transcranial Magnetic Stimulation (TMS), as an adjunctive treatment, has shown significant advantages in accelerating the recovery of urinary control function. In clinical practice, we adopt individualized stimulation protocols. First, the Resting Motor Threshold (RMT) is determined through measurement of Motor Evoked Potential (MEP), and the stimulation intensity is set based on this value (usually at 110% RMT) [10]. Three sets of parameter schemes have been designed for various anatomical targets:

Sacral nerve root stimulation: High-frequency stimulation (10Hz) with continuous output of 1200 pulses. This protocol directly targets the sacral micturition center through enhanced corticospinal excitability, promoting urethral sphincter function recovery; Suprapubic Stimulation: Intermittent stimulation at 5Hz frequency, each burst consisting of 25 pulses over 20 bursts with a 10-second interval between bursts. This scheme activates somatic nerve innervation of the pelvic floor muscles, improving muscle coordination; Perineal Stimulation: Parameters are set similarly to suprapubic stimulation, requiring patient cooperation by actively contracting the pelvic floor muscles according to the stimulation rhythm, forming a “stimulation-active contraction” neuromuscular coupling pattern.

Clinical data indicate that patients receiving TMS-assisted therapy have shorter times to recover urinary continence compared to controls, with reduced rates of severe urinary incontinence. Urodynamics show increased Maximum Urethral Closure Pressure (MUCP) and elevated bladder neck height, suggesting multi-target regulation optimizing the biomechanics of the urethral support structures. The analysis of urination diaries further confirms

fewer daytime leakage episodes and nighttime awakenings, along with improved quality-of-life scores (I-QOL). (The final data of our research team is expected to be released by the end of this year).

Functional reconstruction of neurogenic bladder dysfunction

Neurogenic bladder dysfunction is a common complication following Spinal Cord Injury (SCI) or Multiple Sclerosis (MS), challenging due to restoring detrusor-sphincter synergy. A randomized controlled trial conducted by El-Habashy et al. [11] demonstrated that MS patients treated with TMS had a 67% improvement rate in Lower Urinary Tract Symptoms (LUTS) compared to sham-stimulated groups. It was specifically manifested as: The frequency of frequent urination decreased by 58% (from an average of 12.3 times per day to 5.2 times per day; The severity score of urgency decreased by 62% (Visual Analogue Scale, AS); The incidence of urinary incontinence has decreased 71%. Mechanistic studies have revealed that Transcranial Magnetic Stimulation (TMS) achieves functional reorganization by regulating neural pathways in the cerebral cortex that control lower urinary tract function. In Spinal Cord Injury (SCI) animal models, high-frequency TMS intervention can promote axonal regeneration in the corticospinal tract and enhance the regulatory capacity of the pontine micturition center over sacral spinal reflex arcs. Notably, TMS exerts dual regulatory effects on detrusor-sphincter synergy: in SCI rats, TMS not only suppresses detrusor overactivity but also strengthens phasic contractions of the external urethral sphincter, resulting in a 43% improvement in voiding efficiency [11].

Neuromodulation therapy for Overactive Bladder (OAB)

Overactive bladder (OAB) presents significant unmet clinical needs in both pediatric and adult female populations. For refractory OAB cases that anticholinergic medications fail, Transcranial Magnetic Stimulation (TMS) offers a novel therapeutic option. Kemp, Breported on a cohort of 48 female patients, showing that among the 26 who completed the treatment, 84.6% achieved symptom improvement, which was specifically manifested as: daytime urgency episodes decreased by approximately 76%, urge urinary incontinence frequency declined by about 82%, and mean voided volume increased by around 65ml [12]. In pediatrics, Barroso Jr. et al. [13] study on Percutaneous Nerve Electrical Stimulation (PENS) provides indirect evidence supporting TMS application. This study demonstrated that 66% of children with OAB showed symptom relief after PENS treatment, with urodynamic indices indicating an increase in bladder capacity by 37% and a reduction in detrusor instability contractions by 81%. Given TMS's deeper tissue penetration and more precise target localization, its potential in treating childhood OAB deserves further exploration [13].

Novel interventions for Chronic Pelvic Pain Syndrome (CPPS)

Chronic Pelvic Pain Syndrome (CPPS) is a challenging condition in urology, involving complex interactions between central sensitization and peripheral sensitization. Relevant studies show that TMS treatment can reduce CPPS patients' Numerical Rating

Scale (NRS) scores for pain by 58% and improve quality-of-life scores (SF-36) by 2.3 times. Mechanism studies suggest that TMS may regulate abnormal activities in the Anterior Cingulate Cortex (ACC) and insula, breaking the “pain-anxiety” vicious cycle [14]. For Interstitial Cystitis (IC), some exploratory studies have confirmed that TMS can significantly improve the Bladder Pain Syndrome Score (BPSS) and O’Leary-Sant Symptom Index. The specific therapeutic effects include a 69% decrease in daytime pain episodes, a 73% reduction in nocturia episodes, and a 52% increase in maximum bladder capacity [15]. Luo, Chunmei’s review further highlighted that the therapeutic effects of Transcranial Magnetic Stimulation (TMS) on chronic pelvic pain may stem from its regulatory action on the Default Mode Network (DMN). By reducing functional connectivity between the medial Prefrontal Cortex (mPFC) and the Posterior Cingulate Cortex (PCC), TMS can attenuate the abnormal amplification of pain signals within the cerebral cortex [16].

Key Issues in Clinical Transformation

Despite the promising applications of Transcranial Magnetic Stimulation (TMS) in urology, three major challenges must be addressed for successful clinical translation: Individualized Treatment Protocols: A database of stimulation parameters based on the patient’s age, etiology, and disease course needs to be established. For example, spinal cord injury patients may require higher stimulation intensities (120% RMT) and longer treatment durations (over six weeks), whereas Overactive Bladder (OAB) patients respond better to low-frequency stimulation (1Hz). Development of Efficacy Prediction Biomarkers: Combining resting-state functional MRI (rs-fMRI) and Electroencephalography (EEG) technologies can help identify biomarkers that predict good responses to TMS treatment. Preliminary research indicates a positive correlation between pre-treatment Default Mode Network (DMN) connectivity strength and TMS efficacy ($r=0.72$, $p<0.001$). Strategies for Maintaining Long-Term Efficacy: Exploring synergistic effects of combining TMS with Pelvic Floor Muscle Training (PFMT) and biofeedback therapy is crucial. Animal studies have confirmed that combined TMS and PFMT increase pelvic floor muscle cross-sectional area by 41%, which is significantly more effective than single-modality interventions ($p<0.01$) [15]. Future research should focus on developing closed-loop neuromodulation systems to achieve dynamic adjustment of stimulus parameters, through real-time monitoring of bladder pressure and brain activity. Additionally, conducting multi-center and large-scale randomized controlled trials will establish guidelines for TMS treatments based on disease classification, facilitating the transition from experimental research to clinical practice.

Clinical Advantages and Challenges

Transcranial Magnetic Stimulation (TMS) has demonstrated unique clinical advantages in urology. Its non-invasive nature avoids the possible side effects of pharmacotherapy, such as anticholinergic adverse reactions like dry mouth and constipation, while also avoiding the risks of infection and bleeding brought about by surgical operations. The treatment process is simple.

Patients only need regular outpatient treatment without anesthesia or hospitalization, which significantly improves safety and patient tolerance. In addition, TMS can synergize with traditional therapies like pelvic floor muscle training and biofeedback, enhancing the overall efficacy through the dual mechanisms of central nervous system regulation and peripheral muscle strengthening. However, several challenges remain in the clinical application of TMS. At present, there are significant variations among different studies regarding stimulus frequency, intensity, and treatment course, lacking unified treatment standards [16]. To some extent, this variability affects the reproducibility and clinical applicability of therapeutic outcomes. Furthermore, most studies have short follow-up periods, resulting in insufficient systematic evaluation of long-term efficacy and safety of TMS. Moreover, the high cost of TMS therapy limits its application in regions with limited medical resources.

Future Research Directions

In the future, the research of TMS in urology will focus on the following aspects. First of all, precision medicine. It will become an important direction by combining functional Magnetic Resonance Imaging (fMRI), Diffusion Tensor Imaging (DTI) and other images Imaging techniques, as well as urodynamic parameters, serum biomarkers, etc., are used to formulate individualized treatment plans. Secondly, technological innovation will drive the optimization of TMS devices, such as developing dedicated stimulation coils for pelvic floor structures to enhance the accuracy and depth of stimulation. In addition, mechanism exploration will deeply analyze the specific regulatory pathways of TMS on the pelvic floor neural circuits, reveals its mechanism through means such as animal experiments, and provide theoretical support for clinical applications [17]. Meanwhile, multi-center and large-sample clinical studies will contribute to reach a therapeutic consensus on TMS in urology and promote its standardized and normalized application.

Acknowledgment

Compliance with ethical standards

Author Contributions Statement

Nan Wang: Wrote the main manuscript text; Shaohui Jiang: Wrote the main manuscript text; Yunwei Zhang: Supervision Data curation and Formal analysis; Yawen Song: Supervision Data curation and Formal analysis; Hong Chen: Wrote a part of the manuscript text; Feilin Wang: Wrote a part of the manuscript text; Jingyu Li: Review and Editing. All authors reviewed the manuscript.

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