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Review

Non-invasive brain stimulation research in South Korea: Current trends, challenges, and future directions

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Abstract

Objectives: In this review, we summarize the development, current landscape, and future directions of non-invasive brain stimulation (NIBS) research in South Korea.

Materials and methods: A narrative review of South Korean studies investigating repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) in patients with stroke, traumatic brain injury (TBI), and parkinsonism was conducted in the PubMed database. No date restrictions were applied. Eligible studies included randomized- and non-randomized-controlled trials, pilot studies, and pre-post designs that reported outcomes in motor, cognitive, swallowing, and language functions. A comprehensive search was performed in PubMed without time restrictions and was limited to peer-reviewed publications in English.

Results: As of 2006, 88 studies were identified in the literature search. Most studies (n=40) focused on motor rehabilitation after stroke, primarily targeting upper limb function, gait, and balance. Both rTMS and tDCS demonstrated efficacy, with recent studies integrating tDCS with virtual reality and robot-assisted therapies. Despite promising findings, a large randomized-controlled trial failed to show significant improvement in upper limb function with rTMS. Subgroup analysis indicated efficacy in patients without cortical involvement. A new study focusing on subcortical stroke populations was ongoing at the time of this review. Studies on post-stroke cognition (n=20) primarily conducted between 2008 and 2015 addressed visuospatial neglect, memory, and attention. Although only a few recent studies exist, an emerging trial on home-based tDCS suggests its potential for remote cognitive rehabilitation. In patients with parkinsonism (n=13), rTMS improved freezing of gait and gait dysfunction, whereas tDCS studies have recently been expanded to address dual-task performance. Research on dysphagia (n=7) and aphasia (n=5) in stroke patients reported favorable outcomes. Studies on TBI (n=3) remain limited and primarily target cognitive and swallowing functions.

Conclusion: Studies of NIBS in South Korea have usually reported positive outcomes across a range of functional domains. Recent research indicates a shift toward individualized and technology-assisted approaches, including home-based tDCS and rTMS guided by functional near-infrared spectroscopy. Future investigations should focus on the development and evaluation of adaptive, personalized NIBS strategies to optimize therapeutic efficacy.

Keywords: Non-invasive brain stimulation, parkinsonism, repetitive transcranial magnetic stimulation, transcranial direct current stimulation, traumatic brain injury, stroke.

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Neuromodulation refers to the alteration or regulation of neural activity in the central, peripheral, or autonomic nervous system through the targeted delivery of electrical or electromagnetic stimulation.[1] In recent years, it has gained increasing attention in neurorehabilitation as a means of facilitating functional recovery in individuals with neurological disorders.[2,3] Among the various approaches, non-invasive brain stimulation (NIBS) techniques, such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS), have been widely investigated and applied in the rehabilitation of patients with stroke, traumatic brain injury (TBI), and parkinsonism. A growing body of evidence supports their therapeutic potential across diverse functional domains, including motor, cognitive, language, and swallowing functions.[4-7]

Over the past two decades, global interest in NIBS has grown considerably. Simultaneously, there has been a notable increase in research on NIBS in the field of rehabilitation in South Korea.[8-11] Although these studies have meaningfully contributed to global evidence, several important limitations remain. To guide future development, a structured review is needed to identify current trends and methodological gaps in South Korean NIBS research. However, to date, no systematic review has been conducted to comprehensively evaluate the scope and characteristics of NIBS research in South Korea.

In this review, we summarize landmark clinical trials, identify major limitations, assess current regulatory considerations, and discuss future directions for NIBS. The primary focus is on the rehabilitation-oriented applications of rTMS and tDCS in individuals with stroke, parkinsonism, and TBI across functional domains, including motor, speech, swallowing, and cognition.

MATERIALS AND METHODS

Search strategy

A comprehensive literature search was performed using the PubMed database to identify relevant studies. No date restrictions were applied. The search strategy included a combination of Medical Subject Headings and free-text keywords related to "stroke," "traumatic brain injury," "Parkinson's disease," "rTMS," and "tDCS," combined with "Korea" or "Korean." A total of 298 studies were identified through database searches. After screening the titles and abstracts, 191 studies were excluded, and 107 full-text studies were assessed for eligibility. Following a full-text review, 19 additional studies were excluded, resulting in 88 studies being included in the final review (Figure 1).

Study selection criteria

Inclusion criteria were as follows: (1) studies involving human participants with stroke, TBI, or parkinsonism; (2) the intervention included rTMS or tDCS; (3) outcomes were reported in at least one of the following domains: motor, cognition, language, or swallowing; (4) the study was conducted in South Korea; and (5) the article was published in English in a peer-reviewed journal. The detailed inclusion and exclusion criteria are presented in Table 1.

Data extraction and synthesis

Study selection and data extraction were performed by the first author and independently reviewed by a second reviewer, with complete agreement on study inclusion. The following information was extracted from each study: study design, population characteristics, intervention and control conditions, stimulation parameters, and main findings. Given the narrative nature of this review, a quantitative meta-analysis was not performed. Instead, the findings were synthesized descriptively. Studies were grouped by neurological condition (stroke, TBI, or parkinsonism) and further categorized by primary functional outcome domains (motor, cognitive, language, and swallowing). To highlight research trends over time, the studies were presented in chronological order.

RESULTS

Rapid review

A total of 88 studies met the inclusion criteria, with the earliest study published in 2006. The number of publications increased over time, peaking in 2015, and remained relatively stable in the subsequent years (Figure 2). The majority of

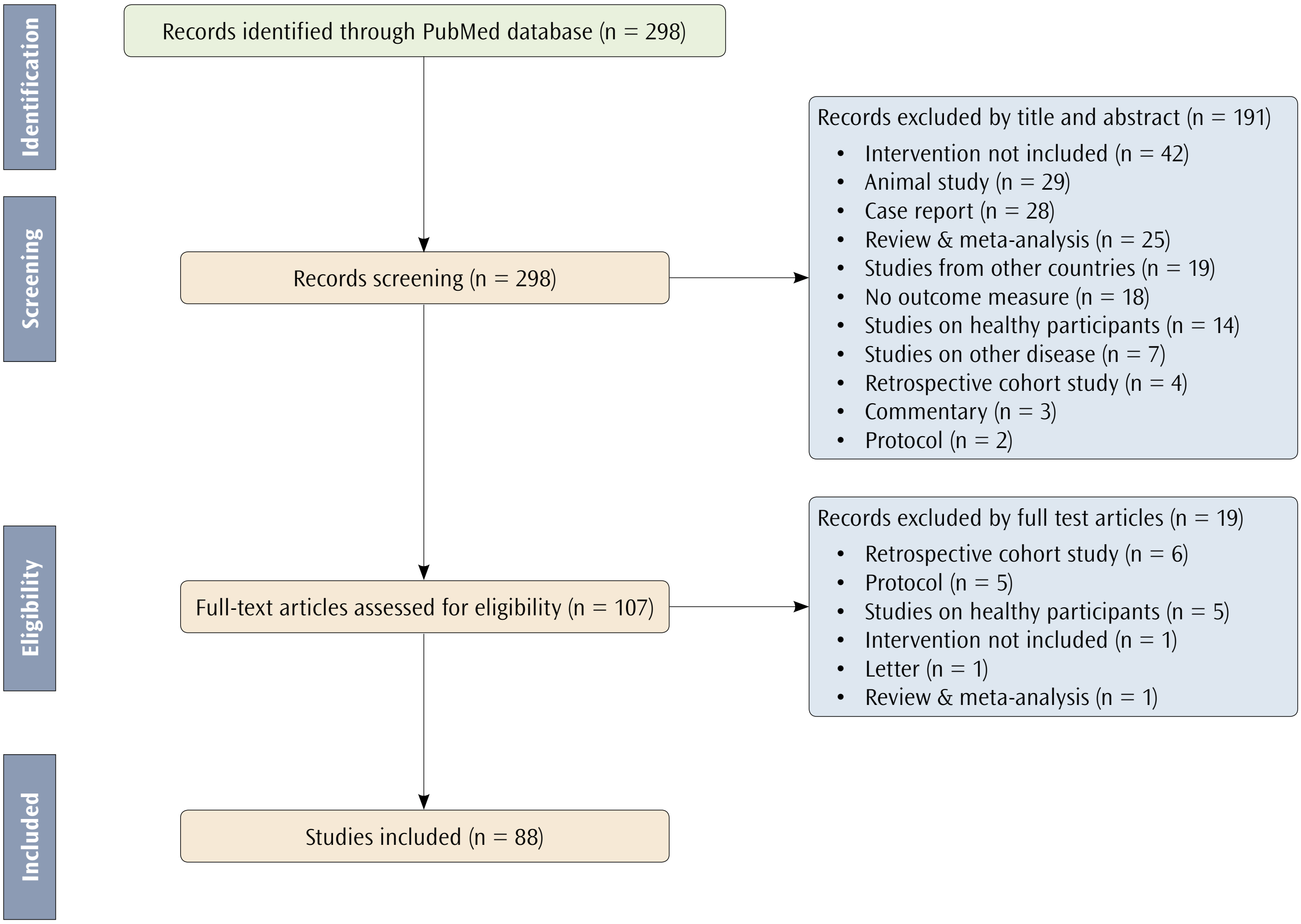

Figure 1. Flow diagram.

studies focused on stroke (n = 72, 81.8%), followed by parkinsonism (n = 13, 14.8%) and TBI (n = 3, 3.4%).

Among stroke-related studies, motor function was the most frequently investigated domain (n = 40, 55.6%), with a primary focus on upper limb

Table 1. Eligibility criteria for studies included in the narrative review

	Inclusion criteria	Exclusion criteria
Population	Patients with stroke (ischemic or hemorrhagic), TBI, or parkinsonism	Other conditions
Intervention	rTMS, tDCS	Other neuromodulation (e.g. DBS and VNS.) or no neuromodulation
Comparison	Pre-post comparison or sham/control group	No comparison or pre-post data
Outcome	Motor, aphasia, dysphagia, or cognitive improvement	No relevant functional outcome reported
Study design	RCTs, CCTs, pilot studies, and pre-post studies	Animal studies, reviews, case reports, protocols, and retrospective cohort study
Publication	Conducted in Korea and published in peer-reviewed English journals	Conducted in other countries

TBI, traumatic brain injury; rTMS, repetitive transcranial magnetic stimulation; tDCS, transcranial direct current stimulation; DBS, deep brain stimulation; VNS, vagus nerve stimulation; RCTs, randomized- controlled trials; CCTs, controlled clinical trials.

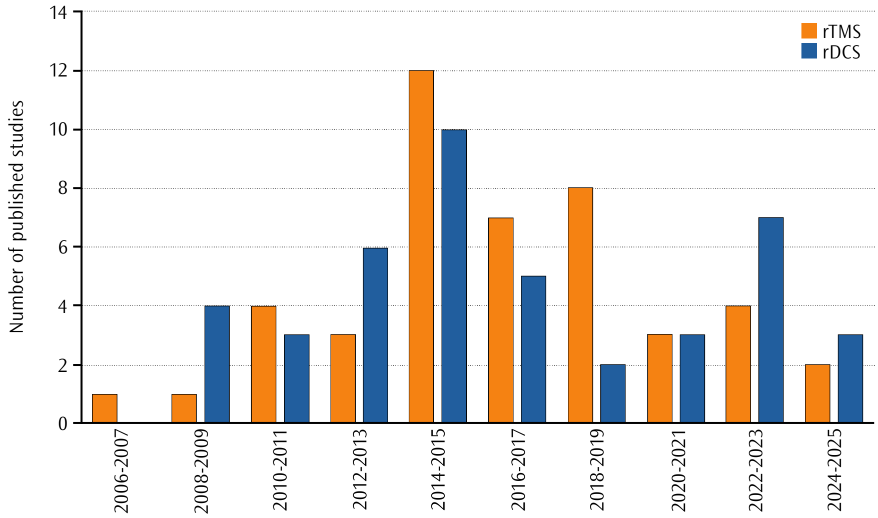

Figure 2. Annual distribution of NIBS studies in South Korea (2006-2025).

NIBS, non-invasive brain stimulation; rTMS, repetitive transcranial magnetic stimulation; tDCS, transcranial direct current stimulation.

function, gait, and balance. Cognitive function was addressed in 20 studies (27.8%), particularly in relation to visuospatial neglect, attention, and memory. Language (n = 5, 6.9%) and swallowing function (n = 7, 9.7%) were investigated less frequently. In terms of intervention modality, rTMS was applied in 45 studies and tDCS in 43 studies. A comprehensive summary of the included studies, categorized by target condition, functional domain, and stimulation technique, is provided in supplementary digital content Tables 1-7.

Stroke

Motor function

Among the 40 studies on motor recovery following stroke, rTMS and tDCS were each investigated in 20 studies. Key representative studies are summarized in Tables 2 (rTMS) and 3 (tDCS). The earliest Korean study that applied high-frequency rTMS to patients with chronic stroke examined its effects on corticomotor excitability and motor skill acquisition. The rTMS group showed significantly greater increases in motor-evoked potential (MEP) amplitude ($F[8, 112] = 17.01$, $p < 0.01$) and greater improvements in movement accuracy ($F[7, 196] = 6.92$, $p < 0.01$) than the sham group.[12]

Notably, several studies were the earliest to explore the novel applications of rTMS in neurorehabilitation. One randomized, sham-controlled trial investigated the long-term effects of multisession high-frequency rTMS on upper limb recovery after stroke. The study demonstrated that 10 consecutive daily sessions of 10 Hz rTMS led to additional and sustained improvements in upper limb function. Improvements in Fugl-Meyer Assessment for Upper Limb (FMA-UL) and grip strength were found only in the real rTMS group ($p < 0.05$). In addition, the increase in Motricity Index-Arm scores was significantly greater in the real rTMS group than in the sham group ($F[2, 52] = 4.07$, $p < 0.05$), with benefits maintained for up to three months.[13] Kim et al.[14] further expanded the scope of rTMS by applying cerebellar rTMS to patients with posterior circulation stroke and cerebellar ataxia, showing promising improvements in balance and gait. In the real rTMS group, significant improvements in the Berg Balance Scale (BBS) were observed both immediately after the last session ($p = 0.004$) and at one-month follow-up ($p = 0.001$), whereas time and step count in the 10-meter walk test (10MWT) improved significantly only at one month. Although between-group differences were not statistically significant, within-group analysis showed functional gains in the real rTMS group,

Table 2. Representative rTMS studies on motor function in South Korea

Source	Total	Stage	Target	Design	Stimulation site	Frequency (Hz)	Intensity (%)	No. of pulses per session	Duration	Comparison group	Concurrent therapy	Main findings
Kim et al.[12] (2006)	15	Subacute stroke	Mortor learning, CME	RCT (crossover)	M1 (affected, hand area)	10	80 RMT	160	1 session/ condition; 1-week interval	Sham (coil tilted)	Sequential finger motor task	Improved accuracy, speed and CME *vs.* sham (all $p < 0.01$)
Chang et al.[13] (2010)	28	Subacute stroke	UL motor recovery	RCT	M1 (affected, hand area)	10	90 RMT	1,000	10 sessions (2 weeks)	Sham (coil tilted)	Reaching/ grasping task	Improved MI-A, FMA-UL, GS *vs.* sham; sustained at 3 months (all $p < 0.05$)
Kim et al.[14] (2014)	32	Acute posterior circulation stroke	Gait, balance	RCT	Cerebellum (unaffected)	1	100 RMT	900	5 sessions (5 days)	Sham (coil tilted)	Gait and balance training	Improved 10 MWT and BBS ($p = 0.004$ post, $p = 0.001$ at 1 month); no group difference
Kim et al.[17] (2020)	77	Subacute stroke	UL motor recovery	RCT	M1 (unaffected, hand area)	1	100 RMT	1,800	10 sessions (2 weeks)	Sham (coil tilted)	Task-based OT (30 min)	Subgroup (subcortical) improved BBT, Brunnstrom stage *vs.* sham ($p = 0.017–0.023$)

rTMS, repetitive transcranial magnetic stimulation; CME, corticomotor excitability; RCT, randomized- controlled trial; RMT, resting motor threshold; UL, upper limb; MI-A, Motor Index (arm); FMA-UL, Fugl-Meyer Assessment (upper limb); GS, grip strength; 10 MWT, 10-Meter Walk Test; BBS, Berg Balance Scale; BBT, Box and Block Test.

Table 3. Representative tDCS studies on motor function in South Korea

Source	Total	Stage	Target	Design	Stimulation site	Intensity (mA)	Duration (min)	Schedule	Comparison group	Concurrent therapy	Main findings
Kim et al.[18] (2010)	18	Subacute stroke	UL motor recovery	RCT	atDCS:M1 (affected) ctDCS: M1 (unaffected)	2	20	10 sessions (2 weeks)	atDCS *vs.* ctDCS *vs.* sham	OT 30 min	ctDCS improved FMA *vs.* sham; at 6 months ($p < 0.05$)
Lee et al.[19] (2014)	59	Subacute stroke	UL motor recovery	RCT	ctDCS: M1 (unaffected)	2	20	15 sessions (3 weeks)	tDCS *vs.* VR *vs.* tDCS+VR	Group A: tDCS; Group B: VR; Group C: tDCS+VR	tDCS+VR improved MFT, FMA *vs.* tDCS or VR only ($p = 0.021–0.030$)
Kim et al.[20] (2024)	24	Chronic stroke	Gait	RCT	HD-tDCS: Leg M1 (Cz-centered)	2	30	10 sessions (4 weeks)	Sham (Identical montage, 0 mA)	RACT 30 min	Improved 10 MWT, TUG, BBS, DGI, FMA-LE *vs.* sham; sustained at 1 month (all $p < 0.05$)

tDCS, transcranial direct current stimulation; UL, upper limb; RCT, randomized- controlled trial; atDCS, anodal transcranial direct current stimulation; ctDCS, cathodal transcranial direct current stimulation; OT, occupational therapy; FMA, Fugl-Meyer Assessment; VR, virtual reality; MFT, manual function test; HD-tDCS, high-definition transcranial direct current stimulation; RACT, robot-assisted gait training; 10 MWT, 10-meter walk test; BBS, Berg Balance Scale; DGI, dynamic gait index; FMA-LE, Fugl-Meyer Assessment for Lower Extremity.

with the notable effect sizes (−0.17 for time in 10MWT, −0.33 for steps, and 0.11 for BBS).

Beyond these landmark studies, several trials have reported positive effects of rTMS on upper limb motor recovery in stroke patients.[15,16] However, a large-scale randomized-controlled trial (RCT) involving 77 patients with subacute ischemic stroke failed to demonstrate significant improvements in upper limb function following low-frequency rTMS compared to sham stimulation. Remarkably, subgroup analysis showed that patients without cortical involvement (i.e., those with subcortical lesions) exhibited greater functional gains. At one-month post-treatment, the Box and Block Test improved more in the real rTMS group than in the sham group (17.4 ± 9.8 real *vs.* 10.9 ± 10.3 sham, $p = 0.023$). Other measures, including the finger tapping test (11.6 ± 8.1 real *vs.* 5.8 ± 8.4 sham, $p = 0.017$), and Brunnstrom hand stage (0.6 ± 0.5 real *vs.* 0.2 ± 0.5 sham, $p = 0.023$), also favored in the real rTMS group.[17]

In studies investigating tDCS, Korean researchers have explored a range of innovative protocols for post-stroke rehabilitation. To the best of our knowledge, one early study was the first to investigate the long-term effects of both anodal and cathodal tDCS on upper limb motor recovery. In an RCT involving three groups (anodal stimulation, cathodal stimulation, and sham stimulation), cathodal tDCS resulted in significantly greater improvements in the FMA score at six-month follow-up compared to sham stimulation ($p < 0.05$; time: $F[2, 30] = 16.95$, $p < 0.001$; interaction: $F[4, 30] = 3.55$, $p = 0.017$).[18]

Recent studies have increasingly explored the integration of tDCS with other rehabilitation technologies to enhance therapeutic outcomes. One study pioneered the combination of cathodal tDCS with virtual reality-based rehabilitation to promote upper limb motor recovery. In this pilot RCT involving 59 patients, the combination group showed significantly greater improvements in upper limb motor function than those receiving either intervention alone, as measured by the Manual Function Test (4.7 ± 3.3 *vs.* 2.4 ± 1.9 and 4.3 ± 3.8, $p = 0.021$) and the FMA score (10.3 ± 5.0 *vs.* 6.3 ± 4.9 and 8.7 ± 10.8, $p = 0.03$).[19]

Recently, high-definition tDCS (HD-tDCS), which enables enhanced spatial focality through a multi-electrode configuration, has been combined with robot-assisted gait training in chronic stroke patients, yielding significant and sustained improvements in gait and balance compared to sham stimulation. Specifically, the real HD-tDCS group showed greater improvements from baseline to follow-up in 10MWT ($Z = -2.732$, $p = 0.006$), Timed Up and Go test (TUG; $Z = -2.746$, $p = 0.006$), Functional Reach Test ($Z = -2.446$, $p = 0.014$), BBS ($Z = -2.706$, $p = 0.007$), and Dynamic Gait Index ($Z = -2.056$, $p = 0.040$), whereas the sham group showed limited improvements.[20]

Cognition

Twenty studies examined the effects of NIBS on post-stroke cognitive function, primarily focusing on visuospatial neglect, memory, and attention. Most of these studies were published in the 2010s and usually reported favorable outcomes. Among these, two of the earliest global investigations applying rTMS for hemispatial neglect were conducted in Korea (Table 4). Lim et al.[21] performed a pilot study using low-frequency rTMS over the contralesional parietal cortex of patients with hemispatial neglect following a right hemispheric stroke. Compared to the controls, the rTMS group showed greater improvement in the line bisection test (LBT); however, the difference did not reach statistical significance (33.4 ± 27.5% *vs.* 13.7 ± 35.3%, $p = 0.053$). A subsequent RCT compared low- and high-frequency rTMS applied to the posterior parietal cortex in patients with acute stroke. Both stimulation protocols led to functional improvement; however, high-frequency rTMS showed significantly greater improvements in the LBT (−36.9 ± 11.2 *vs.* −8.3 ± 4.2, $p = 0.03$) and larger gains in the Korean version of the Modified Barthel Index (K-MBI: 30.6 ± 9.9 *vs.* 15.1 ± 5.7, $p < 0.01$) compared to sham stimulation. Improvements in K-MBI were also significant in the low-frequency rTMS group compared to sham ($p = 0.02$).[22]

In line with the growing interest in telerehabilitation for post-stroke care,[23] a recent RCT investigated the feasibility and efficacy of home-based, remotely supervised tDCS (RS-tDCS) combined with computerized cognitive training

Table 4. Representative rTMS studies for cognition, swallowing, and language functions in South Korea

Source	Total	Stage	Target	Design	Stimulation site	Frequency (Hz)	Intensity (%)	No. of pulses per session	Duration	Comparison group	Concurrent therapy	Main findings
Lim et al.[21] (2010)	14	Subacute stroke	Visuospatial neglect	NRCT	Parietal lobe (P5)	1	90 RMT	900	10 sessions (2 weeks)	rTMS+BT *vs.* BT	Standardized neglect rehabilitation	Improved LBT *vs.* BT only, but not significant ($p = 0.053$)
Kim et al.[22] (2013)	27	Subacute stroke	Visuospatial neglect	RCT	HF: PPC (Right, P4) LF: PPC (Left, P3)	HF: 10 LF: 1	90 RMT	HF: 1,000	10 sessions (2 weeks)	HF *vs.* LF *vs.* sham (coil tilted)	Conventional neglect rehabilitation	HF improved LBT *vs.* sham ($p = 0.03$); both LF/HF improved K-MBI *vs.* sham (HF: $p < 0.01$; LF: $p = 0.02$)
Park et al.[26] (2013)	18	Subacute stroke	Dysphagia	RCT	M1 (unaffected, pharynx)	5	90 RMT	LF: 1,200	10 sessions (2 weeks)	Sham (coil tilted)	Not mentioned	Improved VDS and PAS *vs.* sham; sustained at 2 weeks (all $p < 0.05$)
Park et al.[25] (2017)	35	Subacute stroke	Dysphagia	RCT	Bilateral: M1 (both mylohyoid) Unilateral: M1 (affected mylohyoid)	10	90 RMT	500	10 sessions (2 weeks)	Bilateral rTMS *vs.* unilateral rTMS *vs.* sham	Conventional dysphagia rehabilitation	Bilateral rTMS improved CDS and PAS *vs.* unilateral/sham; sustained at 5 weeks (all $p < 0.05$)
Chang et al.[28] (2022)	5	Chronic stroke	Non-fluent aphasia	Single-arm pilot	Language area (fNIRS-guided)	10	100 RMT	500×2 (bilateral)	10 sessions (2 weeks)	None	Speech therapy	Improved K-WAB ($p = 0.043$); connectivity in language area ↑ (fNIRS)

rTMS, repetitive transcranial magnetic stimulation; NRCT, non-randomized- controlled trial; RMT, resting motor threshold; BT, behavioral therapy; LBT, line Bisection test; RCT, randomized- controlled trial; HF, high-frequency; PPC, posterior parietal cortex; LF, low-frequency; K-MBI, Korean version of the Modified Barthel Index; VDS, Videofluoroscopic Dysphagia Scale; CDS, Clinical Dysphagia Scale; PAS, Penetration-Aspiration Scale; fNIRS, functional near-infrared spectroscopy; K-WAB, Korean version of the Western Aphasia Battery.

(Table 5). A total of 26 participants underwent the intervention five times per week for a total of four weeks. The adherence rate was high (98.4%) and no serious adverse events were reported. Significant improvement in the Korean version of the Montreal Cognitive Assessment (K-MoCA) was observed only in the RS-tDCS group (p = 0.004), whereas no significant change was found in the sham group ($p = 0.132$). These improvements were more pronounced in participants with lower baseline cognitive scores (K-MoCA 10–17: $p = 0.001$ *vs.* $p = 0.835$).[24]

Dysphagia

A total of five studies on rTMS and 2 on tDCS have been conducted, the majority of which were published in the 2010s. Although recent studies are limited, several early investigations have contributed significantly to the advancement of research in this field (Table 4). Park et al.[25] evaluated the effects of high-frequency (5 Hz) rTMS applied to the contralesional pharyngeal motor cortex. In a RCT involving 18 patients, the rTMS group showed significant improvements in swallowing function, particularly in the Videofluoroscopic Dysphagia Scale (from 33.6 ± 12.1 to 25.3 ± 9.8 at Week 2, 25.2 ± 10.2 at Week 4; $p < 0.05$). Similarly, the Penetration-Aspiration Scale (PAS) improved significantly in the rTMS group (from 3.41 ± 2.32 to 1.37 ± 0.87 at Week 4; $p < 0.05$), whereas no significant changes were observed in the sham group.[26] The same research group also conducted one of the earliest trials to assess the effects of bilateral rTMS. While all groups showed improvement over time, the bilateral rTMS group demonstrated significantly greater early improvements in the Clinical Dysphagia Scale (mean difference, –10.2, $p < 0.05$) and the PAS (mean difference, –2.0, $p < 0.05$) compared to the unilateral and sham stimulation. These effects were maintained for up to two weeks after treatment.

In addition, Korean researchers have contributed to the early clinical application of tDCS for dysphagia (Table 5). Yang et al.[27] conducted a RCT to evaluate the effects of anodal tDCS combined with swallowing training in patients with post-stroke dysphagia. Sixteen patients were randomized to receive either anodal tDCS or sham stimulation over the affected pharyngeal motor cortex for 30 min during conventional swallowing therapy for 10 days. Only the anodal tDCS group showed significantly greater improvement in the Functional Dysphagia Scale (FDS) score (mean difference, –7.79, $p = 0.041$) at the three-month follow-up.

Aphasia

A total of two studies using rTMS and three using tDCS have been conducted in patients with aphasia, indicating that NIBS studies in this area are relatively limited. A recent pilot study attempted to personalize stimulation by using functional near-infrared spectroscopy (fNIRS) to guide rTMS targeting (Table 4). Chang et al.[28] investigated the feasibility of applying high-frequency rTMS in patients with chronic non-fluent aphasia using fNIRS to identify the most activated cortical area during a picture naming task. Five patients received high-frequency rTMS followed by speech therapy for more than 10 days. Significant improvements in the Aphasia Quotient in the Korean version of the Western Aphasia Battery (from 57.72 to 62.72, $p = 0.043$) were observed, along with increased functional connectivity in language-related regions and altered brain network properties.

Parkinsonism

Among the 13 studies on parkinsonism, rTMS has been actively investigated to improve freezing of gait (FOG) and gait dysfunction. South Korea has played a leading role in this area, conducting the majority of clinical trials on rTMS for FOG in Parkinson's disease patients.[29] The representative studies are summarized in Tables 6 (rTMS) and 7 (tDCS). The earliest study applied a single session of high-frequency (10 Hz) rTMS to various brain regions, lower limb primary motor cortex (M1-LL), dorsolateral prefrontal cortex (DLPFC), supplementary motor area (SMA), and sham, to evaluate FOG-related outcomes. Significant improvements were observed after M1-LL and DLPFC stimulation in the TUG test (M1-LL: from 52.7 ± 13.0 to 38.0 ± 5.8, $p = 0.003$; DLPFC: from 47.3 ± 9.7 to 42.0 ± 8.6, $p = 0.046$), UPDRS-III scores (M1-LL: from 22.0 ± 2.5 to 20.7 ± 2.5, $p = 0.002$; DLPFC: from 22.5 ± 2.6 to 21.5 ± 2.5, $p = 0.005$).[30] Based on these findings, a subsequent

Tablee 5. Representative tDCS studies for cognition and swallowing function in South Korea

Source	Total	Stage	Target	Design	Stimulation site	Intensity (mA)	Duration (min)	Schedule	Comparison group	Concurrent therapy	Main findings
Ko et al.[24] (2022)	26	Chronic stroke	Cognitive impairment	RCT	atDCS: DLPFC (Left, F3)	2	30	Home based, 20 sessions (4 weeks)	Sham (Identical montage, 10s fade-in/out)	Computerized cognitive training (CogTx, Comcog®)	Improved K-MoCA (p = 0.004); greater gain in low baseline group; adherence 98.4%;
Yang et al.[27] (2012)	16	Subacute stroke	Dysphagia	RCT	atDCS: M1 (affected, pharynx area)	1	20	10 sessions (2 weeks)	Sham (Identical montage, 30 seconds)	Conventional swallowing therapy	Improved in FDS vs. sham; sustained at 3 months (p = 0.041)

tDCS, transcranial direct current stimulation; RCT, randomized- controlled trial; atDCS, anodal transcranial direct current stimulation; DLPFC, dorsolateral prefrontal cortex; K-MoCA, Korean version of the Montreal Cognitive Assessment; FDS, Functional Dysphagia Scale.

Table 6. Representative rTMS studies for Parkinsonism in South Korea

Source	Total	Stage	Target	Design	Stimulation site	Frequency (Hz)	Intensity (%)	No. of pulses per session	Duration	Comparison group	Concurrent therapy	Main findings
Lee et al.[19] (2014)	20	Parkinsonism	FOG	RCT (crossover)	M1 (dominant, leg), SMA, DLPFC	10	90 RMT	1,000	1 session per site; 24 h interval	M1 *vs.* SMA *vs.* DLPFC *vs.* sham (coil tilted)	Not mentioned	M1-LL and DLPFC rTMS improved TUG, Turn Steps/time *vs.* base (all p < 0.05)
Kim et al.[31] (2015)	17	Parkinson's disease	FOG	RCT (crossover)	M1 (dominant, leg)	10	90 RMT	1,000	5 sessions (1 week); 2 weeks interval	Sham (coil tilted)	Not mentioned	Improved FOG-Q, SS-180, *vs.* sham; sustained at 1 week (all p < 0.05)
Chang et al.[34] (2017)	32	Parkinson's disease	FOG	RCT	M1 (dominant, leg) atDCS (F3)	10	90 RMT	1,000	5 sessions (1 week)	Dual *vs.* atDCS	Not mentioned	Both improved FOG and motor/ambulation; no group difference executive function improved only in dual-mode (p = 0.032)
Moon et al.[32] (2018)	12	Parkinson's disease	FOG	RCT	M1 (Left, hand), SMA	25	100 RMT	1,500-2,500	2 sessions (consecutive days)	M1 *vs.* SMA	Not mentioned	SMA rTMS improved FOG; trend for SMA > MC (p = 0.071–0.097)

rTMS, repetitive transcranial magnetic stimulation; FOG, freezing of gait; RCT, randomized- controlled trial; SMA, supplementary motor area; DLPFC, dorsolateral prefrontal cortex; RMT, resting motor threshold; LL, lower limb; TUG, Timed Up and Go test; SS-180, Stand and Spin 180° test.

Table 7. Representative tDCS Studies for Parkinsonism in South Korea

Source	Total	Disease	Target	Design	Stimulation site	Intensity (mA)	Duration (min)	Schedule	Comparison group	Concurrent therapy	Main findings
Yun et al.[33] (2025)	19	Parkinson's disease	Dual task performance	RCT (crossover)	M1: atDCS (Cz-Fp2) DLPFC: atDCS (F3-Fp2) vmPFC: atDCS (Fpz-F4)	2	20	4 crossover sessions (7-day washout)	M1 *vs.* DLPFC *vs.* vmPFC *vs.* sham	Not mentioned	M1 stimulation improved TUG (single-task: $p = 0.028$; dual-task: $p = 0.044$); DLPFC improved executive function ($p = 0.013$), but no change in DTE

tDCS, transcranial direct current stimulation; RCT, randomized- controlled trial; atDCS, anodal transcranial direct current stimulation; DLPFC, dorsolateral prefrontal cortex; vmPFC, ventromedial prefrontal cortex; TUG, Timed Up and Go test; DTE, dual-task interference effect.

Table 8. NIBS studies for TBI in South Korea

Source	Total	Stage	Target	Design	Stimulation site	Frequency (Hz)	Intensity (%)	No. of pulses per session	Duration	Comparison group	Concurrent therapy	Main findings
Kim et al.[35] (2011)	30	Brain injury	Dysphagia	RCT	HF: M1 (affected) LF: M1 (unaffected)	HF: 5 LF: 1	100 RMT	HF: 1,000 LF: 1,200	10 sessions (2 weeks)	HF *vs.* LF *vs.* sham	Swallowing training	LF rTMS improved FDS, PAS *vs.* HF and sham (all $p < 0.05$)
Lee et al.[36] (2018)	13	TBI	Cognition	RCT	Right DLPFC (F4)	1	100 RMT	2,000	10 sessions (2 weeks)	Sham coil	NDT	Improved in MADRS, TMT, SCWT *vs.* sham (all $p < 0.01$)
Kang et al.[37] (2012)	9	TBI	Attention	RCT (crossover)	Left DLPFC (F3)	N/A	2 mA, 20 minutes	N/A	1 session/ condition; 48 hours washout	Sham (Identical montage, 1 minute)	Not men- tioned	Improved reaction time immediately after tDCS *vs.* sham ($p < 0.05$); not significant after 3, 24 hours

NIBS, non-invasive brain stimulation; TBI, traumatic brain injury; RCT, randomized- controlled trial; HF, high frequency; LF, low frequency; rTMS, repetitive transcranial magnetic stimulation; PAS, Penetration-Aspiration Scale; FDS, Functional Dysphagia Scale; NDT, Neurodevelopmental therapy; MADRS, Montgomery-Asberg Depression Rating Scale; TMT, Trail Making Test; SCWT, Stroop Color-Word Test; DLPFC, dorsolateral prefrontal cortex.

randomized, crossover study applied five sessions of rTMS over one week to the M1-LL. The results showed sustained improvements in FOG-related measures, including the Standing Start 180° Turn Test (SS-180) and FOG Questionnaire (FOG-Q), lasting for at least one week post-intervention (FOG-Q: $\chi^2 = 13.44$, $p = 0.001$; SS-180: $\chi^2 = 13.32$, $p = 0.001$).[31]

Another study demonstrated that high-frequency rTMS over the SMA improved FOG. While there were no statistically significant differences between the SMA and motor cortex stimulation groups, the SMA group showed a trend toward greater improvement than the motor cortex group in freezing episodes during the straight walking with sudden stop test (–127.8 ± 85.4% *vs.* –44.8 ± 78.0%, $p = 0.097$) and turning (–114.9 ± 81.0% *vs.* 1.7 ± 141.5%, $p = 0.071$).[32]

A recent tDCS study investigated its effects on dual-task performance in patients with Parkinson's disease. In a pilot randomized, crossover trial, Yun et al.[33] assessed the site-specific effects of anodal tDCS. Stimulation of the primary motor cortex improved gait performance, reducing TUG time under both single-task conditions (from 12.92 ± 4.16 to 12.55 ± 3.88, $p = 0.028$) and cognitive dual-task conditions (from 15.47 ± 5.48 to 14.94 ± 4.97 seconds, $p = 0.044$), whereas stimulation of the DLPFC enhanced executive function in the color-word test (from 35.79 ± 11.25 to 39.05 ± 11.27, $p = 0.013$). However, neither site showed significant changes in the dual-task interference effect.

Attempts have also been made to combine rTMS and tDCS to enhance the therapeutic outcomes. A dual-mode approach combining high-frequency rTMS over the lower limb motor cortex with anodal tDCS over the left dorsolateral prefrontal cortex was investigated to simultaneously modulate motor and cognitive circuits. Although no superiority over rTMS alone was observed in terms of motor outcomes, including the FOG-Q and TUG test, the dual-mode group showed greater improvement in turning steps ($p = 0.002$), and in executive function, measured by the Trail Making Test (TMT) ($p = 0.032$).[34]

Traumatic brain injury

Studies involving TBI remain scarce, with only three studies identified: two focusing on cognitive function and one on dysphagia (Table 8). Kim et al.[35] investigated the effects of rTMS on swallowing function in patients with brain injury. In an RCT, low-frequency rTMS significantly improved both the FDS (from 44.1 ± 14.6 to 33.8 ± 14.1, $p < 0.05$) and the PAS (from 4.5 ± 1.4 to 3.2 ± 1.2, $p < 0.05$) compared to the high-frequency or sham group. Lee and Kim[36] examined the cognitive effects of low-frequency rTMS over the right DLPFC in patients with TBI. In an RCT, low-frequency rTMS significantly improved the TMT (from 91.0 ± 12.3 to 70.2 ± 10.5, $p < 0.01$), and Stroop Color and Word Test scores (from 65.4 ± 8.9 to 52.3 ± 9.1, $p < 0.01$) compared to sham group. Kang et al.[37] investigated whether a single session of anodal tDCS over the left DLPFC improved attention in patients with TBI. Anodal tDCS resulted in a trend toward faster reaction time immediately after stimulation (87.3 ± 7.8% of baseline), whereas the sham stimulation did not (122.4 ± 715.5%, $p = 0.056$); however, the effect was not sustained at 24 hours.

DISCUSSION

In this narrative review, we summarize recent clinical research on NIBS for neurorehabilitation conducted in South Korea. A total of 88 studies were identified, with the majority focusing on stroke, particularly motor and cognitive recovery. In stroke rehabilitation studies, rTMS was frequently applied to promote upper limb motor recovery, while tDCS studies increasingly explored combination protocols with technologies such as virtual reality and robotics. Cognitive rehabilitation studies commonly addressed visuospatial neglect and attention, including the use of RS-tDCS, which extends the application of NIBS from the clinic to the patient's home. Although relatively few studies have investigated NIBS for dysphagia and aphasia, preliminary trials have reported promising outcomes, suggesting the need for further investigation in these domains. In studies on Parkinsonism, rTMS has primarily targeted FOG and gait dysfunction, while recent tDCS studies have explored dual-task performance. In contrast, clinical research on TBI remains sparse.

Globally, rTMS has been actively investigated as a therapeutic modality to improve upper limb function in patients with stroke. Consistent with findings from South Korea, numerous studies have reported positive outcomes, and several meta-analyses have supported the efficacy of rTMS for motor recovery in stroke rehabilitation.[38,39] However, despite these promising results, clinical trials focusing on low-frequency rTMS during the subacute phase have shown inconsistent findings.[40-42]

Similarly, a recent large-scale RCT conducted in South Korea failed to demonstrate significant improvements in upper limb function following low-frequency rTMS. Notably, subgroup analysis revealed greater functional gains in patients with subcortical lesions, suggesting that lesion location may influence responsiveness to rTMS. Patients with subcortical or brainstem infarctions have been reported to respond more favorably to NIBS than those with cortical involvement.[43,44] This enhanced responsiveness may be due to the relatively preserved structural integrity of the motor network and reduced cortical inhibition in these patients. Consequently, the neuromodulatory effects of NIBS can spread more efficiently across brain regions.[17]

Therefore, further investigation into lesion-specific responsiveness is warranted. To this end, a follow-up RCT is currently being conducted in South Korea to assess the efficacy of low-frequency rTMS in patients with subacute stroke with subcortical or brainstem lesions.[45] This ongoing study is expected to contribute meaningfully to the field by helping to identify patient subgroups most likely to benefit from rTMS, ultimately supporting the development of more personalized and effective stimulation protocols in stroke rehabilitation.

In recent years, cognitive rehabilitation using NIBS has gained attention in stroke patients. Globally, several RCTs and meta-analyses have reported that both rTMS and tDCS can improve cognitive functions such as attention, executive function, and working memory in post-stroke patients.[46-48] This trend is consistent with findings from South Korean studies, which have also shown the potential of NIBS to enhance cognitive recovery in stroke survivors.

However, hospital-based cognitive rehabilitation faces limitations due to factors such as restricted treatment duration and geographical barriers, particularly for individuals with mobility impairments. In this context, telerehabilitation has emerged as a promising alternative, allowing the remote delivery of personalized cognitive therapies. Accordingly, there is a growing need to investigate the potential benefits of combining telerehabilitation with NIBS to enhance cognitive recovery in stroke patients.[49]

To the best of our knowledge, Ko et al.[24] conducted the only study in South Korea that combined remotely supervised, home-based, RS-tDCS with computerized cognitive training for post-stroke cognitive impairment. The study demonstrated that home-based RS-tDCS was a safe, feasible, and potentially effective strategy for enhancing cognitive rehabilitation in stroke survivors.

Although recent studies remain scarce, early Korean studies have contributed significantly to the advancement of research in this field. One of the earliest RCTs applied bilateral rTMS to the pharyngeal motor cortex, demonstrating superior outcomes compared to unilateral or sham stimulation. This study contributed to a better understanding of the interhemispheric mechanisms involved in swallowing recovery. By generating early clinical evidence for the use of rTMS in the treatment of post-stroke dysphagia, these pioneering studies have helped shape global research directions.

Building on these early findings, global research on rTMS for post-stroke dysphagia has gradually expanded. Multiple systematic reviews and meta-analyses have reported moderate therapeutic effects of rTMS on swallowing function.[50-52] An umbrella review synthesizing 19 systematic reviews further reinforced this trend, indicating consistent improvements in swallowing outcomes across diverse protocols and patient populations.[53]

Recent studies have reported that the language network exhibits substantial individual variability in its location, size, and topography, particularly following stroke.[54,55] This variability poses a major challenge in applying uniform stimulation protocols for post-stroke aphasia. Consequently, individualized targeting of language-related regions has become increasingly important for optimizing the outcomes of NIBS.

Advancements in functional imaging techniques, such as functional magnetic resonance imaging (fMRI) and fNIRS, have enabled precise mapping of reorganized language networks.[56,57] A few recent clinical trials have adopted personalized targeting strategies guided by such neuroimaging. Ren et al.[58] targeted the individually defined superior frontal gyrus using fMRI-guided theta-burst stimulation, demonstrating significant improvements in language outcomes as measured by the Western Aphasia Battery-Revised Aphasia Quotient.

In line with this global trend, a pilot study in South Korea applied fNIRS-guided high-frequency rTMS to the most activated cortical region during a picture naming task in patients with chronic non-fluent aphasia. As the first study to utilize fNIRS-based individualized targeting for rTMS in aphasia, it demonstrated the potential of personalized NIBS approaches for post-stroke language rehabilitation.

South Korea has played a leading role in advancing rTMS research for FOG in Parkinson's disease. These studies have consistently reported positive outcomes, with improvements in FOG-related measures such as TUG, SS-180, and FOG-Q. Although one study failed to show significant effects on dual-task interference, it marked an early attempt to extend the application of tDCS to dual-task performance in Parkinson's disease. Furthermore, a recent dual-mode intervention combining rTMS and tDCS demonstrated additional improvements in cognitive performance. These studies reflect an evolving body of evidence supporting NIBS as a promising intervention for parkinsonism, with a growing interest in optimizing stimulation targets and combining modalities.

To date, studies investigating the use of NIBS in TBI populations in South Korea remain scarce. However, preliminary findings suggest beneficial effects, particularly in domains such as cognition and swallowing. Likewise, at the global level, clinical evidence for rTMS and tDCS in TBI remains limited and inconclusive. A recent meta-analysis failed to demonstrate significant cognitive improvements with either intervention, highlighting the need for further research.[59]

A major barrier to the clinical adoption of NIBS in neurorehabilitation is the absence of standardized clinical guidelines. This lack of consensus contributes to variability in treatment protocols and leads to clinicians' reluctance to incorporate NIBS into routine practice.[60] Furthermore, although most adverse effects of rTMS and tDCS are mild and transient, such as scalp discomfort, headache, or tingling, there have been rare but serious reports including seizures. These safety concerns, even if infrequent, may contribute to clinician's hesitation to adopt NIBS in standard neurorehabilitation protocols.[61,62] Additionally, limited insurance coverage and reimbursement pose substantial challenges to accessibility. In South Korea, rTMS is approved only for treatment-resistant depression and is not reimbursed for neurorehabilitation. Similar reimbursement barriers are present in other countries such as Japan and much of Europe, where rTMS is typically not covered by national health insurance systems.[63,64] In the United States, although initial TMS sessions may be eligible for coverage, insurance rarely reimburses repeated treatment courses, making it difficult to sustain long-term therapeutic strategies.[65]

Despite the growing number of NIBS studies on neurorehabilitation conducted in South Korea, several critical limitations still remain in the current literature. First, most studies have small sample sizes, substantially limiting the generalizability and reproducibility of the findings. Second, there is considerable heterogeneity in the stimulation parameters, treatment duration, and outcome measures across the studies, which complicates the interpretation of the results and poses a major barrier to the development of standardized clinical protocols. Third, the scope of the current research remains relatively narrow, with most studies concentrating on motor and cognitive recovery in stroke and Parkinsonism.

Other domains, such as dysphagia, aphasia, sensory integration, and balance control, remain underexplored. Finally, patient-specific targeting was lacking. Therefore, future efforts should prioritize the development of evidence-based, standardized treatment protocols to ensure consistency and safety and facilitate regulatory approval. To achieve this, multi-center, large-scale RCTs are required.

Concurrently, future NIBS research should emphasize a personalized approach, with individualized stimulation strategies based on neurophysiological characteristics. Recent advances in neuroimaging such as fMRI, fNIRS, diffusion tensor imaging (DTI), and MEP offer promising tools for guiding personalized interventions.

In South Korea, two ongoing multi-center trials exemplify this trend. A trial involving patients with stroke investigated the effects of personalized rTMS protocols tailored to individual functional reserves. Based on MEP and DTI, patients were stratified into three groups and received different high-frequency rTMS protocols targeting the ipsilesional M1, premotor cortex, or contralesional M1. This trial attempted to determine whether individualized stimulation improves upper limb motor recovery more effectively than conventional protocols.[66] Another trial on Parkinson's disease applied personalized rTMS based on dual-task gait performance. Patients were classified into motor- or cognitive-priority groups using the dual-task TUG test and received stimulation to either the lower limb M1 or the dorsolateral prefrontal cortex accordingly. The aim of this study was to determine whether this individualized approach improves ambulatory function more effectively than standard rTMS protocols.[67]

Furthermore, emerging technologies such as brain-computer interfaces (BCIs) and artificial intelligence (AI) are expected to further enhance the adaptability of NIBS protocols.[68,69] The former enables real-time decoding of brain activity, allowing the stimulation to be dynamically adjusted based on the patient's state. Meanwhile, AI algorithms can integrate multimodal inputs such as motor performance, cortical excitability, and hemodynamic signals to personalize stimulation parameters.[70] The integration of these technologies holds significant potential for establishing closed-loop systems that respond in real time to neural and behavioral feedback, ultimately facilitating more effective and individualized neuromodulation.[71]

Moreover, novel forms of NIBS, such as temporal interference stimulation (TIS) and focused ultrasound stimulation, are being explored for their ability to modulate deep brain structures with high spatial precision and minimal invasiveness.[72,73]

In line with this trajectory, recent research efforts in South Korea have focused on expanding the reach of NIBS to deep brain structures using TIS. Temporal interference stimulation utilizes intersecting high-frequency electric fields to generate low-frequency envelopes at subcortical targets, such as the striatum and fornix, enabling non-invasive deep brain stimulation.[74] Building on this, a Closed-Loop TIS (CLoTIS) system is currently under development that integrates subject-specific head modeling, electric field simulation, and real-time neurophysiological feedback via electroencephalography and fMRI. Thus, CLoTIS may offer a high-resolution adaptive neuromodulation platform capable of precisely targeting subcortical circuits involved in motor and cognitive recovery.

In conclusion, studies of NIBS in South Korea have usually reported positive outcomes across a range of functional domains. Recent research indicates a shift toward individualized and technology-assisted approaches, including home-based tDCS and rTMS guided by fNIRS. Future investigations should focus on the development and evaluation of adaptive, personalized NIBS strategies to optimize therapeutic efficacy. Ongoing studies in South Korea align with this trend, and their outcomes are expected to contribute meaningfully to the field.

Declaration of Conflicting Interests

The authors declare that there are no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author Contributions

N.J.P., W.S.K.: Designed research; S.C., W.K.C.: Conducted research and extracted data, analyzed data; S.C.: Wrote the manuscript; N.J.P.: Was primarily responsible for final content. All authors read and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

AI Disclosure

The authors declare that artificial intelligence (AI) tools were not used, or were used solely for language editing, and had no role in data analysis, interpretation, or the formulation of conclusions. All scientific content, data interpretation, and conclusions are the sole responsibility of the authors. The authors further confirm that AI tools were not used to generate, fabricate, or 'hallucinate' references, and that all references have been carefully verified for accuracy.

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