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EFFECTS OF TRANSCRANIAL DIRECT CURRENT STIMULATION ON PAIN, ISOKINETIC MUSCLE STRENGTH, AND BALANCE FUNCTION IN PATIENTS WITH ANKLE FRACTURES: A RANDOMIZED-CONTROLLED CLINICAL STUDY

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ABSTRACT

Aims: To investigate the efficacy of transcranial direct current stimulation (tDCS) combined with conventional rehabilitation interventions in improving pain scores, lower limb isokinetic muscle strength, balance, and motor control in patients with ankle fractures, thereby providing a clinical basis for optimizing central-targeted rehabilitation protocols for these patients.

Methods: A total of 48 patients who had undergone ankle fracture surgery were enrolled and randomly divided into an observation group and a control group using a numerical table method, with 24 cases in each group. The control group received standard rehabilitation therapy for 6 weeks, while the observation group received additional tDCS intervention (20 minutes, 2.0 mA, stimulating the contralateral primary motor cortex) in addition to standard rehabilitation. Prior to and after intervention, various parameters were assessed using the isokinetic muscle strength testing system, TecnoBody balance testing system, Tinetti scale, three-dimensional gait analyzer, and VAS pain scale, including hip muscle strength, static and dynamic balance function, gait parameters, and pain levels in both groups.

Results: All patients successfully completed all interventions and assessments without any severe adverse events. The relative peak torque of hip abduction and extension was significantly increased in all enrolled patients compared to pre-intervention levels, with the observation group showing significantly better results than the control group ($p < 0.001$). Post-intervention, the Tinetti balance gait score significantly improved, while the center of gravity swing path length, swing area, and swing velocity were significantly reduced ($p < 0.05$). The range of motion of the affected hip joint and step length parameters showed significant improvement ($p < 0.05$). The VAS pain score decreased significantly compared to pre-intervention levels and remained significantly lower than that of the control group ($p < 0.05$).

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Conclusion: tDCS can effectively alleviate pain symptoms in patients after ankle fracture surgery, enhance lower limb muscle strength, improve proprioceptive integration function, and significantly improve static balance, dynamic posture control, and gait performance. It effectively addresses postoperative functional impairments following ankle fractures, reduces the risks of falls and secondary injuries, and serves as a novel, highly effective intervention for rehabilitation following ankle fracture surgery.

KEYWORDS

Transcranial direct current, ankle fracture, posture control, isokinetic muscle strength, balance, motor control, pain

INTRODUCTION

Ankle fractures are one of the common injuries in orthopedics and rehabilitation medicine. Improper treatment or inadequate rehabilitation training may lead to chronic pain, joint dysfunction, and other complications, significantly impairing patients' quality of life[1,2]. Therefore, exploring effective rehabilitation therapies is crucial for promoting patient recovery and reducing disability rates. In recent years, with advancements in neuroscience, regulating neuromuscular control functions to enhance muscle fitness and improve quality of life has become a critical issue requiring urgent attention in clinical sports rehabilitation practice[3-5].

Meanwhile, with advancements in brain science research, brain-targeting interventions such as acupuncture, meditation, and electrical stimulation have been widely applied in clinical practice[6]. Among these, transcranial direct current stimulation (tDCS), a non-invasive neuromodulation technique that delivers direct current through scalp electrodes to modulate cerebral cortex excitability, has emerged as a novel strategy for rehabilitation therapy[1]. Growing evidence demonstrates that tDCS enhances neural plasticity, improves neurotransmission function, improves adherence to exercise regimens, and increases compliance with motor rehabilitation interventions[7]. Currently, tDCS is being explored for rehabilitation across various conditions, including motor dysfunction disorders[8]. However, research on its application in ankle fracture rehabilitation remains limited. This study aims to investigate the effects of tDCS on the recovery process of patients with ankle fractures and evaluate its efficacy and safety in improving motor function and alleviating pain[5].

Patients with ankle fractures exhibit impaired balance ability and reduced lower limb muscle strength due to disuse of the hip muscles following ankle injury[9]. Human balance is primarily associated with lower limb muscle strength and proprioceptive functions, with neural control mechanisms involving critical regions such as the brainstem reticular formation, cerebellum, and sensory-motor areas of the cerebral cortex[10,11]. The primary motor cortex (M1) serves as the most crucial brain region involved in somatosensory-motor functions and posture maintenance[3,4]. Therefore, this study aims to evaluate the intervention effects of tDCS on pain scores, isokinetic muscle strength, and balance ability in ankle fracture patients by modulating excitability in the sensory-motor cortex combined with rehabilitation training assessments.

Rehabilitation therapy for ankle joint fractures primarily includes physical therapy, functional exercises, and surgical intervention. While these approaches can promote fracture healing and functional recovery to some extent, certain patients still experience slow recovery and persistent pain relief challenges[2,3]. Consequently, exploring novel rehabilitation methodologies to enhance treatment efficacy has become a key focus of current research. This study aims to investigate alterations in neural control mechanisms in patients with ankle joint fractures, propose improvements to conventional rehabilitation protocols, and provide evidence-based insights for further optimization of subsequent rehabilitation strategies.

MATERIALS AND METHODS

General information

A total of 48 patients with ankle fractures admitted to Xuzhou Rehabilitation Hospital between April 2025 and April 2026 were selected. They were randomly divided into an observation group and a control group using a random number table, with 24 cases in each group. No significant differences were observed in baseline characteristics between the two groups ($p > 0.05$). Details are presented in *Table 1*. The inclusion criteria for ankle fracture patients were as follows:

1) Age 18–55 years, regardless of gender, with a disease duration of 6 weeks to 6 months;
2) Early surgical intervention with no significant deformities in the hip, knee, or ankle joints of the lower limb;
3) Unilateral ankle fracture;
4) Absence of significant cognitive impairment;
5) No prior history of other trauma;
6) All patients signed informed consent forms prior to the study.

Exclusion criteria included:

1) Presence of consciousness disorders, severe cognitive impairment, or severe mental illnesses that prevented cooperation with the study;
2) Other severe central nervous system diseases;

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Group	Man, n (%)	Woman, n (%)	Age (years)	stature (cm)	BMI
Observation group (n = 24)	14 (58.3)	10 (41.7)	42.1 ± 13.4	169.4 ± 8.2	22.5 ± 1.9
Control group (n = 24)	12 (50)	12 (50)	41.1 ± 14.6	170.95 ± 7.10	21.7 ± 2.0
t/x^2	0.335		0.247	0.700	1.421
p value	0.562		0.806	0.487	0.162

Table 1. *Comparison of baseline characteristics between the two groups (mean ± standard deviation).*

3) Congenital or acquired limb disabilities that prevented participation in rehabilitation exercises;
4) Severe functional impairments in vital organs such as the heart, lungs, liver, or kidneys (e.g cardiac insufficiency or chronic obstructive pulmonary disease), inability to tolerate rehabilitation exercises, or presence of a pacemaker;
5) Other structural brain lesions;
6) Bone or joint deformities or severe skin injuries;
7) Active epilepsy;
8) Severe dependence on psychotropic medications or drug abuse;
9) Death or loss of follow-up within 4 weeks of treatment;
10) Poor treatment adherence.

This study strictly adhered to the ethical principles of informed consent, confidentiality, and benefit-over-harm. A written informed consent was obtained from each patient. The study protocol was approved by the Xuzhou Rehabilitation Hospital Ethics Committee (date: 3.04.2025, No.: XK-LSW-2025-007). The study was conducted in accordance with the principles of the Declaration of Helsinki. Clinical trial number: ChiCTR2500107213. (This study is part of a serial research program. Minor protocol amendments were adopted for this sub-study; these revisions did not change the study population, inclusion/exclusion criteria, sample size, primary outcomes or study timeline. The amended protocol is now applying for modification registration at the Chinese Clinical Trial Registry).

Research methods

To ensure blinding in the study, neither therapists nor assessors were aware of the patients' group assignments. The observation group received tDCS combined with conventional rehabilitation therapy, while the control group received only conventional rehabilitation therapy. The study duration was 6 weeks.

Conventional rehabilitation therapy

Conventional rehabilitation therapy includes physical therapy, functional exercises, and necessary pharmacological treatment[11]. All patients receive the same standard rehabilitation regimen.

1) *Restoration of joint range of motion:*
   i) *Active movement:* Patients perform movements along all axes of motion to gently stretch contracted or adherent tissues, following a progressive approach with gradually increasing range of motion. Under therapist guidance, exercises should be performed pain-free for at least 20 minutes daily.
   ii) *Joint mobilization techniques:* The therapist fixes the proximal end of the joint with one hand while holding the distal end with the other, performing anterior-posterior, medial-posteral, and rotational maneuvers under mild traction to allow bone ends to move within the elastic range of soft tissues such as the joint capsule and ligaments.

   These techniques alleviate pain and stiffness while enhancing range of motion, with manual manipulation levels (grades 1–4) progressively increased according to patient condition. Sessions are conducted twice daily for 15–20 minutes each time, six days per week.
2) *Muscle strength training:* Lower limb muscle strength training primarily involves isometric contractions and resistance exercises, which should be performed under the supervision of a therapist following a progressive principle to induce moderate muscle fatigue. The recommended duration is 30 minutes daily, five days per week.
3) *Balance and coordination exercises:*
   i) *Proprioceptive training:* Perform ball throwing and catching exercises on a balance mat under the guidance of a rehabilitation therapist; the difficulty can be gradually increased later, such as by increasing knee flexion angles or practicing ball control in all directions; alternatively, use the Italian TecnoBody balance device. Each session lasts 30 minutes, performed six days per week.
   ii) *Gait training:* Under therapist supervision, perform walking exercises involving straight-line progression, turns, and circular paths to correct abnormal gait patterns; advanced sessions may include walking on complex surfaces (e.g., over obstacles or up/stairs) based on patient progress.

   Each session lasts 20 minutes, once daily for six days per week.
4) *Physical factor therapy:* Local polarized light physical factor therapy. 20–30 minutes daily, six times per week.

Intervention measures in the observation group

Patients in the observation group received tDCS therapy[5], using a current intensity of 12 mA applied to the contralateral motor cortex for a duration of 20 minutes[8]. Three times a week.

The specific procedure for transcranial electrical stimulation is as follows: The patient is placed in a seated position, instructed to relax while maintaining relative posture stability. A VC-8000C transcranial direct current stimulator (Nanjing Wogao Company) is selected. After soaking the electrodes with 0.9% normal saline or conductive gel, the anode electrode is placed over the contralateral primary motor cortex (M1) corresponding to the affected lower limb, and the reference cathode electrode was attached to the contralateral supraorbital region. To ensure electrode stability during treatment, a headrest is used for fixation. Direct current mode is selected, with current intensity adjusted according to the patient's tolerance, typically using 2.0 mA[5.6], for a duration of approximately 20 minutes. If the patient experiences any discomfort or adverse reactions (such as upper limb pain, localized stabbing pain, burning sensation, etc.), treatment should be discontinued immediately, the patient's condition assessed, and appropriate diagnostic and therapeutic measures taken promptly. After initial management or treatment, the case should be reported to the hospital ethics committee.

Efficacy evaluation

Isokinetic muscle strength assessment of hip abduction and extension

The Yikang A8-3 isokinetic muscle strength testing and training system was employed to assess hip abduction and extension strength in both patient groups before and after intervention. Results from three measurements before and after treatment were recorded and averaged, with comparisons made using the relative peak torque value (peak torque-to-body-weight ratio). Peak torque refers to the maximum torque output during testing, representing the maximal muscle force generated by contraction; a higher peak torque indicates stronger muscle strength. The peak torque-to-body-weight ratio is defined as the peak torque value per unit body weight, reflecting the relative muscle strength and enabling comparisons across individuals with different body weights.

Balance ability analysis

Assessment was conducted using the Tinetti Scale (Tinetti Balance and Gait Analysis) and the Italian TecnoBody balance testing and training system[12]. The Tinetti Scale comprises two components: balance and gait tests, with a maximum score of 28 points. A Tinetti score below 24 indicates balance dysfunction; a score below 15 suggests a risk of falls[13]. The Italian TecnoBody balance tester measures the following parameters (with eyes closed): Sway length (SL), which reflects the amplitude of center-of-gravity movement; Sway area (SA), which quantifies the extent of center-of-gravity displacement. Higher values obtained with the Pro-kin balance tester indicate greater body sway amplitude, poorer stability, and diminished proprioception, reflecting impaired balance function.

Gait analysis

Three-dimensional gait analysis was performed on patients using the Italian TecnoBody Walker-view digital treadmill. The specific procedure involved: prior to testing, patients walked for two minutes on the gait analyzer to familiarize themselves with its operation and warm up. Tests were conducted before and after intervention, recording hip joint range of motion during each gait cycle and step length.

Pain rating

The degree of pain in patients was assessed before and after intervention using the Visual Analogue Scale (VAS). A score of 0 indicates no pain; a maximum score of 10 indicates severe pain; scores of 1–3 indicate mild pain; scores of 4–6 indicate moderate pain affecting sleep; and scores of 7–10 indicate intense, unbearable pain.

Statistical methods

Sample size

Sample size calculation was performed using G Power V.3.1.9.6 software.Referring to gait changes, the outcome indicator from previous studies[14], the estimated effect size was calculated as 1.03. Using a significance level of $\alpha = 0.05$ and a power test $(1- \beta) = 0.90$ as criteria, the results indicated that each group required 17 participants, resulting in a total sample size of 34 cases. Assuming a dropout rate of 20%, it was determined that each group should include at least 22 participants, yielding a minimum total sample size of 44 cases for this study.

Statistical analysis

Data were analyzed using SPSS 25.0 software. Continuous variables conforming to a normal distribution were expressed as (mean ± standard deviation); pairwise comparisons were performed using the paired t-test, while between-group comparisons employed the independent samples t-test. If normality was not met, the rank-sum test was applied. Categorical variables were compared using the χ^2 test. The significance level was set at $\alpha = 0.05$.

RESULTS

A total of 48 participants were enrolled in this study, and all participants completed the allocated intervention without dropout. No serious adverse events occurred during stimulation. Only a small number of participants reported mild scalp itching or slight tingling sensation.

Comparison of relative peak torque values for isokinetic muscle strength in hip abduction and extension between the two patient groups before and after treatment

Before intervention, no significant differences were observed in the relative peak torque values of hip abduction and extension between the two groups. After intervention, both groups exhibited increased relative peak torque values compared to pre-treatment levels, with a more pronounced increase in the observation group than in the control group. This indicates enhanced muscle strength in the hip abduction and extension muscles in both groups, with the observation group demonstrating significantly greater improvement than the control group *(Table 2)*.

Balance and gait assessment

Comparison of Tinetti scores between the two groups before and after treatment

Both groups showed improvement in the Tinetti score before and after intervention, with a significant increase observed in the observation group compared to the control group. Additionally, statistical results demonstrated that the fall risk (Tinetti score <15) was lower in the observation group post-intervention than in the control group *(Table 3)*.

Evaluation of the Italian TecnoBody balance testing and training system

After intervention, both groups showed declines in balance test scores (SL and SA), with a significantly greater decrease observed in the observation group compared to the control group *(Table 4)*.

Gait analysis

After intervention, both groups showed improvements in gait parameters (range of motion of the affected hip joint and step length on the affected side), with the observation group demonstrating significantly greater improvements than the control group *(Table 5)*.

VAS

The differences in VAS pain scores between the two groups were statistically significant ($p < 0.05$). VAS scores improved in both groups before and after intervention, with a more pronounced improvement observed in the observation group compared to the control group *(Table 6)*.

Group	Relative peak torque of the hip abductor muscles			Relative peak torque of hip extension muscle strength		
	Before intervention	After intervention	p value	Before intervention	After intervention	p value
Observation group (n = 24)	0.42 ± 0.11	0.88 ± 0.14	<0.001	0.36 ± 0.14	0.57 ± 0.26	<0.05
Control group (n = 24)	0.48 ± 0.12	0.75 ± 0.11	<0.001	0.29 ± 0.23	0.44 ± 0.13	<0.05
t value	1.806	3.577		1.273	2.191	
p value	0.077	<0.001		0.209	<0.05	

Table 2. *Relative peak torque (peak torque-to-body-weight ratio) of isokinetic muscle strength in abduction and extension between the two groups before and after treatment.*

Group	Tinetti balance and gait score (points)			Scoring results for both groups after intervention (in points)	
	Before intervention	After intervention	p value	<15	≥15
Observation group (n = 24)	8.8 ± 2.4	18.9 ± 3.2	<0.001	2 (12.5%)	22 (87.5%)
Control group (n = 24)	9.2 ± 1.9	16.7 ± 4.1	<0.001	8 (37.5%)	16 (62.5%)
t value	0.640	2.072		4.547*	
p value	0.525	0.043		0.033	

Table 3. *Comparison of Tinetti scores between the two groups before and after intervention.*
**Count data were analyzed using the chi-square test ($\alpha < 0.05$).*

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Group	SL (mm)			SA (mm^2)		
	Before intervention	After intervention	p value	Before intervention	After intervention	p value
Observation group (n = 24)	484.4 ± 64.5	243.7 ± 41.5	<0.001	524.7 ± 73.3	328.4 ± 29.7	<0.001
Control group (n = 24)	510.1 ± 39.0	375.1 ± 48.4	<0.001	498.6 ± 63.4	374.8 ± 47.2	<0.001
t value	1.670	10.096		1.319	4.076	
p value	0.101	<0.001		0.193	<0.001	

Table 4. *Comparison of balance instrument parameters between the two groups before and after intervention.*

Group	Range of motion of the affected hip joint during gait (°)			Step length on the affected side (cm)		
	Before intervention	After intervention	p value	Before intervention	After intervention	p value
Observation group (n = 24)	24.1 ± 2.4	32.6 ± 2.8	<0.001	24.9 ± 3.2	32.1 ± 3.2	<0.001
Control group (n = 24)	22.7 ± 3.2	31.2 ± 1.5	<0.001	24.2 ± 1.6	30.4 ± 1.5	<0.001
t value	1.71	2.159		0.958	2.356	
p value	0.093	0.036		0.342	0.022	

Table 5. *Analysis of gait-related hip joint range of motion and step length in the two groups before and after intervention.*

Group	VAS (points)		
	Before intervention	After intervention	p value
Observation group (n = 24)	5.3 ± 1.1	2.5 ± 1.2	<0.001
Control group (n = 24)	5.5 ± 1.5	3.5 ± 0.7	<0.001
t value	0.526	3.526	
p value	0.601	<0.05	

Table 6. *Comparison of VAS scores before and after intervention between the two groups.*

DISCUSSION

Transcranial direct current stimulation (tDCS) is a non-invasive central nervous system modulation technique that utilizes weak direct current to modulate cortical excitability and induce neural plasticity remodeling in the brain[5,15], thereby achieving interventions across multiple dimensions of neural functions such as motor control, sensory integration, and emotional regulation. It has been extensively studied and clinically explored in the field of neurological rehabilitation[16]. Numerous evidence-based studies have demonstrated that tDCS, by targeting the motor cortex, can enhance neural plasticity in damaged brain regions and reconstruct impaired neural circuits, effectively promoting the recovery of limb motor function in rehabilitation for motor disorders associated with central nervous system injuries such as stroke, Parkinson's disease, and multiple sclerosis[17]. These central modulation mechanisms provide a solid theoretical foundation for applying tDCS in ankle fracture rehabilitation and implementing combined "central-peripheral" interventions[8,18].

Traditional rehabilitation for ankle fractures has predominantly focused on peripheral interventions such as localized flexion-extension exercises and muscle

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strength training, overlooking the role of plasticity changes in the central motor regulatory cortex following fracture immobilization in limiting functional recovery. This study introduced tDCS into the rehabilitation protocol for ankle fractures, transcending conventional localized approaches by modulating neural activity at the central level and forming a synergistic intervention system with standard limb rehabilitation[19]. Results demonstrated that combined intervention effectively improved patients' pain levels, isokinetic muscle strength, and balance function, highlighting the therapeutic value of central regulation in post-traumatic orthopedic rehabilitation[20].

Analysis of the effects of tDCS on muscle strength in patients with ankle fractures

Muscle atrophy and decreased muscle strength are common complications resulting from prolonged immobilization following ankle fractures, and they represent critical factors limiting weight-bearing capacity and the recovery of joint mobility. Previous basic and clinical studies have demonstrated that anodal transcranial direct current stimulation (tDCS) can enhance excitability in the primary motor cortex[21], improve neural drive efficiency along descending motor pathways, thereby boosting skeletal muscle contraction efficacy in the lower limbs[8]. Studies have shown that anodal tDCS significantly increases isometric muscle strength during quadriceps strength testing[22]. In postoperative rehabilitation following anterior cruciate ligament reconstruction, combined conventional rehabilitation with tDCS intervention improves knee function scores, enhances proprioception and muscle strength in the affected limb, underscoring the therapeutic potential of tDCS in post-traumatic lower limb muscle rehabilitation. The findings of this study align with previous research, demonstrating that high-definition tDCS combined with conventional rehabilitation significantly enhances isometric muscle strength in the lower limbs. The underlying mechanism involves targeted modulation of the contralateral motor cortex by tDCS, which increases cortical neuronal excitability, optimizes central motor command output to the lower limb muscles, alleviates motor cortical inhibition induced by fracture immobilization, reverses disuse-induced muscle atrophy, and establishes a muscular foundation for restoring fundamental lower limb functions such as flexion, extension, and weight-bearing[23]. Compared to single-focused local muscle training, combined central modulation and peripheral exercise promotes muscle strength recovery at both neural and effector organ levels, effectively addressing the limitations of traditional rehabilitation approaches that primarily focus on localized muscle exercises.

Effects of tDCS on sensation and proprioception in patients with ankle fractures

Impaired plantar sensation, diminished ankle proprioception, and persistent post-traumatic pain are typical sequelae following ankle fractures[24]. The local soft tissue injuries, inflammatory stimuli, and prolonged limb immobilization induced by fractures can, on one hand, reduce signals transmitted by peripheral receptors and lead to downregulation of central sensory cortex plasticity, resulting in proprioceptive deficits; on the other hand, they may sensitize central pain regulation pathways, triggering postoperative rest pain and rehabilitation-induced pain, which in turn restricts patients' active rehabilitation exercises and further impedes muscle strength and joint function recovery, creating a vicious cycle of "pain → activity limitation → functional impairment"[4]. From the perspective of pain regulation mechanisms, the prefrontal cortex and somatosensory cortex are involved in pain perception and descending inhibitory modulation. tDCS can modulate cortical excitability in these brain regions[25], activate the endogenous analgesic system, suppress nociceptive signals at the spinal level, reduce central pain hypersensitivity, thereby alleviating postoperative inflammatory pain and rehabilitation-induced pain in ankle fracture patients[26]. Meanwhile, tDCS can modulate sensory-related cortical excitability, optimizing the efficiency of peripheral tactile and vibratory signal transmission and integration to the central nervous system. Relevant studies have demonstrated that tDCS intervention reduces the perception thresholds for foot tactile and vibratory sensations while enhancing plantar sensory acuity[27]. This study confirmed that post-tDCS treatment, patients exhibited significant reductions in pain scores; according to previous literature, these functional gains may be partially related to enhanced foot sensory function and ankle proprioception induced by tDCS, although these sensory parameters were not directly assessed in our trial. The restoration of proprioception enhances joint position awareness and fine motor control, mitigating secondary pain stimuli caused by abnormal force distribution and thereby contributing to sustained pain relief. Following pain improvement, patients showed markedly increased adherence to rehabilitation exercises, creating favorable conditions for subsequent recovery of balance function and daily activity capacity[28].

The study found that following tDCS intervention, patients exhibited significant improvements in foot sensory function and ankle proprioception. The underlying mechanism is believed to involve: fracture trauma and limb immobilization reduce input signals from peripheral receptors, and prolonged deprivation of such input may lead to decreased plasticity in the central sensory cortex; tDCS enhances the central processing capacity for foot sensory information by reshaping plasticity in the sensorimotor cortex, improves the central integration efficiency of peripheral sensory signals, and gradually restores impaired proprioception[29]. This recovery of proprioception further optimizes joint position awareness and fine motor control[30], laying the foundation for subsequent restoration of balance function and daily activity abilities.

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Mechanisms of tDCS in improving balance function in patients with ankle fractures

Human balance maintenance relies on the central nervous system to integrate multi-source information—including muscle strength, proprioception, and visual input—and precisely regulate coordinated contraction of muscle groups. Research findings demonstrate that following tDCS intervention, patients exhibited significant improvements in both static balance (standing on one foot with eyes closed) and dynamic landing balance, manifested as reduced amplitude and velocity of center of gravity oscillation, decreased compensatory trunk flexion and ankle eversion during landing, consistent with previous studies on tDCS-induced limb balance enhancement[15]. From a mechanistic perspective, tDCS not only enhances lower limb muscle strength and restores foot proprioception to optimize peripheral foundations for balance regulation, but also precisely modulates motor cortex excitability via high-precision tDCS, improves central multisensory information integration, reduces abnormal compensatory postures, decreases abnormal movements of the trunk and ankle joints, and enhances static standing stability and dynamic landing control[5]. These improvements in balance capacity enable patients to discontinue reliance on assistive devices earlier, restore independent ambulation, and shorten overall rehabilitation duration[31].

Safety of tDCS and clinical advantages of combined rehabilitation therapy

Safety is a critical prerequisite for the clinical translation of rehabilitation technologies. This study monitored adverse reactions throughout the entire course, with only a minority of subjects in the observation group experiencing transient mild scalp pruritus or tingling sensations, which rapidly alleviated upon adjustment of electrode placement or stimulation current intensity. No severe adverse events occurred, confirming the safety profile of tDCS as a non-invasive technique with excellent tolerability and minimal adverse effects, consistent with findings from domestic and international safety studies on tDCS. In terms of clinical efficacy, tDCS combined with conventional rehabilitation protocols demonstrated superior outcomes compared to standard rehabilitation alone in alleviating pain in the affected limb, enhancing muscle strength, and improving balance function. Traditional rehabilitation primarily focuses on local joint mobilization and muscle strength training, targeting only peripheral injured tissues; in contrast, tDCS intervenes at the level of central neural plasticity by activating impaired motor and sensory cortices. This dual approach creates a synergistic effect of "central modulation + peripheral training," accelerating local tissue functional recovery while addressing post-traumatic central functional inhibition at the neural regulatory level, thereby achieving enhanced rehabilitation outcomes[32]. These findings suggest that tDCS serves as a preferred adjunctive intervention for ankle fracture rehabilitation. The convenience, non-invasiveness, and painlessness of tDCS make it well-suited for widespread adoption in orthopedic rehabilitation across medical institutions.

Limitations of this study and prospects for future research

While this study confirms the positive role of tDCS in the rehabilitation of ankle fractures, several limitations remain: First, the sample size was limited, and evidence for generalizing these findings to broader populations requires further investigation; Second, the follow-up period was short, focusing solely on short-term rehabilitation outcomes, leaving the long-term functional prognosis and impact of tDCS on joint degeneration unclear; Third, no stratified analysis was conducted, lacking comparative studies across different stimulation intensities, durations, intervention frequencies, or individualized target sites, thus failing to establish optimal stimulation protocols tailored to specific fracture types and rehabilitation stages. This analytical strategy was chosen because our main aim was to evaluate cumulative effects at the endpoint rather than dynamic changes over time. This method cannot assess group-by-time interaction and may limit interpretation of differences in changing trajectories between groups.

Based on the aforementioned limitations, future research can be improved in three aspects:

1) Expanding multi-center large-sample study cohorts and extending long-term follow-up periods to systematically evaluate the medium-and long-term rehabilitation outcomes of tDCS;
2) Conducting gradient-parameter controlled trials to individualize tDCS stimulation protocols according to fracture type, injury site, and rehabilitation stage;
3) Extending high-precision tDCS applications to rehabilitation studies for other limb traumatic fractures (e.g., femur, tibia, and fibula) to further explore its application potential and clinical value in trauma orthopedic rehabilitation.

CONCLUSION

In summary, tDCS leverages its central nervous system modulation effects by enhancing excitability in the brain's motor and sensory cortices and inducing neural plasticity remodeling, thereby effectively improving postoperative pain, isokinetic muscle strength in the lower limbs, as well as foot proprioception and balance function in patients with ankle fractures. When combined with conventional rehabilitation protocols, it demonstrates synergistic benefits that optimize overall recovery outcomes. Furthermore, due to its non-invasive nature, safety profile, and low incidence of adverse reactions, tDCS represents a novel central nervous system intervention strategy for ankle fracture rehabilitation with significant clinical translational and application potential.

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