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Review Article

Changes in Postural Control due to Electrical Stimulation Therapy for Ankle Instability: A Systematic Review

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ABSTRACT

Background: Ankle instability results in sensory and motor impairments. Typically, health professionals recommend conservative treatment as the initial approach for individuals with this condition. One such treatment option is Electrical Stimulation (ES). This systematic review assesses the effects of ES techniques on postural control measures in cases of ankle instability.
Methods: We systematically searched five electronic databases: ClinicalTrials.gov, PubMed, Scopus, SPORTDiscus, and Web of Science. To evaluate the quality of the included articles, we utilized the PEDro checklist. We extracted data on population, intervention, and outcomes and synthesized them narratively.
Results: ES decreased the time needed to stabilize the center of pressure, velocity, displacement, and area, thereby enhancing the performance of clinical tests. While postural stability indexes remained unaffected, the gait inversion angle increased with electrical stimulation.
Conclusion: These results suggest that ES interventions are crucial in enhancing postural control in subjects with ankle instability compared to coordination exercises therapy alone. Stochastic resonance reduced A/P and M/L TTS, COP velocity, COP displacement, and COP area, resulting in enhanced postural control.

Introduction

Globally, approximately 712,000 people experience ankle sprains daily [1]. Despite its significant impact on healthcare, an ankle sprain is often perceived as an insignificant injury that should heal quickly with minimal intervention [2]. However, in 70% of cases, symptoms such as giving way and recurring sprains can occur even after the acute symptoms have disappeared [3]. These issues, either independently or combined, can lead to

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ankle instability. This instability may adversely affect the quality of life [4] and physical function [5] and increase the risk for early onset of ankle osteoarthritis [6].

Ankle instability is a complex syndrome with an unknown cause [7]. Some researchers propose that it is a neurophysiological disorder resulting from mechanical and functional instability [8]. However, not all individuals with ankle instability experience mechanical instability following an acute sprain [9, 10]. Many attribute the functional dysfunction in ankle instability to a reduction in mechanoreceptors within the injured ankle joint, leading to deficits in proprioception [11]. In elite sports such as dancing, football, and gymnastics, ankle proprioception has demonstrated the strongest correlation with competition level compared to other joints, with a correlation coefficient of 0.45 ($P<0.001$) [12]. Recent studies have discovered that individuals with ankle instability exhibit impairments in the motor output patterns of their lower limbs before heel contact during walking [13] and before landing during a drop landing [14, 15]. These findings suggest that ankle instability not only leads to sensory deficiencies but also results in changes in motor control.

Systematic studies investigating various aspects of ankle instability, such as deficits in peroneal muscle reaction time and strength [16] and the kinetics and kinematics of gait and running [17], have yielded inconsistent results. The only factor firmly established as a significant contributor to ankle instability is impaired postural control [18, 19].

Sensory interventions targeting afferent input could improve postural control [20]. This improvement could arise from the refinement of motor skills, including muscle activity, joint angle, and velocity, either through explicit involvement of the cortico-striatal system, which encompasses both conscious and unconscious proprioception, or through implicit engagement of the cortico-cerebellar system, which is associated with unconscious proprioception [21]. Various electrical stimulation modalities have been utilized to induce sensory adaptations [22-27]. Electrical current specifically adjusts sensory input through these interventions [23]. In recent years, researchers have been working to identify rehabilitative interventions that can modify postural control in individuals with ankle instability by manipulating sensory input [20, 28]. However, improving postural control remains a topic of debate in ankle instability rehabilitation [29]. This systematic review aimed to evaluate the effects of electrical stimulation techniques on postural control measures in patients with ankle instability. Our hypothesis suggested that considering their potential impact on improved sensory input and muscle strength, changes in postural control would be noticeable among this cohort.

Methods

Bibliographical Databases and Search Strategy

We conducted this review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart. Five electronic databases, including ClinicalTrials.gov, PubMed, Scopus, SPORTDiscus, and Web of Science, underwent a systematic search on January 25, 2024, to retrieve scientific literature published in peer-reviewed journals. The search query was constructed based on Population, Intervention, Comparison, and Outcome items. We used Boolean logical operators ("OR" and "AND") to connect the keywords. We sourced the keywords from the principal author (M.B.) and obtained their synonyms from the medical subject heading database. These keywords included "ankle instabilit*", "ankle injur*", "ankle sprain", "ankle strain", "electrical stimulation", "postural control", "balance", "postural stability", "postural equilibrium", "single leg stance test", "hop test", "star excursion balance test", "jump height", "agility", and "center of pressure".

Eligibility Criteria

Original peer-reviewed studies (such as randomized controlled trials, cross-sectional studies, and case-control studies) conducted anywhere and published between 2000 and 2024 were considered eligible. Participants were young subjects aged 18 to 30 years with ankle instability, based on the International Ankle Consortium statement criteria [30]. The intervention included electrical stimulation. The trial condition was compared with a control condition that included pre-treatment, conventional treatment, or no treatment. The outcomes were variables that correlated with the postural control concept and were measured with laboratory devices or clinical tests. Studies in the form of expert opinions, case reports, conference papers, animal studies, abstract-only studies, and letters to the editor were excluded.

Study Selection

We evaluated all articles obtained from the database searches for eligibility after identifying and removing duplicates using Endnote20 software. Two separate reviewers (M.A. and M.B.) evaluated the titles and abstracts of the identified articles compared to the selection criteria. Following this, two other reviewers thoroughly scrutinized the remaining articles (H.K. and F.G.).

Risk of Bias Evaluation Tool

Two reviewers (H.K. and M.B.) individually evaluated the methodological quality of each study using the Physiotherapy Evidence Database (PEDro) tool. In the evaluation, a rating of 1 point is allocated for answering "Yes" to each question, whereas 0 point is given for answering "No." Question 1 (regarding eligibility criteria) is not included in the scoring (Scores<4: poor, 4-5: fair, 6-8: good, and 9-10: excellent) [31].

Data Extraction

Upon establishing the studies to be included in the review, two reviewers (H.K. and M.B.) independently extracted the total number and demographic characteristics of the population, type, and device characteristics of electrical stimulation, duration and location of electrical stimulation, characteristics of the control condition, and type and statistical measures of outcomes.

Data Synthesis

The results were synthesized based on methodological aspects (outcomes) and clinical factors (population and intervention characteristics). A narrative synthesis of all data elements was performed in a tabular format and discussed in text. The specific P values indicating significance levels from the studies were extracted and presented to discuss potential associations and/or correlations. Conflicts were resolved with input from all authors throughout the entire review procedure.

Results

Search Process and Findings

In the initial search, 218 records were identified, and two additional records were found from the reference lists of included studies. The PRISMA flowchart process led to the inclusion of 11 articles in this review. From the initial search to the final decision, the entire process can be visualized through the PRISMA diagram in Figure 1.

Quality Assessment

Two evaluators (H.K. and M.B.) independently appraised the methodological rigor of 11 research investigations by scrutinizing 121 criteria, aligning each study with 11 specific criteria. Initially, they reached a consensus on 111 criteria, indicating a concurrence rate of 92%. The inter-rater reliability assessment utilizing Cohen's kappa demonstrated nearly flawless accord between the evaluators, yielding a k-coefficient of 0.89 and a 95% confidence interval from 0.840 to 0.920. After further discussion, they achieved 100% agreement. Table 1 displays the quality index scores for each study, with two studies categorized as excellent, five as good, and four as fair. The mean score of 6.63 indicates that the study quality was good overall.

Across the eleven studies analyzed, all investigations established eligibility criteria, ensured baseline similarity across groups, collected primary outcome data from over 85% of initially enrolled participants, utilized intention-to-treat analysis, and provided point estimates and measures of variability. Additionally, 63.63% of the studies employed random allocation, 18.18% used concealed allocation [39, 42], 63.63% implemented subject blinding [32, 34, 36, 37, 39, 41, 42], 18.18% applied blinding for therapists [39, 42] and assessors [41, 42], and 81.81% conducted between-group analysis [32, 34, 36-42].

Study Characteristics

Population

In the selected studies, 403 participants underwent examination. This group consisted of 309 individuals with ankle instability and 90 healthy controls. The participants had an average age of 23.47 years, an average weight of 72.32 kg, and an average height of 172.79 cm. Table 2 summarizes the characteristics of each study's participants.

Intervention

The included research utilized stochastic resonance [32-37], functional electrical stimulation [40], neuromuscular electrical stimulation [41, 42], and transcutaneous electrical nerve stimulation [38, 39, 41, 42]. Electrical stimulation is commonly used to change sensory input by adjusting specific stimulus parameters such as pulse pattern, location, frequency, and amplitude [37, 38].

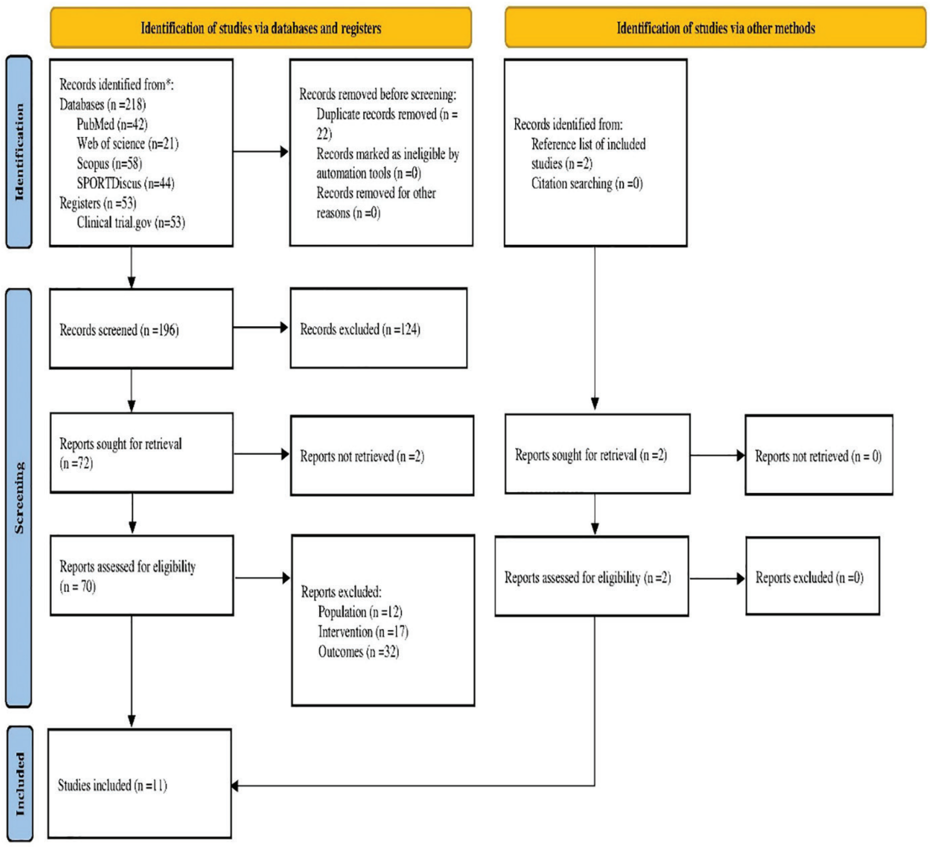

Figure 1: PRISMA diagram depicting the literature review process

Table 1: PEDro's assessment result

Author, year	Eligibility criteria	Random allocation	Concealed allocation	Similar groups at baseline	Subject blinding	Therapist blinding	Assessor blinding	> 85% key outcomes	Intention to treat	Between-group statistical analysis	Point and variability measures	Final score
Ross et al., 2006 [32]	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	6
Ross et al., 2007 [33]	Yes	Yes	No	Yes	No	No	No	Yes	Yes	No	Yes	5
Ross et al, 2007 [34]	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	7
Ross et al., 2012 [35]	Yes	Yes	No	Yes	No	No	No	Yes	Yes	No	Yes	5
Ross et al, 2012 [36]	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	7
Glass et al., 2014 [37]	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	6
Yoshida, et al, 2015 [38]	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Khalid et al, 2020 [39]	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	9
Gottlieb et al, 2022 [40]	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Needle et al., 2023 [41]	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	8
Gottlieb et al, 2024 [42]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	10

Table 2: Participants characteristics

Author, year	n	Groups	Male / female	Mean age (years)	Mean weight (kg)	Mean height (cm)
Ross et al., 2006 [32]	60	TG_1:20, TG_2:20, CG:20	N/C	20.83	74.83	173.33
Ross et al., 2007 [33]	30	TG_1:10, TG_2:10, CG:10	14/16	21	76	177
Ross et al, 2007 [34]	12	TG: 12	6/6	22	71	173
Ross et al., 2012 [35]	96	TG_1:36, TG_2:36, CG:24	48/48	21	75	176
Ross et al, 2012 [36]	12	TG: 12	5/7	21	69	173
Glass et al, 2014 [37]	24	TG: 24	12/12	22.5	66.5	172
Yoshida et al, 2015 [38]	7	TG: 7	7/0	20.3	N/C	N/C
Khalid et al, 2020 [39]	60	TG_1:20, TG_2:20, CG:20	60/0	25.8	69.13	166.66
Gottlieb et al, 2022 [40]	48	TG:24, CG:24	30/18	30.25	73	172.5
Needle et al., 2023 [41]	20	TG_1:11, TG_2: 9	12/8	22.75	73.75	170.95
Gottlieb et al, 2024 [42]	34	TG_1:14, TG_2:15	14/20	30.8	75	173.5

N/C: No Comment, TG: Trial Group, CG: Control Group

In five investigations [32-36], stochastic resonance stimulation was characterized by Gaussian white noise with a zero mean, a standard deviation of 0.05 mA, and band-pass filtering below 1000 Hz. The targeted anatomical locations included the lateral soleus, peroneus longus, tibialis anterior muscles, and mediolateral ankle ligaments. In a separate study [37], a LabVIEW program generated white noise ranging from 0 to 100 Hz at sensory thresholds of 25%, 50%, 75%, and 90%. The generated signal branched to four tactors to stimulate the gastrocnemius, peroneus longus, and tibialis anterior and posterior muscles.

In another study [38], researchers administered a transcutaneous electrical nerve stimulation intervention with an amplitude of 4.8 mA and a frequency of 10 Hz. They utilized an Intellect Mobile Stim device and placed a 5×5 cm electrode at the distal end of the fibula to target the common peroneal nerve.

The functional electrical stimulation system [40], NESS L300Plus, comprises three interconnected components that communicate wirelessly. These components include (1) a stimulator, (2) a gait sensor positioned beneath the heel, and (3) a control unit used to stimulate the peroneus longus muscle belly. The waveform produced by the NESS L300Plus system is symmetrical and biphasic, with a frequency of 35 Hz and a pulse duration of 200 µs.

In other studies [39, 41, 42], researchers used a portable device equipped with adhesive surface electrodes to administer transcutaneous electrical nerve stimulation (TENS) and neuromuscular electrical stimulation (NMES). They employed a bi-phasic square wave pattern and targeted different anatomical locations, including the sciatic nerve (1 mA, 75 Hz) [41], the lateral aspect of the shin (35 Hz for NMES, 10 Hz for TENS) [42], and the triceps surae muscle (50 Hz) [39].

Comparisons

Six studies compared a specific form of electrical stimulation involving stochastic resonance and transcutaneous electrical nerve stimulation to coordination exercises [32, 33, 35, 38] and stretching exercises [39]. One study investigated different stochastic resonance thresholds [37], while the other studies compared electrical stimulation with each other [41, 42] or with a control condition without any intervention [40].

Outcomes

Time to Stabilization (TTS)

Out of the 11 studies, three utilized Center of Pressure (COP) Time to Stabilization (TTS) to assess postural control [32, 36, 42]. Applying Stochastic Resonance (SR) to ankle muscles and mediolateral ligaments reduced anteroposterior (A/P) ($F(3,108)=4.27$, $P=0.01$, effect size=0.4) and mediolateral (M/L) ($F(3,108)=8.02$, $P<0.01$, effect size=0.3) TTS compared to coordination exercise and no intervention after six weeks. Post hoc analysis using Tukey's Honestly Significant Difference test revealed a notable enhancement of TTS by 22% due to stochastic resonance [32]. Nevertheless, the evaluation of the immediate impact of stochastic resonance indicated a reduction in A/P TTS (1.32±0.31 s compared to 1.74±0.8 s, $t(11)=-2.04$, $P=0.03$), while the M/L TTS (1.95±0.4 versus 1.92±0.48, $t(11)=-0.2$, $P=0.42$, $d=-0.07$) remained unaltered. The mean percentage of instant enhancement for A/P TTS utilizing stochastic resonance was 24% [36]. There was no significant effect on TTS between applying transcutaneous electrical nerve stimulation and neuromuscular electrical stimulation on the lateral side of the shin (1.2±0.8 compared to 2±2.8, effect size (95% CI): -0.26 (-1.04, 0.52)) [42]. An effect size equal to 0.2 is considered small, 0.5 is seen as moderate, and 0.8 is classified as large.

COP Velocity

Among the three groups - coordination training, stochastic resonance, and no intervention - there was a significant interaction between treatment and test (Wilk's Lambda=0.78, $F[8, 126]=2.08$, $P=0.04$, $\eta 2P=0.12$) [35]. When stochastic resonance was applied to the ankle muscles and ligaments, there was a reduction in posttest A/P (2.3±0.4 cm/s compared to 2.7±0.6 cm/s, $t(27)=1.88$, $P=0.036$) and M/L (2.6±0.5 cm/s compared to 2.9±0.5 cm/s, $t(27)=1.71$, $P=0.049$) COP velocity compared to pretest [33]. The stochastic resonance group had positive responses of 75% (A/P at week 2), 88% (A/P at week 4), 83% (M/L at week 2), and 88% (M/L at week 4) [35].

When comparing stochastic resonance with 25%, 50%, 75%, and 95% sensory thresholds, a main effect for treatment (Wilks' lambda=0.57, $F(5, 18)=2.77$, $P=0.05$; Cohen's $f=0.83$) was found. At a sensory threshold of 25%, resultant COP velocity decreased (no stochastic resonance: 0.94±0.32 cm/s, 25%: 0.80±0.19 cm/s, 50%: 0.88±0.24 cm/s, 75%: 0.94±0.25 cm/s, 95%: 1.00±0.28 cm/s). It was found that the 25% sensory threshold stochastic resonance made single-legged balance better than no stochastic resonance by 17% to 10% for COP frontal- and sagittal-plane velocity assessments ($P<0.05$) [37].

COP Displacement

Stochastic resonance significantly changed M/L COPsd (0.63±0.12 cm versus 0.73±0.11 cm, $t(27)=-2.37$, $P=0.013$) and M/L COP maximum excursion (1.76±0.25 cm versus 1.98±0.25 cm, $t(27)=2.29$, $P=0.015$) compared to the pooled means of pre-intervention ($P<0.05$) [33]. A significant enhancement in COP resultant vector by 8.29% was observed with effective stochastic resonance stimulation compared to the control condition (6.60±1.06 cm/s compared to 7.20±1.03 cm/s, $t(11)=5.17$, $P<0.01$, effect size=0.56) [34]. In the transcutaneous electrical nerve stimulation group, the length of the COP on the sprain side notably decreased, measuring 627.0±235.4 mm prior and 551.8±172.1 mm after the activity [38].

COP Area

The stochastic resonance decreased COP area (0.13±0.03 cm2 versus 0.16±0.04 cm2, $t(27)=1.79$, $P=0.043$) compared to the means of pre-stochastic resonance ($P<0.05$) [33]. There was no difference in COP area for different stochastic resonance thresholds (25%, 50%, 75%, and 95% sensory thresholds) ($F(5, 18)=0.82$, $P=0.55$, Cohen's $f=0.45$) [37].

Clinical Tests

The transcutaneous electrical nerve stimulation group showed a significant increase ($P\leq0.01$) in balance after treatment for anterior (5.4%, $P=0.01$, $\eta 2P=0.61$), posterior (4.2%, $P=0.01$, $\eta 2P=0.65$), posterolateral (3.9% $P=0.01$, $\eta 2P=0.67$), and posteromedial (5.6%, $P=0.01$, $\eta 2P=0.63$) directions in the pre- to follow-up period compared to stretching (1.3%, 1.2%, 0.7%, and 0.8%, respectively) [39]. Significant positive effect sizes were noted in favor of the neuromuscular electrical stimulation group for the star excursion balance test posteromedial direction at post-treatment (Cohen's $d=0.38$) with a 95% confidence interval of -0.38 to 1.13 over the transcutaneous electrical nerve stimulation group [42]. The side hop test showed no significant group (transcutaneous electrical nerve stimulation and neuromuscular electrical stimulation)-by-time (baseline, two weeks, and four weeks) interaction effect ($F(2, 36)=0.142$, $P=0.868$) [41].

Postural Control Indexes

There is no significant difference between applying transcutaneous electrical nerve stimulation or neuromuscular electrical stimulation and the control group in terms of dynamic postural stability index ($F=0.079$, $P=0.924$), anteroposterior stability index ($F=0.055$, $P=0.947$), mediolateral stability index ($F=1.2$, $P=0.28$), and vertical stability index ($F=0.5$, $P=0.611$) [41].

Inversion Angle

A notable disparity within the functional electrical stimulation cohort revealed heightened ankle eversion during 0–7% ($P=0.011$) and 67–81% ($P=0.006$) of the stance phase post-intervention. Table 3 outlines the details of each study's attributes.

Table 3: Study characteristics

Author, year	Study design	Population	Trial and control groups or conditions	Duration	Assessment protocol and instruments	Outcome	Conclusion
Ross et al., 2006 [32]	Experimental with repeated measures	FAI	-Single-leg coordination exercise -Single leg coordination exercise with SR stimulation - no intervention	6 weeks 5day/week 10 min/ session	Participants underwent evaluation using a unilateral leg jump-landing assessment. The assessment involved performing a jump with both legs at a height between 50% and 55% of their highest jump while standing 70 cm away from the midpoint of the force plate.	A/P and M/L TTS	Utilizing SR stimulation could be considered a viable treatment option for FAI. This is because it has the potential to enhance dynamic postural stability at a faster pace and to a greater degree than coordination exercises without SR stimulation.
Ross et al., 2007 [33]	Pre-post intervention design	FAI	-Coordination exercises -SR with Coordination exercises -no intervention	6 weeks 5 times/ week	The postural stability of one leg was evaluated using a force plate. Data was captured at a rate of 180 Hz, and the signals were transmitted through a BNC adapter chassis.	-A/P and M/L COP velocity -M/L COP SD -M/L COP maximum excursion -COP area	A six-week coordination practice regimen, which includes SR, has resulted in improved postural stability
Ross et al., 2007 [34]	Cross over	FAI	- SR Stimulation (0.01 and 0.05 mA) -no intervention	20 seconds	Data was gathered during the assessment of single-leg stance using a force plate operating at 180 Hz. The analog signals underwent amplification and were subsequently conveyed through a BNC adapter chassis.	COPV-R	SR could enhance postural maintenance
Ross et al., 2012 [35]	Repeated measured	FAI	-Balance training -Balance training with SR -NO intervention	4 weeks 5 times/ week 10 min/ session	Single-leg equilibrium assessments were conducted thrice: pre-training, 2 weeks, and 4 weeks post-assessment. To evaluate dynamic balance, participants executed a unilateral jump-landing maneuver, leaping to a level equivalent to 50-55% of their peak vertical jump and alighted on a singular leg atop a force platform, promptly stabilizing their posture.	A/P COP velocity M/L COP velocity	SR led to improved sagittal plane stability, while the non-SR group showed improvement after 4 weeks. As for frontal plane stability, SR enhanced balance after 4 weeks.
Ross et al., 2012 [36]	Cross over	FAI	-SR condition -no SR condition	Immedi-ately	To assess dynamic balance, participants performed a single-leg jump-landing test. They were instructed to jump and reach a height between 50% and 55% of their maximum vertical jump. Afterward, they were required to land on one leg on a force plate and quickly stabilize themselves.	A/P TTS M/L TTS	Health professionals could use SR to improve balance during dynamic single-leg exercises in the frontal and sagittal planes. This would allow patients to participate in exercises that may otherwise be difficult.
Glass et al., 2014 [37]	Case control with a cross-over design	FAI	SR at 25,50,75% of sensory threshold	20 seconds	Participants were directed to stand without shoes on one foot on a force platform for 20 seconds. The affected leg needed to be flexed at the knee, while the foot should be in a neutral alignment. The unaffected leg was to be slightly bent at both the hip and knee joints. Data collection commenced upon the participants attaining equilibrium.	M/L and A/P COP velocity and excursion R-COPV COP ellipse area	25% sensory threshold SR led to enhancements in single-legged and double-legged balance.
Yoshida et al, 2015 [38]	Crossover	FAI	-Balance training with TENS -Balance training	1 session 3times Each time 10min 5 min rest between times 40 min TENS	Participants were asked to perform a sideways jump over a 20 cm high platform. They were instructed to use only one leg and maintain this position for 10 seconds.	COP length Peroneal muscle EMG	When combined with TENS, the balance exercises significantly decreased ankle instability on the sprained side. This decrease can be attributed to the increased activity of the peroneal muscles, which results from the shared innervation of the common peroneal nerve.

Author, year	Study design	Population	Trial and control groups or conditions	Duration	Assessment protocol and instruments	Outcome	Conclusion
Khalid et al, 2020 [39]	Randomized controlled trial	FAI	-The PNF technique -TENS and PNF -No intervention	5 weeks 4 times per week	All three groups underwent assessment during the pretreatment, posttreatment in the third week, and follow-up at the start of the fifth week. They used the SEBT to evaluate dynamic postural control. The SEBT consists of 8 directions set at 45-degree angles from the center. The primary measurement in this evaluation is the maximum distance a limb can move in any direction without losing balance.	SEBT	It was observed that a treatment program involving triceps sural muscle PNF stretching in combination with TENS, which induced muscle contraction during the PNF stretch phase, led to substantial improvements in balance compared to PNF stretching alone.
Gottlieb et al, 2022 [40]	Repeated measured crossover	CAI	-FES -no FES	10 min	Ankle angles in the sagittal plane were determined while walking through the utilization of the Cardan rotation order—a motion tracking setup comprising eight cameras documented ankle motions in three dimensions at 100 Hz. Subsequently, the information underwent analysis in a Visual 3D application employing a six-degree-of-freedom anatomical model. Peroneal EMG readings were obtained utilizing a wireless EMG device operating at 2000 Hz.	Ankle inversion angle Peroneal EMG	The results indicate that peroneal FES can induce changes in ankle movements during walking. This has the potential to inform future interventions for individuals with CAI.
Needle et al., 2023 [41]	Randomized controlled trial	CAI	NMES TENS	2 weeks intervention 5 sessions 10 minutes per session 4 weeks retention	Baseline, post-intervention (following 2 weeks), and retention assessments (after 4 weeks) were carried out. During MVC, EMG of the PL, TA, and SOL muscles was performed. Participants' maximal jump height was assessed utilizing a Vertec jump trainer. Participants executed forward hops from a 70 cm distance towards a force plate integrated into the floor, achieving a vertical height equivalent to 50% of their maximal jump. Functional performance was gauged through a single-leg lateral hop test.	Competition time of hop test EMG of PL, TA, and SOL muscles the A/P, M/L, and vertical directions Stability indexes, and combined dynamic postural stability index	TENS had some impact on neural excitability, but it did not significantly affect clinical functionality. While TENS shows promise for neuromodulation, it may require the addition of rehabilitative exercises to bring about lasting changes.
Gottlieb et al, 2024 [42]	Randomized controlled trial	CAI	-Training with NMES -Training with TENS	4-6 weeks 12 sessions 6min	The experimental groups were assessed at baseline, pre-intervention, post-intervention, and follow-up at 6 months and 12 months. Participants were tasked with executing a unilateral drop-jump from a raised platform 25 cm high onto a force plate measuring 50 × 60 × 5 cm, produced by Kistler in Switzerland. Following the landing, participants were directed to promptly regain stability and sustain equilibrium for 20 seconds.	SEBT TTS	The consistent pattern of enhanced functional results observed with the combination of NMES and training, as opposed to training with TENS, suggests a potential advantage that warrants additional exploration as a therapeutic approach for individuals with CAI.

TTS: Time To Stabilization; FAI: Functional Ankle Instability; SR: Stochastic Resonance; A/P: Anteroposterior; M/L: Mediolateral; COP: Center Of Pressure; TA: Tibialis Anterior; SD: Standard Deviation; COPV-R: COP Vector- Resultant; CAI: Chronic Ankle Instability; LS: Lateral Soleus; PL: peroneus longus; ATFL: anterior talofibular ligament; PNF: proprioceptive neuromuscular facilitation; SEBT: Star Excursion Balance Test; MVC: Maximum Voluntary Contracture; GRF: Ground Reaction Forces; Electromyography: EMG; SOL: Soleus

Discussion

This review explores the potential benefits of electrical stimulation for improving postural stability in individuals with ankle instability. Studies show that people with ankle instability have a shorter reach distance on the star excursion balance test [43], longer durations on hop tests [43], and larger center of pressure (COP) excursion parameters [44]. Our review showed that applying electrical stimulation can reduce COP Time to Stabilization (TTS) [32, 36, 42] and velocity [33, 35, 37] in the anteroposterior (A/P) and mediolateral (M/L) directions. Additionally, COP displacement [34, 38] and area [33, 37] were significantly reduced with electrical stimulation, leading to improved clinical test performance [39, 41, 42]. While electrical stimulation did not affect postural stability indexes [41], it did increase the eversion angle during gait [40].

One possible reason for these impacts might be the increased muscle activity caused by electrical stimulation, as mentioned in previous discussions on anterior cruciate ligament injuries [45]. Electrical stimulation activates specific muscle nerves, leading to muscle contractions [46, 47]. It is thought to arise from the disinhibitory impacts of heightened activation of afferent fibers [48]. The strength of the peroneal muscles could be essential in preventing recurrent ankle sprains by assisting in ankle eversion, especially when the foot is susceptible to rolling [49]. Electrical stimulation applied to the common peroneal nerve influenced the dorsal motor area, increasing activity in the primary motor cortex [50].

Additionally, the peroneal muscles exhibited heightened activity due to the common peroneal innervation induced following the methodology detailed by Wu et al. [51]. Another study demonstrated enhanced pinch force in stroke patients following transcutaneous electrical stimulation [52]. Participants with ankle instability had a higher bilateral peroneus longus resting motor threshold. Elevated resting motor threshold levels may indicate impaired peroneus longus corticomotor excitability in individuals with ankle instability. The correlation between resting motor threshold and self-reported function was moderate, suggesting that deficiencies in corticomotor excitability could impact functional abilities [53].

When contemplating the application of electrical stimulation to individuals with ankle instability, the potential impacts extend beyond neural excitability [41]. Two reviews indicated that treatment strategies incorporating balance exercises effectively improve the functionality of individuals with ankle instability. For this reason, the included studies used electrical stimulation in combination with exercise therapy [54, 55]. Prioritizing proprioceptive rehabilitation following an ankle injury is crucial, given the potential spinal and supraspinal adaptations thought to result from a lack of proprioception in the ankle joint [48].

One detrimental effect of electrical stimulation could be muscle fatigue. Electrical stimulation can reduce muscle fatigue by modifying various elements such as stimulation parameters, training duration, and electrode size and placement [56]. Prior research has utilized various durations of functional electrical stimulation, ranging from under one minute to 15 minutes [57, 58]. We could infer that using a briefer training period might have reduced muscle fatigue [57]. Increasing stimulation intensity gradually during the electrical stimulation (ES) session could lead to improved adaptation and postpone the onset of muscle fatigue [58]. Employing multiple electrodes with asynchronous activation sequences represents an alternative approach to reducing muscle fatigue while applying electrical stimulation. In this review, certain studies employed electrodes of considerable size (50 cm2) for delivering the stimulation [40], while others utilized smaller dimensions. Although larger electrodes might cause reduced discomfort, they could engage a more extensive array of motor units, potentially leading to earlier fatigue onset [40].

Limitations

In previous studies, a comprehensive analysis of the optimal timing, frequency, and amplitude for applying electrical stimulation appeared to be lacking. Additionally, no comparative study has been conducted to determine the best type of electrical stimulation. It is necessary to acknowledge that the studies were conducted within controlled laboratory settings, thus casting doubt on the transferability of these interventions' effects to real-world performance.

Conclusion

The application of electrical stimulation significantly impacts postural control measures compared to coordination exercises and no intervention in ankle instability. Stochastic resonance led to a reduction in anteroposterior (A/P) and mediolateral (M/L) Time to Stabilization (TTS), center of pressure (COP) velocity, COP displacement, and COP area, resulting in enhanced postural control. Notably, at a 25% sensory threshold, stochastic resonance showed the most consistent improvements in postural control parameters. Additionally, the transcutaneous electrical nerve stimulation group demonstrated improved postural control outcomes in various directions compared to stretching exercises. The neuromuscular electrical nerve stimulation group also positively affected specific postural tests. Further research and clinical trials may provide deeper insights into these interventions' long-term effectiveness and applicability for ankle instability.

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