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Clinical Efficacy of Neuromodulation Interventions and Rehabilitation Advancements in Ataxic Subtypes

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Abstract: Ataxia is a progressive neurological disorder that impairs motor and functional ability due to cerebellar dysfunction. Conventional therapies, which include pharmacological interventions, offer limited benefits, creating a need for mechanism-based and objectively measurable alternatives. Current therapeutic strategies increasingly focus on neuromodulation techniques, physical training, hybrid protocols, and the use of smart wearable technology in some of these therapies. This review compares the clinical efficacy of physical therapy, neuromodulation techniques—deep brain stimulation, repetitive transcranial magnetic stimulation, and transcranial direct current stimulation (tDCS)—and their hybrid therapy modalities, aiming to assess how stimulation-induced neuroplasticity interacts with motor training to optimize rehabilitation techniques across hereditary and acquired ataxias. Gait indices such as the Scale for the Assessment and Rating of Ataxia, International Cooperative Ataxia Rating Scale, Berg Balance Scale, Timed Up and Go, stimulation settings, and intensity of the therapy were considered for evaluating the impact of the intervention. All interventions demonstrated short-term gains in coordination, gait, and balance. However, hybrid protocols, which integrate different physical rehabilitation techniques or a neuromodulation technique paired with physical therapy, showed stronger and more durable recovery. Mechanistically, neuromodulation models induce neuroplasticity in cerebellar-cortical pathways, while physical therapy stabilizes neuroplastic adaptations. Robot-assisted, remote tDCS interventions and wearable sensor-supported monitoring have increased ease of access and participant compliance. Limitations across studies included small cohorts, variability in stimulation parameters, and short follow-up durations. Collectively, hybrid and technology-integrated rehabilitation is a promising framework for reinforcing motor function and independence in ataxic patients. Future multicenter trials incorporating wearable gait biomarkers, neuroimaging, and personalized strategies are required to validate long-term efficiency and enable precision in therapies for ataxic patients.

Keywords: cerebellar ataxia (CA), spinocerebellar ataxia (SCA), neuromodulation, physical rehabilitation for ataxia, wearable technology

1. Introduction

Ataxia is a coordination disorder caused by the dysfunction of the neurophysiological network of the cerebellum [1]. This condition is characterized by deficient muscle coordination. Ataxia encompasses a group of heterogeneous neurological disorders marked by impaired coordination, balance, and speech. It may be caused by genetic mutations or acquired causes like trauma or infection. Most ataxic disorders are slowly progressive, indicative of cerebellar neurodegeneration [2]. The base classification of an ataxic condition is whether it is genetic or acquired, followed by the subclassifications—autosomal recessive, autosomal dominant, X-linked, and mitochondrial [3]. Autosomal recessive ataxic types are identified at an earlier stage of life through gait and limb incoordination, oculomotor deficits, or cardiomyopathy (e.g., Friedreich's ataxia) [3]. Autosomal dominant ataxias, which are also known as spinocerebellar ataxias (SCA), typically have onset in adulthood, which involves brainstem and cerebellar deterioration (e.g., SCA 1, 2, 3, 6, 7). Recessive and rare types of ataxias are mitochondrial and X-linked forms, in which the former involves defective DNA repair or mitochondrial energy metabolism and the latter predominantly affects males [3]. Excluding the hereditary forms, ataxia also occurs due to acquired and reversible determinants such as vitamin deficiency or immune-associated ataxia [4].

The gait patterns of patients with ataxia are characterized by an increased width of steps, a shortened stride, an inconsistent gait rhythm, and a poor control of limb placement [5]. Analyzing the gait of SCA in the biomechanical aspect showed decreased lower-limb joint motion amplitude and a longer phase of double-foot contact, pointing toward compensatory mechanisms for gait stabilization [6]. Shorter step length in patients with Friedrich's ataxia was marked as different from that of SCA1 or 2 patients [7]. An extended 3D analysis of the gait of SCA 38 patients showed a wider base of support, reduced motion in the hip/ankle/knee joints, and prolonged stance phases [8]. Patients with ataxia are evaluated using clinical and real-world assessments to quantify balance and gait impairments. Ataxia severity is measured using the Scale for the Assessment and Rating of Ataxia

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(SARA) and the International Cooperative Ataxia Rating Scale (ICARS) [9]. Balance is evaluated using the Berg Balance Scale (BBS), while functional mobility is assessed using the Timed Up and Go (TUG) test [9]. Specific gait parameters such as walking speed, length of the steps, and variability in stride lengths are measured using the 10-Meter Walk Test (10-MWT) in clinical settings [10]. However, these clinical assessments provide only limited snapshots of performance in controlled environments, and there is a possibility of missing subtle fluctuations in the results. Recent works have highlighted the efficiency of capturing continuous, high-resolution data through the use of smart wearable technologies such as accelerometers, gyroscopes, and smartphone sensors. Smartphone-based sensors are used to objectively quantify gait irregularity, limb dyscoordination, balance, and speech in ataxia [11]. Wearable Inertial Measurement Units (IMU) can extract detailed spatiotemporal gait characteristics, including variability, sway patterns, and trunk instability. The outcomes from these wearables serve as a framework for remote monitoring and early detection of subtle motor decline. These sensor-driven digital biomarkers contain valuable data that can potentially be missed while measuring through clinical scales [12]. Adding to the wearable sensor platforms for outcome measurement, applying machine learning models to wearable datasets shows potential for automated gait pattern identification and customized motor profiling, supporting the development of patient-centered digital health tools for ataxia [13]. Wearable systems, on the whole, provide an essential foundation for objective, real-world quantification of ataxic gait and help with emerging smart-health technologies.

Adjunctive to pharmacological treatments, a range of current interventions is employed to alleviate ataxic symptoms, which includes physical therapy, neuromodulation techniques, and surgical approaches. Riluzole, which is a glutamate-release inhibitor, modulated the excitotoxic pathways of patients with hereditary cerebellar ataxias (CA), improving ataxic symptoms [14]. While aminopyridines improve early Purkinje cell function and motor efficiency, long-term effects on the progression of the disease are uncertain. Certain drugs, such as antiepileptics, lithium, etc., can induce or worsen CA [15]. Side effects such as tremor, paresthesia, and cardiac arrhythmias limit the chronic usage of drugs for treating ataxia [16]. In addition to pharmacotherapy, rehabilitation-based interventions, including physical therapy and neuromodulation techniques, are recognized as key interventions for managing functional improvements, including balance, coordination, and limb control. Early initiation of physical therapy is essential to avoid further decline of the functional parameters of patients diagnosed with ataxia [17]. Integrated physiotherapy interventions, including aerobic exercise, balance training, and coordination exercises, significantly reduce the severity and symptoms of ataxia [18]. Clinical reviews have highlighted that while various physical therapy approaches can improve symptoms, most trials are low level or small, and current randomized data fall short of establishing the durability of these therapies [19]. Although physical rehabilitation promotes compensatory motor learning, it may not address the reduced cerebellar-cortical connectivity linked to ataxia. Consequently, neuromodulation techniques modulate neural activity and promote neuroplasticity [20].

Neuromodulation methods incorporate magnetic or electrical stimulation to alter brain dynamics. Deep brain stimulation (DBS), repetitive transcranial magnetic stimulation (rTMS), and transcranial direct current stimulation (tDCS) are the three general neuromodulation methods utilized [21]. rTMS modulates the brain state by delivering magnetic pulses that induce noninvasive electrical currents in target areas of the brain. This technique has been associated with improved motor coordination and reduced primary ataxic symptoms, especially when directed at the motor cortex region [22, 23]. Likewise, tDCS alters cortical excitability by applying low-intensity electrical currents via scalp electrodes [23]. DBS is an invasive procedure in which electrodes are inserted into deep brain regions, such as the dentate nuclei or subthalamic areas. Electric stimulation from an implanted pulse generator modulates abnormal cerebellar activity and facilitates motor recovery [24]. Despite the positive measurable results delivered by isolated neuromodulation trials, variability in stimulation parameters and limited follow-up durations constrain their clinical applicability. Their outcomes often vary across ataxia types and disease stages. Recent explorations have examined integrated approaches combining neuromodulation with targeted physical therapy or gait training. Combining physical therapy with a neuromodulation technique shows greater improvements in balance, gait, and coordination compared to the interventions performed alone. This approach allows the amplification of the outcomes of each intervention [25]. As emphasized by Ilg et al. [5], gait and balance are among the earliest and most disabling manifestations of CA, yet current clinical and patient-reported scales remain insensitive to subtle functional change. There remains a lack of consolidated comparison of the relative efficacy of physical therapy, neuromodulation, and hybrid rehabilitation protocols across different forms of ataxia. Therefore, this review aims to systematically evaluate a broad range of interventions—physical interventions, neuromodulation interventions, and combinations of multiple interventions for multiple ataxia subtypes—SCA2, SCA3, SCA7, SCA38, and mixed CA. The goal is to compare study design, stimulation or drug parameters, rehabilitation dose/intensity, functional outcome measures (SARA, ICARS, BBS, TUG, 10-MWT, Nine-Hole Peg Test (9-HPT), gait kinematics), and follow-up duration to determine the optimal evidence-supported treatment paradigms tailored to specific ataxia subtypes and disease stages.

2. Methodology

2.1. Search strategy

This literature review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). An extensive search was performed from 2007 to 2025 in PubMed, Scopus, IEEE, and ScienceDirect to identify studies on treating hereditary and acquired ataxias using various interventions such as physical therapy, neuromodulation techniques, and hybrid protocols. Search terms included "cerebellar ataxia" OR "spinocerebellar ataxia" AND "neuromodulation techniques" OR "transcranial Magnetic stimulation (TMS)" OR "repetitive TMS (rTMS)" OR "Transcranial Direct Current Stimulation (tDCS)" OR "deep brain stimulation (DBS)" OR "physical rehabilitation" OR "gait training" AND "The Scale for the Assessment and Rating of Ataxia (SARA) score" OR "The International Cooperative Ataxia Rating Scale (ICARS)" OR "gait improvements" OR "tremor reduction" OR "symptom reduction" OR "smart wearable technology for ataxia."

2.2. Search outcomes

The comprehensive search using the keywords yielded around 2750 discrete articles from 2007 to 2025. Based on the title, 810 papers were included. One thousand nine hundred and forty articles were eliminated after reviewing their abstracts. A full-text

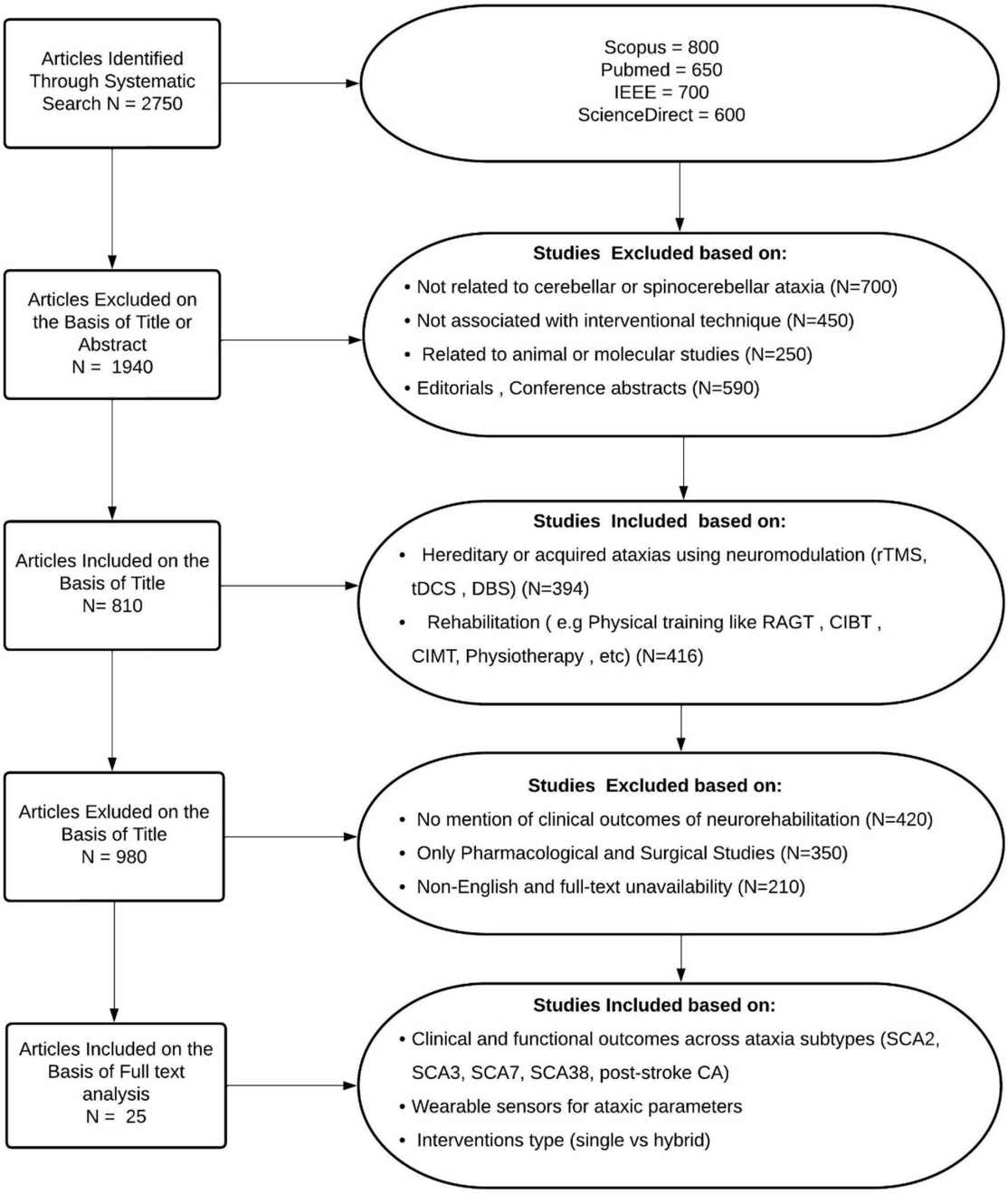
analysis was conducted on 25 articles that provided information on the impact of various interventions used for treating patients with hereditary or acquired ataxic conditions. Figure 1 represents the specification by which the articles were chosen.

Figure 1 depicts the comprehensive search and screening strategy following the PRISMA guidelines employed to filter the suitable studies from multiple databases. Articles not relevant to the study's objective were excluded through methodological screening of titles, abstracts, and full texts to ensure the validity and relevance of the included studies [11–13, 24, 26–46].

2.3. Inclusion and exclusion criteria

The studies published in English between 2007 and 2025 were included. The studies that involved patients diagnosed with acquired (SCA2, SCA3, SCA7, SCA38, post-stroke ataxia, mixed CA) or hereditary ataxias were included for the review. Studies that employed quantifiable clinical scales for outcome measurement, such as ICARS, Functional Independence Measure (FIM), TUG, BBS, SARA, and objective measurement systems using smart wearable technologies were included. The trials that

Figure 1
PRISMA-based flowchart for literature review



reported data before and after intervention or comparative data were included. Both observational and randomized controlled studies were included if intervention data were presented in the article.

The studies involving animal studies or computational models were excluded. The trials that lacked measurable clinical outcomes, such as ICARS and SARA, were excluded. Studies that were purely surgical or pharmacological without a neuromodulation and neurorehabilitation component were excluded. Inaccessible full-text articles and non-English publications were excluded. Case reports that lacked methodological details and intervention outcomes were excluded. Studies that focused only on molecular mechanisms or biochemical assays and diagnostic tools without functional rehabilitation outcomes measures and data were excluded.

2.4. Classification of the articles

The articles were classified based on the type of ataxic condition investigated to enable subtype-specific comparison of outcomes—(1) Spinocerebellar Ataxia Type 2 (SCA2), (2) Spinocerebellar Ataxia Type 3 (SCA3), (3) Spinocerebellar Ataxia Type 7 (SCA7), (4) Spinocerebellar Ataxia Type 38 (SCA38), (5) Post-Stroke Ataxia, and (6) General or Mixed CA. Further subclassification includes the type of intervention administered.

Graphical representation of the classification of reviewed studies ($n = 25$) based on ataxia subtypes is shown in Figure 2. The graph represents the percentage allocation of studies across six major classifications—SCA2, SCA3, SCA7, SCA38, post-stroke ataxia, and mixed CA—highlighting the dominance of SCA3 and mixed CA studied within the reviewed literature [11–13, 24, 26–46].

2.5. Risk of bias

There were fewer than 20 participants in most studies included in the review. Heterogeneity was observed across the patient subtypes—SCA2, SCA3, SCA7, SCA38, post-stroke ataxia, and mixed CA—of the studies included. There were variations in the blinding procedures of the study; that is, some of them were single blind, others double blind, and a few were open-label studies. Evaluation of lasting therapeutic effects was limited by short-term follow-ups. Outcome measures compatibility was affected by variability in stimulation parameters such as duration, intensity, and frequency of the neuromodulation treatments. There was a lack of control or sham groups leading to placebo bias. In addition, there are possibilities of publication bias, as there are only reports of positive outcomes compared to null findings. There were difficulties in analyzing the effects of individual treatments, as most interventions reported combined effects.

2.6. Study design characteristics

The review encompassed pilot studies, randomized controlled trials (RCTs), case reports, and feasibility trials published between 2007 and 2025. The types of intervention included in the review are physical therapies including aerobic training, gait and balance training, home-based programs, and treadmill-based physiotherapies; neuromodulation models including DBS, tDCS, rTMS, and theta burst stimulation (iTBS); and hybrid models including the integration of neuromodulation and physical training modalities. The duration of the studies varied from single session to multi-week programs (i.e., up to 24 weeks). There was variation in follow-up intervals from immediate post-treatment to 6 months in some of the trials. ICARS, SARA, TUG, BBS, FIM, 10-MWT, and 9-HPT were the outcomes measured and analyzed. A few other studies incorporated spectroscopic and neuroimaging markers such as NAA/Cr ratios and MRS to assess metabolic changes. Studies that involved adults between 18 and 75 years with one pediatric cohort between 8 and 18 years were added to the review. Data synthesis categorized the studies by intervention model and the subtypes of ataxia, that is, hybrid versus single.

Figure 2
Graphical representation of classification of articles based on type of ataxia

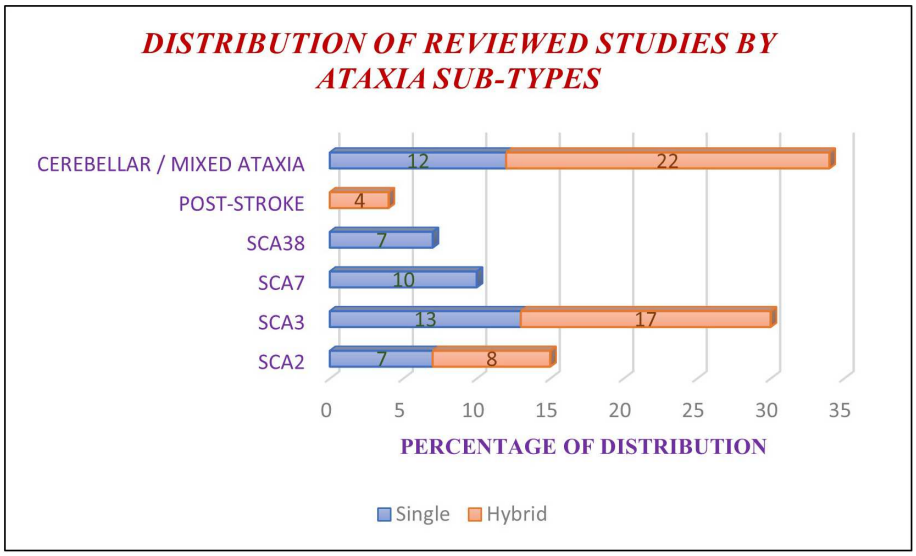


Table 1 presents the ethical standards, consent procedures, and safety considerations documented across the reviewed articles. All studies adhered to recognized ethical guidelines, with minimal adverse events reported, reflecting high compliance and participant safety.

3. Results

3.1. SCA2

3.1.1. Single model

Freund et al. [26] examined the effectiveness of DBS in the subthalamic-thalamic region in people with SCA2. The trial aimed to examine the efficiency of the DBS in a person with SCA2 with rapidly progressing tremors. The 22-year-old female patient with SCA2 who was recruited underwent DBS stimulation with electrodes implanted in both hemispheres. This strategy of stimulation targeted to stimulate the ventral intermediolateral, ventral oralis complex, and the neighboring subthalamic and zona incerta structures. On the third postoperative day, DBS was initiated at 130 Hz and 4.2 V, optimized for suppressing the tremor, and as a result of the stimulation, there were no tremor signs. The patient started to show positive improvements gradually; each parameter showed significant improvement one after the other. Over the course of 2 years of follow-up, the treatment has enabled the patient to sit, stand with support, communicate verbally with much better clarity, and perform everyday activities independently. Her overall symptoms due to ataxia were stabilized without further progression. Most importantly, the intervention's effect lasted even after 2 years of the procedure.

Table 1
Summary of ethical approval and participant safety measures

Study	Ethical approval body	Ethic approval ID/number	Informed consent was obtained from participants	Ethical guidelines followed	Adverse events/safety concerns
Sikandar et al. [28]	The First Affiliated Hospital of Fujian Medical University	MRCTA, ECFAH of FMU [2018] 201	Yes	–	Two participants in both groups experienced mild nausea, but no other adverse effects were reported
Chen et al. [31]	First Affiliated Hospital of Fujian Medical University	MRCTA, ECFAH of FMU [2018] 201	Yes	–	No adverse events were reported
Manor et al. [32]	Beth Israel Deaconess Medical Center (BIDMC) Institutional Review Board	–	Yes	Declaration of Helsinki	No adverse events were reported
Barretto et al. [41]	The Research Ethics Committee of the Medical School of Bahia	–	Yes	–	Mild to moderate adverse effects were observed
Kumar et al. [39]	Institutional Review Board (IRB), Columbia University Irving Medical Center	–	Yes	–	No adverse events were reported
Winser et al. [40]	Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University	HSEARS20190322001	Yes	–	Mild muscle pain was experienced by 7 patients, which subsided within a day; no other adverse events were reported
Barbuto et al. [42]	Columbia University Institutional Review Board	AAAS0414	Yes	Declaration of Helsinki	None reported
dos Santos et al. [38]	Universidade Federal do Estado de São Paulo (UNIFESP) ethics committee	933.112	Yes	–	No adverse events occurred
Lepoura et al. [43]	Ethics Committee of the University of West Attica and "ATTIKON" General University Hospital of Athens	14η/26-04-2021	Yes	Declaration of Helsinki, Good Clinical Practice, and CONSORT statement	No adverse events were faced.

(*Continued*)

Table 1
(*Continued*)

Study	Ethical approval body	Ethic approval ID/number	Informed consent was obtained from participants	Ethical guidelines followed	Adverse events/safety concerns
Rodríguez-Díaz et al. [27]	Ethics Committee of the Center for the Research and Rehabilitation of Hereditary Ataxias, Holguín, Cuba.	–	Yes	Declaration of Helsinki	4/19 had mild muscle cramps; no serious adverse events; 100% retention
Grobe-Einsler et al. [33]	Ethics Committee of the University Hospital of Bonn, Germany	No. 208/20	Yes	Declaration of Helsinki	Painful muscle twitches during stimulation (6 patients); Headache after stimulation (1 patient); Claustrophobia during stimulation (1 patient)
Pilloni et al. [46]	NYU Langone Health Institutional Review Board (IRB)	s16–01810	Yes	NYU Langone Health IRB	None reported
Terco Perez et al. [36]	Research and Ethics Committee of Instituto Nacional de Rehabilitación Luis Guillermo Ibarra Ibarra (INRLGII), Mexico	INRLGII-15/12	Yes	Declaration of Helsinki	None reported; psychological support protocols in place for sensitive genetic testing and counseling
Knudson et al. [12]	Partners Healthcare Research Committee Institutional Review Board	2016P001048	Yes	Declaration of Helsinki	No adverse events due to hardware or treatment protocol were encountered.

Table 2
Single model therapy for SCA2 patients

Author and year	Number of participants and groups	Type of disease	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
Freund et al. [26], 2007	1 participant	Spinocerebellar Ataxia 2 (SCA2)	DBS	–	Improvement was observed in communication, sitting and standing positions with support, and day-to-day activities during 2 years of follow-up period.

Neuromodulation protocol—DBS was implemented to evaluate the prolonged functional outcomes. Advancements in communication, sitting, standing, and everyday activities emphasize the sustained benefits of DBS in SCA2 cases as shown in Table 2.

3.1.2. Hybrid model

Rodríguez-Díaz et al. [27] conducted a 24-week RCT examining the impact of neurorehabilitation training on patients with SCA2. Thirty-eight SCA2 patients were evenly randomized between an intervention cohort receiving neurorehabilitation and a control cohort receiving no treatment. The intervention group underwent a 6-hour session of neuromodulation and rehabilitation therapy focused on posture stability, motor coordination, and strengthening of muscles; in contrast, no rehabilitative therapy was given to the control group. Adherence was excellent (98.28%) for the participants of the intervention group, with minor muscle cramps observed in four patients (21%). Primary outcomes were assessed by SARA score within the intervention group ($p < 0.05$) and demonstrated high clinical response with 0.78, indicating post-therapy enhancements in functional coordination, balance, heel-shin tests, and finger chase; no substantial

Table 3
Hybrid model therapy for SCA2 patients

Author and year	Number of participants and groups	Type of disease	Type of physical treatment performed	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
Rodriguez-Diaz et al. [27], 2018	38 participants Intervention (treated) group and control group	Spinocerebellar Ataxia 2 (SCA2)	Neurorehabilitation therapy includes: Motor Coordination Occupational therapy Strength training Psychotherapy	–	**Intervention group:** Standardized Response Mean (SRM) of SARA = 0.78 ($p < 0.05$) Recurring of CAG expansion = (r = -0.48, p = 0.036) Delayed onset of disease improves with intervention = (r = 0.47, p = 0.040)	The intervention group showed improvement in finger chase, heel-shine tests, balance, and functional coordination. INAS and saccadic eye movements showed less improvement. Enhances motor coordination with modulation by specific genetic markers.

changes were reported for the control group. Secondary outcomes depicted minimal improvements in Inventory of Non-Ataxia Symptoms (INAS) and saccadic eye movement gait parameters. The INAS score revealed that the extracerebellar symptoms neither worsened nor improved in either the intervention cohort (3.68 ± 0.21 at baseline and 3.74 ± 0.2 after 24 weeks) or the control cohort, with 3.63 ± 0.21 at baseline and 3.79 ± 0.20 after 24 weeks. The analysis of correlation revealed a reduction in SARA scores in the aspect of cytosine-adenine-guanine (CAG) reoccurring expansions ($r = -0.48$, $p = 0.036$) and delayed onset of disease ($r = 0.47$, $p = 0.040$), indicating that a sample size of mutation triggers response to neuromodulation therapy integrated with rehabilitation. The study supports that neuromodulation, along with rehabilitation, serves as a potential approach to enhance motor skills with modulation by specific genetic markers in genetically defined ataxia.

Table 3 presents data from Rodríguez-Díaz et al. [27], where combined neurorehabilitation and genetic monitoring were implemented in SCA2 participants. The statistical outcomes show the correlation between physical therapy and delayed disease onset, while the functional assessments showed enhanced motor abilities and balance.

3.2. SCA3

3.2.1. Single model

Sikandar et al. [28] investigated the efficiency of cerebellar rTMS in participants with SCA3. 44 participants with SCA3 were involved in this trial. Participants were allocated randomly to the sham rTMS or rTMS active groups and received 30 minutes of 1 Hz rTMS (900 pulses per session) in the cerebellum region of the brain for 15 days. No physical therapy was included. Substantial improvements were documented in the rTMS active groups compared to the sham. Significant enhancements were noticed in these scores: BBS ($p = 0.001$), ICARS ($p = 0.002$), and SARA ($p = 0.001$). This study conveyed findings that rTMS can produce short-term improvements in motor coordination and balance in SCA3. The study suggested that a substantial improvement in posture and motor control was achieved; however, large-scale investigations and exploration of hybrid protocols were necessary for more comprehensive validation.

Hu et al. [29] evaluated the effectiveness of rTMS at high frequencies on control of the cerebellum, gait, and posture in SCA3 patients. The study analyzed the impact of high-frequency rTMS in regions of the cerebellar area and inspected the effects on cerebellar metabolism and symptoms. Three subjects from the same family with SCA3 were included. High-frequency rTMS was administered to patients for 5 consecutive days, 20 minutes each, over 2 weeks. Proton magnetic resonance spectroscopy (^{1}H-MRS), ICARS, and SARA were measured pre-intervention and post-intervention. The outcomes revealed substantial enhancements in the SARA score (pre-rTMS: 23 vs post-rTMS: 17) in case one, and in the ICARS (pre-rTMS: 38.67 ± 16.17 vs post-rTMS: 34.33 ± 15.95; $p = 0.04$) score, the score increased mostly in posture stability and gait subscale and the kinetic function subscale using a paired t-test. No negative side effects were observed in the trial. The study concluded that rTMS improved the posture, cerebellar concentration of NAA/Cr in both vermis and cerebellar hemispheres, improved neurological movements, and limb kinetic function.

For patients with SCA3, Shi et al. [30] conducted a single-blinded RCT to compare the efficiency of intermittent iTBS and low-intensity rTMS. The primary goal of this trial focused on determining the most effective intervention for improving the symptoms of ataxia. The study cohort comprised 120 individuals, who they classified into 3 subgroups. The first group of forty patients with SCA3 underwent 10 sessions of 1 Hz rTMS, each session consisting of 1200 pulses. The treatment duration lasted 2 weeks, with sessions conducted on 5 consecutive days each week. The second group comprised 40 individuals with SCA3 who underwent iTBS on the same schedule as the rTMS group. The remaining 40 individuals with SCA3 belonged to the sham group. Primary evaluation scales included the SARA and the ICARS. Both these assessment scales were evident of ataxia symptoms reduction in the rTMS group and iTBS group compared to sham, with statistical significance of $p < 0.01$. Further secondary assessments were evaluated using 10MWT, 9-HPT, and the PATA Rate Task. There were no notable differences in the results observed between the two intervention groups, including mild, moderate, and severe groups, in the protocol. The therapies were well tolerated by all the participants. This study demonstrated that iTBS and low-frequency rTMS focusing on the cerebellum are both safe and efficient methods in mitigating ataxic symptoms.

A trial was conducted by Chen et al. [31] to examine the effects of rTMS on the cerebellum's cellular activity in people with SCA3. The authors aimed to assess the effectiveness of the

low-frequency rTMS on cerebellar function and examine the association between the enhancements in the functional metabolism and symptoms. About 18 participants with SAC3 were recruited and allocated either to the real-stimulation or a sham-stimulation group. The stimulation was given to the participants for thirty minutes each day for 15 consecutive days. Effectiveness of the intervention was analyzed using ICARS, MARS (magnetic resonance spectroscopy), *t*-test, and Wilcoxon's signed-rank tests before and after the treatment. ICARS and MARS scores were compared using the covariance and individual *t*-test between the groups. Analysis of Pearson's correlation was used to contrast the cerebellar metabolism and ICARS. At the end of the trial, ICARS were decreased but were seen more evidently in the real-stimulation group ($p < 0.001$). Covariance analysis was used to confirm the difference between the ICARS scores ($p < 0.001$, $F = 31.239$). Cho/Cr and NAA/Cr values were increased significantly in the bilateral dentate nucleus, bilateral cerebellar hemisphere, and cerebellar vermis of the real-stimulation group ($p < 0.05$) contrast to the sham-stimulation ($p > 0.05$) group. Subscale scores of ICARS—postural and gait scores ($p = 0.003$; $F = 13.037$) and kinetic function scores ($p < 0.001$; F = 22.679)—improved significantly, but no significant improvements were observed in oculomotor function Oculomotor Subscore (OMS) ($p = 0.617$; $F = 0.261$), and no improvements were observed in dysarthria speech. The NAA/Cr level in the right cerebellar hemisphere showed a negative correlation in the real stimulation group and ICARS ($p = 0.02$, $r = -0.831$). The study concluded that rTMS showed improvements in the cellular metabolism and symptoms in the participants with SCA3.

Cury et al. [24] performed a double-blind, crossover methodology trial to investigate the influence of DBS in the dentate nucleus. The trial aimed to evaluate the efficiency of DBS in the dentate nucleus in improving the coordination of movements and safety. Five participants with SCA3 were involved in the trial and classified as active stimulation and sham stimulation phases of stimulation lasted 3 months, separated by a crossover design. SARA score, safety and endurance, tremor severity using Fahn–Tolosa–Marin Tremor Rating Scale (FTMRS), patient concern, and life quality were analyzed. After the active stimulation, a reduction in SARA scores was seen, decreasing from 10.1 ± 4.1 to 8.6 ± 3.6 with $p = 0.223$. This showed that the ataxia severity did not undergo a huge improvement. In contrast, the tremor severity, with a mean FTMRS score of 18.0 ± 17.2, was observed during active DBS stimulation. The subjective feedback received from the patients aligned with these findings, as the mean Patient Global Impression of Change (PGIC) score was 1.6 ± 0.9 during the active stimulation phase and 3.2 ± 1.1 during the sham phase ($p = 0.038$). The assessment of activities of daily life with the WHOQoL-BREF questionnaire only showed a mean increase of 5.5 points, which was not statistically significant. Stimulation frequencies above 80 Hz worsened the gait factors in two patients, which shows the necessity for this program to be tailored for every individual.

Manor et al. [32] performed a trial to assess the performance of rTMS in people with SCA3. The trial primarily aimed to evaluate the efficacy of rTMS for patients with SCA3 in improving gait, balance, and clinical parameters. Twenty patients aged 18–74 were included. Twenty sessions of MRI-assisted rTMS were delivered to patients in both groups. As this study included no task-specific rehabilitation, it is classified as an exclusive rTMS therapy. SARA scores were evaluated at baseline, immediately post-treatment, and during follow-up at 1 week and 1 month. The outcome revealed that both groups improved after the treatment ($p = 0.16$; $\eta^2 = 0.06$; Cohen's $d = 0.5$; $F = 2.0$). During the follow-up period of 1 month, the SARA scores of the real group ($p = 0.008$; Cohen's $d = 0.5$; $F = 2.0$) improved in contrast to the sham group. In addition, sub-score of stances ($\eta^2 = 0.24$; $p = 0.002$; Cohen's $d = 0.9$; $F = 10.4$) and posture sway ($p < 0.008$) both improved. No changes were observed in gait parameters, TUG, and 9-HPT parameters. Stance and severity of ataxia improved in rTMS in the 1-month follow-up period. Additional physical rehabilitation therapy could help improve the lack of gait-related parameters in the study, as standalone neuromodulation may not engage the functional motor pathways for smooth recovery of locomotion of the individual.

Table 4 outlines the effects of rTMS in three SCA3 participants, as reported by Hu et al. [29]. Post-treatment gait indices reflect significant improvements, accompanied by enhanced cerebellar metabolite ratios, indicating neurochemical modulation after rTMS.

3.2.2. Hybrid model

Grobe-Einsler et al. [33] performed a trial to examine the effectiveness of cerebellar rTMS integrated with physiotherapy. The trial aimed to investigate the efficiency of rTMS with regular physiotherapy. The trial included 33 participants. The participants were categorized into two groups: verum rTMS ($n = 15$; average age = 48.7 ± 13.8 years) and sham rTMS ($n = 18$; average age = 48.7 ± 13.7 years). Groups were given physiotherapy regularly during the study. The verum group's SARA score was reduced during baseline (V0) by −1.6 points and post-intervention (V1). The result of the trial indicates that the severity of ataxia was reduced to 1.6 points ($p_{adj} < 0.001$ and Cohen's $d = 1.54$); in contrast, the sham group did not observe any significant changes ($p_{adj} < 1$ and Cohen's $d = 1.28$). The SARA score in the verum group with $p < 0.001$ was noted. There was a notable improvement in the appendicular coordination ($p_{adj} < 0.01$ and Cohen's $d = 1.09$), but not in the trunc sub-score ($p_{adj} < 0.122$, Cohen's $d = 0.70$), and PATA repetition rate improved in the verum group ($p_{adj} < 0.01$ and Cohen's $d = 1.31$), but not in the sham ($p_{adj} < 0.131$, Cohen's $d = 0.61$), and 8-meter walk test with $p < 0.05$. In both groups, no notable changes were observed in the Nine-Hole Peg test. The trial concluded that rTMS helps patients with SCA reduce symptoms. The treatment can be reduced to 5 days with the same effectiveness, which increases the accessibility of the patients.

Brito et al. [34] performed a trial to analyze the efficiency and standards of the results produced by cerebellar tDCS (C-tDCS), combined with gait training. The trial aimed to study the outcome of C-tDCS on people with CA, in conjunction with gait training, on balance, mobility, and stability of posture. Forty-four participants were included and divided into two groups randomly as real C-tDCS ($n = 11$) or sham C-tDCS ($n = 11$). Participants received five sessions daily. TUG test, MiniBESTest, and SARA scores were measured to evaluate the regular movements, balance, and the symptoms of the ataxia. The trial resulted in a significant improvement with respect to mobility in both cohorts, but the balance performance score showed no difference between the groups. SARA scores have improved significantly in postural stability, speech clarity, seated control, finger-to-nose test, and heel-shin slide test in the active group. No significant changes were demonstrated in the balance test. The study concluded that the severity of ataxic symptoms can be reduced with C-tDCS-integrated gait training specifically but does not significantly improve overall mobility compared to the sham group.

Table 4
Single model therapy for SCA3 patients

Author and year	Number of participants and groups	Type of disease	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
Hu et al. [29], 2023	3 participants	Spinocerebellar Ataxia 3 (SCA3)	rTMS	**SARA Score:** Pre-rTMS-23; Post-rTMS-17 **ICARS Score:** Pre-rTMS-38.67 ± 16.17; Post-rTMS-34.33 ± 15.95; $p = 0.04$	Enhancement of Cho/Cr, NAA/Cr values in the left and right cerebellar hemispheres, vermis post-rTMS treatment.

Table 5
Hybrid model therapy for SCA3 patients

Author and year	Number of participants and groups	Type of disease	Type of physical treatment performed	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
Brito et al. [35], 2024	10 participants C-tDCS group and Sham group	Spinocerebellar Ataxia 3 (SCA3)	Postural training	C-tDCS	**C-tDCS Group: Improvements seen:** Stability: $Z = –2.10$, $p = 0.03$ Nose-finger test: $Z = –2.07$, $p = 0.04$ Fast hand coordination: $Z = –2.15$, $p = 0.03$ Heel-to-shin slide: $Z = –1.91$, $p = 0.05$	No significant changes observed in anteroposterior stability. Improved stability and reduced the symptoms of ataxia in patients.

Brito et al. [35] conducted a randomized, triple-blind, crossover trial to determine the influence of cerebello-spinal tDCS along with postural stability training in patients with SCA3. Ten participants with SCA3 were included, and everyone underwent both active and sham C-tDCS interventions, set 1 week apart. SARA scores, as well as medical lateral, anteroposterior, and total performance balance indices, were measured using the Biodex Balance system. The result indicated that total balance index ($p = 0.03$, $Z = −2.10$), nose-finger test ($p = 0.04$, $Z = −2.07$), heel-to-shin slide ($p = 0.05$, $Z = −1.91$), and fast hand coordination ($p = 0.03$, $Z = −2.15$) were improved significantly in C-tDCS group assessed via 8-item SARA demonstrated decreased appendicular impairments. Symptoms of appendicular ataxia were reduced in the C-tDCS group relative to the sham group. The trial concluded that a one-on-one session of posture training integrated with C-tDCS ameliorates the motor dysfunctions in SCA3 patients.

The outcomes of each intervention—C-tDCS with postural training versus sham stimulation in the study conducted by Brito et al. [35]—are shown in Table 5. The C-tDCS group demonstrated motor coordination improvements, notably in stability and limb coordination tests, evincing the correlated benefit of concurrent neuromodulation and physical therapy.

3.3. SCA7

3.3.1. Single model

Intensity of physical training was trialed and studied by Tercero-Pérez et al. [36] through a single blind randomized cross-sectional observational study. They aimed at analyzing the effects of physical rehabilitation and oxidative stress markers in patients with SCA7. Eighteen participants (13 males, 5 females) of mean age 40 years with SCA7 were recruited for the trial. They were assigned to three groups: intensive training ($n = 5$), moderate training ($n = 6$), and non-training control ($n = 7$). The intensive training group completed five 2-hour sessions weekly over 24 weeks. The moderate training group completed three 2-hour weekly sessions during the same period as the other group. The control group did not engage in any kind of training during the study period. Evaluation took place initially, midway at 12 weeks, and after completion at 24 weeks. The intensive training group displayed a 1.4-point increase, and the moderate training group displayed a 0.5-point increase in SARA scores. The levels of stress markers malondialdehyde (MDA), lipohydroperoxides (LPH), dityrosines, protein carbonylation (DNPH), and antioxidant enzymes were measured in plasma and erythrocyte lysates of all patient groups before and after 24 weeks of training. The two training groups demonstrated a decrease in lipid damage markers (MDA and LPH) and an increase in or the same PON-1 activity. There were no improvements in the no-training group. Baseline SARA scores were 15.64 ± 5.33 in the control group, 18.58 ± 3.64 in the moderate training group, and 16.40 ± 6.39 in the intensive training group, with no significant between-group difference ($p = 0.538$). Baseline INAS scores were also comparable: control 4.14 ± 2.19, moderate 3.89 ± 0.41, and intensive 3.40 ± 0.89 ($p = 0.365$). The Lawton Instrumental Activities of Daily Living (ADL) and Barthel Index ADL Scales were used to examine the functional outcomes. Significant improvements were

Table 6
Single model therapy for SCA7 patients

Author and year	Number of participants and type of group	Type of disease	Type of physical treatment performed	Quantitative outcomes	Functional outcomes
Tercero-Pérez et al. [36], 2019	18 participants, Intensive training group vs moderate training group vs control group	SCA7	Includes (single session): 1. Physical conditioning exercises 2. Balance exercises (static standing balance) 3. Active movement for four limbs 4. Motor and coordination exercises 5. Recovery and breathing exercises	**SARA Score** ($p < 0.05$): Intensive training group:16.40 ± 6.39 Moderate training group:18.58 ± 3.64 Control group: 15.64 ± 5.3 **INAS:** Intensive training group: 3.40 ± 0.89 Moderate training group:3.89 ± 0.41 Control group: 4.14 ± 2.19	SARA scores of the Intensive training and moderate training groups decreased by 0.5 points and 1.4 points, respectively.

observed in daily activities for both the moderate group and the intensive group, about 83.33% and 80%, respectively, versus the non-training control group, about 14.28%. Conversely, no significant differences were detected between the Barthel Index ADL and Lawton Instrumental ADL Scales between the groups.

Table 6 details the outcomes from the study conducted by Tercero-Pérez et al. [36], which compares intensive, moderate, and control training protocols in SCA7 patients. The intensive group exhibited a reduction in gait and severity index, inferring the efficacy of structured physical training.

3.4. SCA38

3.4.1. Single model

SCA38 (spinocerebellar ataxia 38) is a rare hereditary condition triggered by mutations in ELOVL5. A clinical study was conducted by Sanna et al. [37] to compare the efficacy of two different treatment methods of anodal tDCS in a Sardinian family with SCA38. The trial aimed to evaluate the efficacy of the C-tDCS and cerebello-spinal (CS-tDCS) cathode setup. The trial contained 7 participants with SCA38, and these participants underwent 15 sessions of anodal tDCS. The trial consisted of three follow-ups: T0 – baseline; T1 – completion of 15 sessions of tDCS; and T2 – a 1-month follow-up period. The trial measured the Modified International Ataxia Rating Scale (MICARS), the Zimmermann test battery, Alertness and Split Attention Test, the Robertson Dysarthria Profile, and a 3D computerized analysis of gait to assess the severity of ataxia, symptoms of dysarthria, active functions, and motor functions, respectively. Both groups yielded significant improvements. In C-tDCS, gait speed significantly increased (0.729 ± 0.309 to 0.829 ± 0.325 m/s, $p = 0.031$). MICARS decreased (22.71 ± 12.49 to 20.50 ± 11.78, $p = 0.008$), including reduced posture and gait sub-scores (10.57 ± 6.00 to 9.50 ± 6.06, $p = 0.002$). Robertson Dysarthria Profile scores improved from 226.7 ± 20.71 to 231.3 ± 21.45, $p = 0.02$ indicating the improvements in speech function. In CS-tDCS, MICARS score decreased from 22.93 ± 12.35 to 18.64 ± 11.82 ($p < 0.001$), with a decrease in posture and gait from 10.14 ± 5.52 to 8.5 ± 5.11 ($p = 0.001$) and kinetic function from 8.07 ± 4.97 to 6.21 ± 4.72 ($p = 0.001$). Motor performance depicted significant improvement in CS-tDCS, with Friedman =13.56 ($p < 0.001$), and in C-tDCS, Friedman = 8.86 ($p < 0.008$). For the posture and gait subscale, CS-tDCS resulted in a significant enhancement, with Friedman = 10.15 ($p = 0.001$), while C-tDCS demonstrated a comparable effect with a Friedman=10.33 ($p = 0.002$). Similarly, the kinetic function subscale revealed a significant enhancement in CS-tDCS, Friedman = 11.31 ($p = 0.001$). The outcomes of the trial concluded that improvements were observed in motor functions, cognitive, and dysarthric cores in both C-tDCS and CS-tDCS. The study concluded that C-tDCS may enhance functional coordination and cognitive abilities, and CS-tDCS significantly improved balance, posture, and gait in SCA 38 patients.

The comparative outcomes of the study conducted by Sanna et al. [37], which compares C-tDCS and CS-tDCS modalities in SCA38 patients, are highlighted in Table 7. The outcomes conclude improved motor, kinetic, and posture-gait functions, with CS-tDCS producing greater improvements, highlighting the efficacy of targeted multi-site stimulation.

3.5. Post-stroke ataxia

3.5.1. Hybrid model

Dos Santos et al. [38] performed a trial to compare the effectiveness of therapist-assisted gait training (TAGT) versus robot-assisted gait training (RAGT) combined with physiotherapy in improving coordination, functional independence, and balance in individuals with stroke-induced ataxia. Nineteen chronic stroke patients with stroke-induced ataxia duration greater than or equal to 1 year were enrolled. Eight patients were placed in the TAGT group and 11 in the RAGT group. Four participants from the RAGT group were excluded due to noncompliance, resulting in a final sample size of 15 (TAGT: $n = 8$; RAGT: $n = 7$). The median age was 50.8 ± 13.3 years, with an average stroke onset time of 7.8 ± 4.8 years. Demographic variables and baseline clinical characteristics were comparable between groups, except for stroke chronicity, which was notably higher in the TAGT group ($p = 0.021$). Participants underwent a 5-month protocol involving three sessions per week (two conventional physiotherapy + one gait training session). Functional assessments were conducted pre- and post-treatment using the BBS, TUG, FIM, and SARA. Wilcoxon and Mann–Whitney U tests

Table 7
Single model therapy for SCA38 patients

Author and year	Number of participants and groups	Type of disease	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
Sanna et al. [37], 2024	7 participants	Spinocerebellar Ataxia 38 (SCA38)	CS-tDCS and C-tDCS	**Motor Improvements** CS- tDCS Friedman = 13.56, $p < 0.001$ C-tDCS Friedman = 8.86, $p < 0.008$ **Posture and gait subscale** CS-tDCS Friedman = 10.15 $p = 0.001$ C-tDCS Friedman = 10.33, $p = 0.002$ **Kinetic function subscale** CS-tDCS Friedman = 11.31, $p = 0.001$ **Dysarthria subscale** CS-tDCS Friedman = 6.50, $p = 0.07$ C-tDCS Friedman = 6.00, $p = 0.07$	Both treatments depicted significant improvements in motor symptoms and in dysarthria subscale CS-tDCS depicted a significant reduction in both kinetic function, posture, and gait C-tDCS depicted enhancement in posture and gait subscale

were applied for within-group and between-group evaluation, respectively. Within-group analysis showed that both groups exhibited statistically significant improvements across all outcome measures: BBS scores improved in TAGT (27.3 ± 10.8 to 35.5 ± 14.1; $p = 0.012$) and RAGT (26.6 ± 18.0 to 32.4 ± 18.8; $p = 0.018$), TUG performance improved significantly in TAGT (28 ± 11s to 22 ± 10s; $p = 0.017$) and RAGT (46 ± 40s to 27 ± 17s; $p = 0.011$).FIM scores increased in TAGT (80.9 ± 9.6 to 85.4 ± 8.2; $p = 0.016$) and RAGT (73.9 ± 14.6 to 78.5 ± 12.9; $p = 0.042$), SARA scores decreased in TAGT (18.9 ± 6.8 to 15.4 ± 5.6; $p = 0.012$) and RAGT (18.7 ± 7.6 to 15.2 ± 6.8; $p = 0.018$). The outcomes indicated reduced severity for ataxia patients measured at post-treatment.

Table 8 details the outcomes of the study conducted by dos Santos et al. [38], who investigated TAGT and RAGT in chronic stroke patients with SCA38 features. Both interventions yielded substantial improvements in BBS, TUG, and FIM scores.

3.6. General cerebellar ataxia (CA, mixed cause)

3.6.1. Single model

Kumar et al. [39] presented a retrospective analysis to evaluate whether CA patients with cerebellar ataxic signs could see improvement by using low-frequency DBS, especially in gait, stance, and speech. The study aimed to examine the effectiveness of low-frequency DBS at 5 Hz, 10 Hz, and 30 Hz on severe ataxia. A 66-year-old male with CA following implantation of bilateral caudal zona incerta. The participant underwent sham DBS stimulation at 5, 10, and 30 Hz, and ataxia severity was examined, focusing on gait, speed, and posture. Significant improvements were found at the 30 Hz frequency of enhanced speech. This was confirmed using acoustic voice quality analysis, where the Acoustic Voice Quality Index (AVQI) values improved around 4.00 points at baseline and sham to 3.19 at 30 Hz. The patients were asked to perform a few limb coordination tasks to assess the motor improvements, but no meaningful progress was noticed. Importantly, low-frequency DBS at 30 Hz reduced the amplitude of hand tremor, which was documented using accelerometry. The same intervention at 5 and 10 Hz did not show any robust improvement. The stimulation did not attribute to any adverse effects. The study concluded that substantial improvement in ataxia speech can be mediated using low-frequency DBS, while its impact on posture and gait appears limited.

Winser et al. [40] compared the impacts of cognitive-coupled intensive balance training (CIBT) and single-task balance and cognitive enhancement training in patients with CA. Thirty-two patients were assigned to the CIBT group ($n = 16$) and the single-task group ($n = 16$) randomly. The treatment was conducted over 4 weeks with a supervisor, followed by 6 months of home-based exercises, which were unsupervised. Intervention assessments include T1 (baseline 1) and T2 (baseline 2, pre-treatment), T3 (post-treatment), and T4 (follow-up period of 6 months). Significant primary outcomes include dual task performance and dual tasking ability (DTUG score), which were enhanced in the CIBT group at T3, with a mean of −6.93 (−13.16 to −0.7), and $p = 0.03$. No distinctive improvements were recorded in the dual-task cost of the cognitive task. Reductions in the dual-task cost of physical performance were also larger in the CIBT cohort, with a mean difference of −8.36 points and $p < 0.01$. The dependency of patients on visual cues was reduced (T3: mean = −18.53 (−25.81 to −11.2), $p < 0.01$; T4: mean = −16.94 (−23.44 to −10.44), $p < 0.01$) in the CIBT group. SARA scores were not maintained in T4 but were enhanced at T3 in the CIBT group compared to the single-task group (MD = −2.03, $p = 0.04$). No measurable gains were noted between the two groups in terms of activities of daily life, cognition, and severity. Over a 7-month period, the average cost of intervention was HKD 33,380 and HKD 38,571 for the CIBT group and single-task group, respectively. Although the healthcare expenses were reduced in the CIBT group, the expense difference did not reach economic significance. These outcomes indicated that usage of CIBT enhances quality of life, restoring balance and the ability to dual task in patients with CA.

Barretto et al. [41] examined the influence of tDCS on gait, stability of stance, and the coordination of motor functions through a feasibility study with a double-blind, matched control design for patients with CA. Seven participants aged 14–57 were recruited. All seven participants received both real and sham tDCS in separate phases. Each stimulation period lasted for 40

Table 8
Hybrid model therapy for post-stroke ataxia patients

Author and year	Number of participants and groups	Type of disease	Type of physical treatment performed	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
dos Santos et al. [38], 2018	15 chronic stroke participants 8 participants in the TAGT group 7 participants in RAGT	Post-stroke ataxia	Physiotherapy Therapist-assisted gait training (TAGT) Robot-assisted gait training (RAGT)	–	**Improvements seen:** **TAGT group** BBS Score (27.3 ± 10.8 to 35.5 ± 14.1; $p = 0.012$) TUG Performance (28 ± 11s to 22 ± 10s; $p = 0.017$) FIM Score (80.9 ± 9.6 to 85.4 ± 8.2; $p = 0.016$) SARA Score (18.9 ± 6.8 to 15.4 ± 5.6; $p = 0.012$) **RAGT group** BBS Score (26.6 ± 18.0 to 32.4 ± 18.8; $p = 0.018$) TUG Performance (46 ± 40s to 27 ± 17s; $p = 0.011$) FIM Score (73.9 ± 14.6 to 78.5 ± 12.9; $p = 0.042$) SARA Score (18.7 ± 7.6 to 15.2 ± 6.8; $p = 0.018$)	Both groups resulted in significant enhancements in balance, posture, and functional daily activities after treatment with RAGT and TAGT, along with physiotherapy and home exercises.

minutes for 5 consecutive days in the bilateral primary motor cortical region (M1) of the brain. The patient's gait, stability, and posture control were evaluated utilizing the CVMob software and Wii Fit module before and after stimulation. The standardized assessment scale used to quantify the severity of the disorder was SARA. The results showed a clear positive effect in SARA scores after active intervention compared to sham. The post-treatment phase of the group demonstrated a median improvement of 2.5 points, while the group as a sham had a 1-point decline ($p = 0.03$). The analysis of Wii Fit data revealed an increase in balance, with a total gain of 4.64 after the intervention and a decline of −1.36 in the sham group. Even though there were no notable differences in individual CvMob parameters, the total body movement rate was higher post-tDCS. Mild and self-limiting adverse effects, such as itching and tingling, were reported. The paper serves as a reference that tDCS has potential in improving the motor parameters for an affected individual when applied over the bilateral primary motor cortex.

Patient engagement in their therapy will allow them to understand and follow a consistent regimen over extended periods. This step is a necessity for every chronic condition. Barbuto et al. [42] conducted a randomized, assessor-blinded, single-center controlled trial (RCT) to evaluate the outcomes produced by home-based aerobic training and home-based balance training. They aimed at integrating home-based therapy for patient accessibility and allowing them to exercise independently. Thirty-six adults with CA (mean age: 54.9 years) were recruited and separated into two groups. One group ($n = 19$) received home-based aerobic training, and the other group ($n = 17$) received home-based balance training. The aerobic group used the ProGear 225 Folding Magnetic Upright Exercise Bike, which is a home stationary bike with pulse monitoring. And the balance group followed a structured balance exercise every day that focused on functional challenge and variability. Both groups finished their respective training for 6 months, five sessions per week. The outcomes measured at baseline and post-intervention were SARA,10-MWT, DGI, and TUG. The patients who received aerobic training had a significant improvement in SARA scores than the balance training group, that is, 1.9 points with SD of 1.62 compared to a 0.6-point improvement with a standard deviation of 1.34 and $p = 0.025$. The balance group showed higher DGI by 2.6 points versus 1.1 points for aerobic training and $p = 0.017$. The authors reported that home-centered aerobic training is both feasible and safe at the end of the study. This trial concluded with patient independence and accessibility.

Lepoura et al. [43] performed a stratified RCT to assess the outcomes of a high-intensity 4-week partial body weight support treadmill training (PBWSTT) in children (ages 8–18) with ataxia. The main aim of the trial was to test the PBWSTT program and its effect on gait improvement in the recruited patients. The participants recruited from the above-mentioned age group were primarily classified within Gross Motor Function

Classification System levels II–IV. They were then separated into two groups, that is, intervention and control arms. The evaluation setup included the LiteGait partial body weight support system combined with a treadmill. This system provided <40% support of body weight to the patients, which allowed safe and upright gait training. The intervention group underwent 20 sessions total, each session lasting for 45 minutes over 4 weeks, combining 75% of self-paced interval walking with high speed, which increased by 5% per day. The program includes dual-task functional physical exercises. Controls received usual care. Gross motor function measurement (GMFM) D/E, SARA, 6-MWT, 10-MWT, and TUG were measured initially, and a follow-up was done after 2 months. The patients received medical care of 1–3 physiotherapy sessions per week, combined with hippotherapy or hydrotherapy. The spatiotemporal data of patients were assessed through the GaitSens software, and 3D kinetic analysis was conducted. The authors hypothesized clinical improvements in GMFM-D from 0.8% to 5.2%, which turned out be low in pediatric gait disease, and 13 participants per group was determined to provide 80 % accuracy to determine greater than 3% difference between intervention group (5% ± 3) and control group (2% ± 3), with statistical significance of $p < 0.05$; the completed numerical outcomes remain pending. The study concluded that PBWSTT optimized motor relearning in children with ataxia.

Tykalova et al. [44] evaluated the speech difference after motor control training through a preliminary study. The study aimed to evaluate the improvement in speech after the motor control training provided to the patients with CA. Twenty individuals were recruited and were split into two cohorts. The first group consisted of 10 people aged between 34 and 71 years, with 5 affected by SCA and the others with unknown CA. The second group consisted of five healthy individuals, referred to as health controls. The trial consisted of 12 coordinated training sessions, followed by 4 weeks of home-supported training. The trial conducted three phases of evaluation: CAt0: baseline; CAt1: after training sessions; and CAt2: 4 weeks post-training. The study measured six speech parameters, the Kruskal–Wallis test, Spearman's rank correlation, and minimal detectable change. Significant improvement was seen in motor function immediately after training from CAt0 to CAt1 in the miniBESTest with $p = 0.048$, and improvements were maintained at follow-up. There were no notable result differences between the CAt1 and CAt2 in the miniBESTest, resulting in $p = 0.47$. Speech efficacy improved in all patients except one at 4 weeks post-training. The study concluded that improvements in 90% of patients were noticed in speech performance, and intensive rehabilitation beneficially influences fine motor skills, including speech in CA patients.

The outcomes presented in Table 9 show the clinical efficiency of CIBT versus single-task balance exercises in CA patients. CIBT produced significant gains in dynamic balance, reaction time, and sensory abilities of the patients, while single-task training maintained constant baseline performance, excluding cognitive-motor benefits.

3.6.2. Hybrid model

Smartphones are often used to assess ataxic symptoms, but there are no clear statements about the important smartphone tests and guidelines to be followed. Németh et al. [13] conducted a study to analyze the use of smartphone sensors to detect ataxia. The study aimed to select an efficient smartphone and finalized the parameters to be measured. The study consists of a five-stage methodology: (1) literature review, (2) Delphi Survey 1, (3) Delphi Survey 2, (4) consensus on essential measures, and (5) linking existing studies to standards. In stage 1, a literature review was conducted across databases, including PubMed, Web of Science, Embase, and Cochrane, using smartphone sensors to identify ataxia. Seven papers (including gait and posture ($n = 3$), upper limb ($n = 1$), various SARA components ($n = 1$), and oculometer function ($n = 2$)) were found based on smartphone sensors to measure ataxia parameters. In stage 2, 40 AGI WG4 members from 11 countries were included in the study, and 65% of the experts are using smartphone applications for some healthcare-related purposes (iOS: 53%; Android: 44%; others: 3%). Among experts, < 20% of them currently use smartphones to analyze gait, upper limb, speech, and oculomotor function. Experts showed interest in analyzing parameters like sleep, tiredness, falls, daily activity, and symptoms reported by the patient related to ataxia. These experts treat at least 1000 ataxia patients. In stage 3, experts agreed on seven main tasks from three domains ((1) gait/posture; (2) upper limb; (3) speech) to assess ataxia. In the three domains, gait included 8–10 m walking and balance tasks measured using an accelerometer and a gyroscope in a smartphone; for upper limb function, pronation–supination and finger-tapping were selected; for speech, "PATA" repetition, prolonged vowel phonation, and a short reading or monologue were selected. No oculometer tasks were included due to insufficient frame rates to capture accurate eye movements in the smartphone camera. In stage 4, experts established 15 standard guidelines for assessing ataxia through smartphones. In stage 5, the 7 papers were checked based on the 15 standard guidelines. At the end, the selected study only shows validity and some reliability. None of them assessed all the required standard guidelines set by the experts, and no study represented full trial readiness. Usability and acceptability of patient, sensitivity to disease progression, and standardization and interoperability were not addressed.

Vibrotactile systems help individuals with sensory-driven feedback, which allows them to self-correct during home training, increasing their independence. Jabri et al. [45] compared the improvements in mobility and balance outcomes of home-administered training and coordination training. The main purpose was to investigate the efficiency of a feedback-incorporated (vibrotactile) self-directed rehabilitation program versus a non-vibrotactile coordination therapy. The authors recruited 10 participants (5 males, 5 females; 47 ± 12 years) with CA, but only 7 underwent 12 weeks of training. This was a 12-week crossover experimental framework where each participant was engaged in two consecutive 6-week training programs with vibrotactile sensory augmentation (SA) and without the vibrotactile sensory feedback. They were instructed to perform the training through a smartphone-based training system for 5 days per week. The digital balance training modules provided instructions, text, images, and videos, and assisted with real-time trunk sway data. The assessments were done before, during, and post-intervention using standardized scales such as SARA, DGI, Clinical Test of Sensory Interaction in Balance, and TUG. Patients who underwent 12-week training at home showed improvement in SARA scores with a mean of −1.21 (SD = 1.73, $p = 0.15$, $F(1,5) = 2.84$), and the SARA sub-score decreased by −0.71 (SD 1.11, $p = 0.19$, $F(1,5) = 2.29$) but not significantly, and no improvement was observed in clinical measures. Six weeks of training with vibrotactile SA significantly improved the SARA posture and gait score (mean = −1.21, $p = 0.02$, $F(1,5) = 10.67$, SD = 0.91) and the overall SARA score (mean = −1.00, $p = 0.01$, $F(1,5) = 22.23$, SD = 0.58); no improvement ($p \geq 0.05$) was observed in DGI, TUG, mCTSIB, or 5XSST. DGI improved (mean = 2.00, $p = 0.03$, $F(1,4) = 10.34$, SD = 1.26) in 6 weeks of training without

Table 9
Single model therapy for cerebellar ataxia patients

Author and year	Number of participants and groups	Type of disease	Type of physical treatment performed	Quantitative outcomes	Functional outcomes
Winser et al. [40], 2022	32 participants CIBT group (n = 16) Single group (n = 16)	cerebellar ataxia	Cognitive-coupled intensive balance training (CIBT) Single-task balance and cognitive training	**CIBT group** **Dual-task cost (physical task):** Mean Difference (MD) = –8.36 (95% CI –14.47 to –2.26), (p < 0.01) **Dual-task Timed Up and Go (DTUG):** MD = –6.93 (95% CI –13.16 to –0.70), (p = 0.03) **SARA-Bal (balance subscale):** MD = –2.03 (95% CI –4.04 to –0.19), (p = 0.04) **Sensory Organization Test (SOT-VIS):** MD = –18.53 (95% CI –25.81 to –11.24), $p \leq 0.01$ **Limits of Stability (LOS):** Forward Maximal Excursion = +13.84 ($p \leq 0.01$) Forward Reaction Time = –1.11 (p < 0.01) Right Reaction Time = –0.18 (p < 0.01) **Disease severity (SARA total):** No significant change (MD = –3.41, p = 0.17) **Single-task group** No significant change in all quantitative outcomes (p > 0.05)	**CIBT group** Enhanced dynamic balance and posture control Decreased visual dependence, indicating improved sensory adaptation Improved motor-cognitive interaction and short-term posture control **Single-task group** Maintained baseline balance and functional coordination but depicted no motor-cognitive enhancement

vibrotactile SA; no significant improvements were observed in SARA score ($p \geq 0.05$), TUG, or mCTSIB. No differences were observed for any IMU-based kinematic features ($p > 0.05$). The study concluded that vibrotactile SA reduced ataxia severity, whereas non-vibrotactile SA improved dynamic gait measures, and neither method improved clinical or kinematic measures. More broad and deep studies are needed to validate the effects.

Exploring various technology-based measurement systems is taking an important role in providing granular-level outputs of the defined parameters. An IMU is a wearable sensor unit that records the acceleration and rotation of body segments. Knudson and Gupta [12] conducted an observational clinical sensor-based study using IMU data from ataxic, Parkinsonian, and healthy patients. This study aimed to extract movement-based biological parameters by using wearable technology. The identified biomarkers were trained to classify the considered disorders and to predict their severity using machine learning models trained on the basis of time, frequency, and autoregressive hidden Markov models (AR-HMM) features. The hardware used in this trial includes six APDM IMU sensors worn on the wrists, pocket, and lumbar region, which collected 128 Hz accelerometer and gyroscope signals. These signals were processed using wavelet transforms for the extraction of time-frequency features. Implementation of AR-HMMs segmented the movement into dynamic states representing the autoregressive patterns of the patient's movement. A total of 195 participants took part in the therapeutic study conducted across n = 242 sessions (109 ataxic patients, 52 Parkinsonian patients, 34 healthy controls, all with a mean age of 46.9 ± 24.1 years). Wearing the sensor-based devices, the participants performed three neurologic motor tasks, the outcomes of which from the worn devices were processed using principal component analysis, synchrosqueezing transform, and AR-HMM. The results obtained include high diagnostic performance, classifying ataxia from controls (area under the receiver operating characteristic curve (AUROC) 0.93; sensitivity 0.85; specificity 0.87), mild ataxia (AUROC 0.87), and Parkinsonism (AUROC 0.93; sensitivity 0.88; specificity 0.83), with subtype identification reaching 80% accuracy. Severity prediction was also robust, with a mean r = 0.75 in the limb and right arm. The recording duration was less than 5 minutes and was seen as sufficient to achieve accurate prediction. The authors conclude that the strong potential of wearable sensor digital markers can aid in the early detection and monitoring of CA.

Pilloni et al. [46] examined the sustained efficacy of remotely supervised transcranial direct stimulation (tDCS) performed on a 71-year-old female diagnosed with CA to enhance gait, motor function, coordination, and reduce fatigue. The written consent was obtained from the patient. The subject underwent 60 sessions over 8 weeks of tDCS focused on the cerebellum, carried out in a home setting under real-time supervision. Each session,

Table 10
Hybrid model therapy for CA patients

Author and year	Number of participants and groups	Type of disease	Type of physical treatment performed	Type of neuromodulation technique implemented	Quantitative outcomes	Functional outcomes
Jabri et al. [45], 2022	7 participants	Cerebellar ataxia	Vibrotactile sensory augmentation (SA) and non-vibrotactile SA.	–	**Vibrotactile SA** **SARA Score:** Overall score: (mean = –1.21, p = 0.02, SD = 0.91, F (1,5) = 10.67) Sub-score posture and gait: (mean = –1.00, SD = 0.58, F (1,5) = 22.23, p = 0.01) No improvement in TUG and DGI (>= 0.05) **Without Vibrotactile SA** **DGI Score:** (mean = 2.00, SD = 1.26, F (1,4) = 10.34, p = 0.03)	Significant improvement was found in SARA and SARA (posture and gait) in vibrotactile SA treatment, and DGI improved in treatment without vibrotactile SA. No significant improvement in TUG and IMU-based postural sway metric with and without vibrotactile SA.

which is 20 minutes of 2.5 mA anodal stimulation, focuses on the cerebellum, combined with physical therapy exercises, followed by cognitive training. Post therapy, the patient showed a 7% improvement in the 25FWT and a 17% reduction in the TUG test time, which came down to 9.88 s from 11.90 s. Additionally, pegboard finishing times improved to 19% from 18% in nondominant and dominant hands, with a reduction to 2.07 and 1.92 in Z-score, respectively. From the Fatigue Severity Scale, which ranges from 22 to 44, it is observed that subjective fatigue decreased. This study suggests that remotely supervised tDCS paired with personalized physical rehabilitative therapy would be an effective approach to alleviate motor impairments and fatigue in CA patients.

LeMoyne et al. [11] examined the effectiveness of employing wireless and wearable inaction body sensors coupled with machine learning to evaluate the characterization of gait challenges in individuals with Friedreich's ataxia. The study consisted of two patients: one patient with Friedreich's ataxia and one healthy patient were involved. A wireless inertial sensor known as the Texas Instruments Sensor Tag was placed close to the ankle joint during implementation of the Timed 25 Foot Walk Test. Gyroscope and accelerometer signals were wirelessly transmitted to a tablet and then uploaded to a secure cloud-based server for further processing. With each stride, a collection of features was created for a total of eleven gait characteristics, such as gyroscope roll, stride time, and yaw parameters. To distinguish between healthy gait and ataxic gait, a multilayer perceptron neural network was built, with the WEKA Machine Learning framework. The entire collection of characteristics differentiated the gait of healthy patients from all specific persons with Friedreich's ataxia, achieving 100% accuracy in classification. Yaw parameters and gyroscope indicators yielded a classification accuracy of 63% and 74%, respectively. According to the sub-analysis, the stride time parameter was exceptionally accurate. The study outcomes demonstrated that combining machine learning and wearable inertial sensor body with derived gait characteristics can offer an empirical characterization of ataxic gait beyond standard clinical evaluations.

Table 10 illustrates findings from Jabri et al. [45], evaluating vibrotactile SA. Participants receiving SA therapy showed improvements in SARA and gait scores, whereas non-vibrotactile SA enhanced DGI scores.

4. Discussion

This review aimed to compare neuromodulation interventions (rTMS, DBS, and tDCS), physical rehabilitation models, and their hybrid integrations across hereditary, acquired, and mixed CA. The target was to determine which intervention model could produce the highest increase in outcome parameters and to identify gaps that limit clinical standardization.

Across all included studies, all intervention categories demonstrated measurable short-term functional gains, as evidenced by reductions in SARA and ICARS scores, and improvements in BBS, TUG, and other gait-based indices. This is a sign that cerebellar circuitry retains the ability for plastic adaptability even in ataxic conditions. However, the sustained impact of a treatment serves a critical function in collectively affirming that the intervention is ideal for treating ataxic conditions. Also, differences in stimulation protocols, inconsistencies in dosage of the rehabilitation model, and small participant sizes hinder the comparison of cross-studies.

When single model neuromodulation interventions are considered, multiple trials that used rTMS, including Sikandar et al. [28], Hu et al. [29], Shi et al. [30], Chen et al. [31], and Manor et al. [32], provided evidence of consistent improvements in postural stability and motor control measured through gait metrics. For SCA3 and CA ataxic groups, increased NAA/Cr and Cho/Cr ratios were noticed within the cerebellar subregions, evidently showing the increased neuronal activity post-treatment. The effects were predominantly focused on balance and stance stability, with minimal impact on fine motor control. No notable contrasts were found between low-frequency rTMS and iTBS groups; both demonstrated attenuated symptoms with safety. The therapeutic effects declined over time due to short follow-up periods (2–4 weeks). Complete functional recovery of the

ataxic condition can be achieved through integrating active motor training and rTMS, as the neuroplastic changes within cerebellar-cortical circuits induced by rTMS integrate with motor relearning. This method can reinforce adaptive connectivity and restore the coordination of movements.

Unlike rTMS, tDCS extended cognitive and speech domain benefits, suggesting a wider cortical engagement. Using tDCS therapy for patients with SCA38, Sanna et al. [37] suggested multi-domain engagement using a single neuromodulation technique as both C-tDCS and CS-tDCS setups enhanced motor, cognitive, and dysarthric performance. For CA patients, Baretto et al. [41] applied anodal tDCS over M1, which reduced SARA points by ~2.5, indicating significant improvement in the stability of stance. Differences in electrode placement, intensity and duration of sessions, and cohorts with $n \leq 10$ were seen across tDCS trials, which limit comparability. Mild adverse effects like itching and mild tingling were noticed in patients who underwent tDCS therapy.

Bilateral subthalamic-thalamic DBS therapy produced almost complete diminishing of tremor and had sustained effects for over 2 years in the trial conducted by Freund et al. [26] for SCA2 patients. Patients with SCA3 were administered DBS targeted at the dentate nucleus. This procedure yielded moderate tremor reduction with modest enhancements in ataxia ratings or walking performance. For stimulation frequencies < 80 Hz, marginal changes in clinical ataxia and locomotor metrics were recorded. Low-frequency DBS (30 Hz), when introduced to CA participants, improved their speech clarity significantly but had minimal gait benefit. For selective symptom alleviation, DBS provides better efficacy in the outcomes. In contrast, the invasive nature of the therapy brings in the need for individualization based on the severity of ataxia and its symptoms in that individual.

Performing standalone physical therapy for ataxic patients in different patterns of therapy models demonstrated positive clinical outcomes in patients. SARA scores and oxidative stress markers such as MDA and LPH were reduced after the course of moderate and intensive physical training in patients with SCA7. This proves the biochemical linkage between physical training and reduced oxidative damage. CIBT administered by Winser et al. [40] for participants with CA condition outperformed single-task protocols by enhancing simultaneous task handling abilities, visual dependency, and postural stability. Physical therapy alone is effective but requires high frequency, longer duration of therapy, and patient motivation. Its applicability remains constrained, posing challenges to scalability in chronic neurodegenerative disorders.

Unlike standalone therapies, combined protocols have shown superior and durable functional recovery by operating through a two-phase synergistic mechanism. In the first phase, neuromodulation techniques create a temporary increase in cerebellar-cortical responsiveness by regulating Purkinje cell firing patterns, thereby enhancing the excitability of the deep cerebellar nucleus and inducing plasticity. This modulation decreases abnormalities in the cerebellar activities and re-engages weakened motor circuitries, creating a transient state of improved neural responsiveness. The second phase involves the delivery of physical therapy immediately after the course of stimulation, which engages the primed circuits, helping stabilize the new neural changes through repetitive practice. This process plays a pivotal role in the strengthening of movement patterns, improving sensorimotor control, and extending the stimulation effects into lasting functional improvements. Because motor training occurs during the period of increased plasticity of the brain, hybrid approaches tend to yield greater and longer-lasting improvements in gait, balance, and coordination. rTMS paired with physiotherapy was incorporated as a treatment modality for SCA3 patients by Grobe-Einsler et al. [33], significantly reducing SARA scores by ~1.6 points ($p < 0.001$). Major ameliorations were noticed in appendicular coordination and speech repetition. Truncal symptoms were less responsive. While the effects were sustained for a longer period, the actual duration of the entire therapy was shortened to 5 days. Gait training, when given alongside C-tDCS, showed attenuations in specific motor parameters instead of global balance. This protocol produced measurable gains in the aspect of fine motor abilities in patients. DBS, when combined with physical rehabilitation, produced correlated CAG repeat length with clinical response, implying genotype-dependent responsiveness to the combined intervention. Both RAGT and TAGT therapies that were administered in post-stroke ataxic patients reduced SARA scores and improved the functional and gait-based indices, with RAGT showing slightly better gait endurance and symmetry. Vibrotactile feedback-based home training implemented in the study conducted by Jabri et al. [45] enhanced DGI, trunk stability, fatigue levels, and postural control, reducing up to 30% of the trunk sway.

In addition to home-based feedback systems, recent advances in smart wearable technologies offer powerful tools for objectively measuring rehabilitation effects in ataxia. Smartphone sensors equipped with accelerometers and gyroscopes have been proven to acquire subclinical deficits in gait irregularity, balance, limb coordination, and speech, which are often not captured by conventional clinical rating scales. Wearable IMUs further serve as high-resolution spatiotemporal gait descriptors, integrating a variety of fine-grained parameters such as stride variability indices, turning angles and instability markers, and trunk sway measures, providing clear differentiation of healthy and ataxic gait. For enabling data-driven evaluation of ataxic symptoms, machine learning models such as support vector machines, decision trees, and neural networks are being trained on the datasets from the wearables. These algorithmic developments have depicted strong performance in classifying gait patterns in Friedrich's ataxia and identifying subject-specific motor patterns. These findings highlight the scope and ability of wearable technologies to serve as an essential interface between traditional rehabilitation and smart-health systems. Continuous sensor-driven measurement systems help provide a detailed representation of treatment response compared to periodic clinical evaluations. Despite these advantages, several technological limitations currently restrict the clinical deployment of wearable-driven rehabilitation. Sensor systems lack uniformity in calibration, body placement, and sampling rates, making comparative evaluations of different parameters difficult. Continuous real-world recordings generate noisy, high-volume datasets that require artifact-removing models and secure large storage. Machine learning models trained on small cohorts produce lower accuracy and have clinical variability in results. Addressing technological hurdles and combining them with other rehabilitation modules helps create a feedback-based therapy system.

Collectively, hybrid and technology-integrated protocols focused on improving the durability of the therapeutic effects consistently with patient-centered motivation. Single model neuromodulation effectively resolves cerebellar excitability but lacks sustained reinforcement without concurrent motor therapies. Standalone physiotherapy shows neurochemical and functional gains but is limited by patient adherence and disease progression. The convergence of studies suggests a two-step effect

where stimulation prepares the brain for plasticity and physical rehabilitation strengthens the new motor skills. Beyond neuromodulation techniques and physical rehabilitation strategies for ataxia, integrating wearable sensor-driven digital biomarkers within these therapeutic frameworks offers a pathway toward achieving better rehabilitation planning through continuous tracking of therapy adaptation, optimal stimulation response windows, and individualized ability toward intensity of the therapy. This method will also be essential in upgrading the short-term symptomatic gains to truly adaptive, long-term outcome-based therapy for ataxic patients. Upcoming rehabilitation strategies for ataxia will likely rely on adaptive, smart technology treatment models in which neuromodulation parameters, training intensity, and therapy scheduling are dynamically modified based on real-time feedback, which will represent a major step forward toward precision medicine approaches in ataxia.

5. Conclusion

This review compared the clinical efficiency of different therapy modalities such as physical, neuromodulation (rTMS, tDCS, and DBS), and hybrid protocols across various types of ataxias. All treatment modalities infer measurable therapeutic gains, but only for a short duration. While hybrid and technology-assisted protocols produced the most durable improvements due to the mutual reinforcement of motor learning. The combined therapy approaches leverage a two-phase mechanism-1. Neuromodulation phase, which primes the cerebellar-cortical pathways 2. The physical training phase consolidates the neuroplasticity introduced in the previous phase. This can optimize and reinforce cerebellar pathways. The current trials are limited by small sample sizes and short follow-up durations, making it difficult to record the long-term efficacy of the treatments. Inconsistency in the usage of assessment metrics, variability in stimulation parameters, and intensity of the therapy restrict the scope of comparison between different trials. Future works should prioritize conducting trials for large cohorts, be multicenter, and use standardized hybrid protocols for better functional outcomes. Incorporating wearable gait digital biomarkers, sensor-based real-time monitoring of outcomes, and genotype-specific mapping enables the scope for patient-centered therapy strategies. By providing granular, real-world mobility feedback and consistent tracking of motor performance, sensor-driven and machine learning modeled systems ultimately support feedback-guided therapies, which strengthen future trials and design. Future works should also address key technological setbacks, including the lack of standardized wearable sensor protocols, limited generalizable machine learning models, and the challenges involved in merging technology and other rehabilitation interventions. Neuromodulation-assisted rehabilitation holds a strong impact for restoring motor function and independence in both hereditary and acquired ataxic patients, but its full potential will only emerge when combined with hybrid therapy frameworks, thereby improving the quality of life for ataxic patients.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Krishnakumar Sankar: Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Samyuktha Shanmugam:** Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Sanjana Parlikad Krishnan:** Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Sushmitha Sree Saravanan:** Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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