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Research Article

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Neuroplasticity with the Feldenkrais Method in Managing Multiple Sclerosis-related Ataxia

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Abstract

Introduction: Ataxia is a common symptom in patients with multiple sclerosis (MS). Motor-cognitive rehabilitation in such patients involves stimulation and enhancement of different brain regions, both of which rely on physiological pathways between the body and the brain, provoking brain plasticity and learning.

Objective: This study aimed at applying our recently published protocol, the neuroplasticity scale (NS), which is based on the Feldenkrais method (FM), in the context of chronic MS ataxia. Through an integrated process involving the development of a patient's capacity to sense, think and respond in an embodied manner to external stimuli, we sought to record and reinforce brain learning during motor rehabilitation.

Method: A single MS patient presenting gait ataxia, instability, spasticity, executive dysfunction and attention deficits was selected as a case study for intervention. We applied our NS protocol for six weeks and recorded different aspects of the individual's interaction with his environment, in terms of motor control, interoception, perception and spatial embodiment.

Results: Following our applied protocol, the individual showed clear improvement in his motor coordination, significantly reduced gait ataxia, ability to control dual-task functions, as well as improved static and dynamic balance. He also presented significantly reduced spasticity, improved sensory awareness and better embodied cognition. Overall, he showed an evident improvement in his daily functionality.

Conclusion: With further refinement, our NS protocol can provide important insights about brain learning and motor-cognitive regulation, in the context of therapeutic interventions for mild and progressive MS-related ataxia.

Keywords

Feldenkrais method, Multiple sclerosis, Ataxia, Brain-body intervention, Neuroplasticity

Introduction

MS is an inflammatory, demyelinating chronic disorder of the central nervous system (CNS) [1], which directly impairs axonal conductance and viability [2]. Importantly, it is one of the leading causes of disability in young adults, with socioeconomic impact in the United States and Europe [3, 4].

MS individuals exhibit several symptoms, such as ataxic gait [5], generalized leg fatigue during walking [6], truncal ataxia [7], dysarthria [8], ophthalmological signs [9], instability and progressive worsening of the proprioception [10],

amongst others. Ataxia is quite a common symptom, especially in patients with progressive MS who manifest lesions in the sensory pathways and the cerebellum [11]; in fact, up to 85% of MS patients display mild ataxia at some point in their life, while 32% exhibit a severe form that can impair their everyday functionality [7]. Of note, ataxia can be brought about due to dysfunction of the cerebellum (cerebellar ataxia), dysfunction of the vestibular system (vestibular ataxia) or dysfunction of the sensory system (proprioceptive-sensory ataxia) [7].

The cause of ataxia in MS is multifactorial. Lesions in areas of the CNS controlling balance, coordination and movement, especially the cerebellum, are often involved. The cerebellum, a highly plastic region, plays an integrative role in multiple circuits throughout the brain; it is connected, through parallel connectivity loops, to parietal sensory and frontal motor areas of the cerebral cortex, as well as areas involved in visual, auditory and memory functions [11-14]. Importantly, not all MS patients have lesions in their cerebellum; but those who present such lesions perform worse in cognitive tests compared to those who don't. Nonetheless, cognitive-motor interference during action has been poorly investigated [11, 15, 16].

It has been proposed that in MS there is an alteration in the way in which affected brain regions communicate with other areas of the brain that is, in their functional connectivity (FC); in fact, a positive correlation between cognitive performance and FC in brain regions, such as the medial prefrontal cortex, the frontal pole, the left insula and the hippocampus, has been established in MS patients [17]. Moreover, motor dysfunction in MS has been associated with reduced FC in crucial sensorimotor network hubs [17].

It should be stressed that MS individuals do not only suffer in terms of motion and cognition, but also in terms of their social life and personal relationships; as a result, they often experience a reduced quality of life. Unfortunately, evidence-based treatments that involve a multidisciplinary therapeutic approach are missing. For the time being, there is no such thing as a "universal" treatment for ataxia in MS patients, nor does a specific drug for ataxia exist. Several approaches, including pharmacotherapy, physiotherapy and surgical procedures (such as deep brain stimulation of the thalamus or stereotactic thalamotomy [7]), are currently under investigation, but their implementation remains largely empirical. Particularly interesting though are certain motor rehabilitation programs that are being used for managing postural and gate disorders in MS ataxia [18], while improving cognitive function and coordination [19]. Importantly, it has been shown that cognitive engagement during motor function has benefits for the adult brain, including formation of new neurons and increased connectivity among existing ones [20, 21]. Furthermore, it has been established that synaptic plasticity and thereby connectivity is induced by physical activity through the increased production of brain-derived neurotrophic factor and other growth factors [22]. Of note, novel non-pharmacological treatment approaches underline the crucial role of physical activity in the release of neurotransmitters, such as dopamine and serotonin; dopamine is crucial for movement regulation, especially for voluntary movement, reward and motivation, and its imbalance has been associated with fatigue in MS [23], while serotonin is an essential regulator of exercise-induced hippocampal neurogenesis [24].

In our recently published study, we presented the NS, a novel methodology that can be used for the assessment of sensory-motor-cognitive processes during action in MS patients; we demonstrated that an intensive, repetitive training/assessment cycle has a positive effect on brain plasticity and correlates with lasting beneficial changes during action. We showed that the NS helps an MS individual engage actively in a personalized framework, while dynamically participating in the rehabilitative process [25].

In the present study, we have used the NS for MS-related ataxia rehabilitation, in order to identify functional markers that contribute to brain plasticity and long-term potentiation; our aim was to develop a targeted intervention protocol for MS patients exhibiting ataxia and to thus evaluate the effectiveness of NS in such a context.

Method

Recruitment of subject

A 38 year old Greek male of Caucasian origin, clinically diagnosed with MS in 2017, was recruited as a case study in 2023, after obtaining his consent. The subject presented gait ataxia, postural instability, spasticity and executive dysfunction. In addition, he showed poor cognitive performance, especially in terms of working memory and attention.

At the time of his diagnosis, the patient had bilateral superficial sensory disturbances along the lower extremities; more specifically, he presented paresthesia's proximal as well as distal without any specific distribution pattern or intensity. His diagnosis was established based on MRI scans of the brain, cervical and thoracic spinal cord (all of which showed multiple non-enhancing lesions), as well as on cerebrospinal fluid studies showing the presence of oligoclonal bands and an increased IgG index, suggestive of MS. The patient showed spontaneous remission within a few days and thus did not receive any steroid bulk treatment. After three months, he was placed on dimethyl fumarate treatment for the first three years after his diagnosis (2017 to 2020); during this period, he complained only occasionally of abnormal superficial sensory symptoms in both hands and feet (of note, he could not recall when exactly his upper extremity symptoms appeared within this time). In 2020, similar superficial sensory symptoms reappeared in a constant and more pronounced manner, albeit with fluctuating intensity. In addition, bladder dysfunction appeared, mostly in the form of hesitancy. The same year, MRI scanning showed a new enhancing lesion at the C2 level of the spinal cord, which to date remains the only new appearing lesion since his first diagnosis. The patient's treatment was thus switched to biannual ocrelizumab, which he continues to receive until presently.

In February 2023, just prior to the initiation of the current study, the patient's neurological exam was as follows: His higher intellectual functions were within normal in terms of orientation, speech and memory, but there was slowness in the execution of tasks. His cranial nerve exam showed oculomotor abnormalities with impaired smooth pursuit movement.

He denied having diplopia, although he had experienced it once transiently during the previous years in association with decreased left eye abduction. The patient also presented left trigeminal neuralgia. As for his motor function, he showed decreased fine finger movements in both upper extremities, decreased plantar tapping, absence of pronator drift and muscle strength 5/5 in all extremities. A mild-moderate level of spasticity was observed in his lower extremities. Furthermore, the patient's posture was wide-based and got significantly worse when he closed his eyes. He was unable to stand on his toes, whereas he could stand on his heels moderately well. He had significant difficulty walking in a straight line or hopping on either leg. Alternating movements were slightly impaired in both upper extremities and his heel-to-shin bilateral testing also showed impairment. His deep tendon reflexes were 1^+ in all testing areas of both upper extremities, 3^+ in knee jerks, 2^+ in the left ankle and 4^+ in the right ankle. Finally, he had an extensor plantar response on the right and no reaction on the left.

With regards to the patient's MRIs, other than the active lesion at the C2 level of the spinal cord in 2020 there has never been a change in the number of lesions, which involve the brain, the spinal cord from C2 to C6 level and the thoracic spinal cord at the levels of T_1, T_6-T_{10}, T_{11}-T_{12}, most lesions being confluent. Of note, there was no change in his MRIs of the brain, cervical or thoracic spinal cord between the beginning of the study in March 2023 and August 2023.

The NS tool

The design of the NS has been described in detail in our recently published study [25]. Briefly, the NS consists of three sections, during which the practitioner collects data on three sensory-motor-cognitive functional areas, in the form of specific indicators (e.g. fatigue, spasticity, etc.). Section I involves exploratory manipulation during functional integration (FI). In this hands-on approach, the practitioner stimulates the subject's senses, proprioception and tactile perception through attention, to study and control the signs and symptoms of MS during movement patterns. Section II assesses the subject's perception-action framework through constructive sensory-motor-cognitive patterns. Synchronization and conditioning between internal and external stimuli, as well as flexibility of responsiveness, are evaluated by means of awareness-through-movement (ATM) training [26]. Section III involves assessment by the practitioner and the individual alike of reference actions, such as standing, walking, sitting and dancing (in the form of a choreography). Of note, dancing is selectively evaluated as a reference action, since it is known that daily repetitive motor training enhances cortical synchrony in different frequency bands and has been linked to the preparation, execution, perception and imagining of movement [27]. Sections II and III are recorded and used by the subject to guide home-training sessions following auditory cues.

Importantly though, compared to our previously published case study [25], in the present case, the following modifications were made: Section I focused on reducing spasticity and increasing proprioception; in addition to all previously described parameters, the following aspects were assessed: control of dorsiflexion and plantar flexion, reduction of sensory disturbances and spasticity, control of leg flexors and extensors in different planes, minimization of motor patterns' range in different body areas, increase of parasympathetic relaxation response and connection of pelvis, crossing of head and chest in relation to the midline, breathing patterns, motor imagery, eye rotation, clearance of swing and forward propulsion, weight-shifting according to midline and foot border perception. Furthermore, each week section II focused on a different aspect: During week 1, specific focus was given on challenging balance in multiple positions using a rigid, 1-meter foam roller (cylinder). The subject lied in supine position, placing the foam roller on the ground, perpendicularly to his spine, and used the roller as a simulation of his body's midline, to integrate cross-lateral developmental patterns and experience left-right differentiation and reversibility of movement [28]. During week 2, focus was given on the use of breathing as a coordinator for dynamic stability, using the foam roller as a simulator of the midline, to explore the sagittal, parasagittal and transverse planes [29, 30]. During week 3, focus was given on swallowing activation [31]. During week 4, focus was given on coordinating eye movement with the pelvis and shoulders, using the foam roller [32]. During week 5, focus was given on the dynamic stability during standing, as well as on motor imagery [33]; while during week 6, focus was given on motor control. Lastly, in section III, reference actions and choreography focused on organizing the subject's spatial cognition [34, 35] and dual task functions [36].

Procedure overview

The procedure involved one week of baseline evaluation (Week 0), followed by six weeks of intervention (Weeks 1 - 6), all of which took place at The Body and Brain Institute, in Athens, Greece. During the entire procedure, different aspects of the individual's interaction with his environment, in terms of motor control, interoception, perception and spatial embodiment, were recorded. Each week both baseline and intervention consisted of a short self-report by the individual, followed by assessment with the NS. More precisely: During week 0 (baseline evaluation), the subject was first asked to describe any limitations he experienced in his everyday life. Next, section I of the NS was performed by the practitioner, followed by sections II and III, which were executed by the subject to familiarize himself with the required movement patterns. All instructions given by the practitioner in sections II and III were recorded, so that the subject could use them as auditory cues for home-training over the entire week. The following week (Intervention week 1), the subject was first asked to give a short self-report about his home training. Next, sections I, II and III of the NS were performed, appropriately modified by the practitioner according to the subject's responses during self-reporting. Again, instructions for sections II and III were recorded for use in home training. All subsequent weeks of intervention (weeks 2 - 6) followed the above-described pattern.

Results

Baseline evaluation

Baseline evaluation at week 0 consisted of a short self-report by the subject, followed by an evaluation by the practitioner using the NS. During self-report, the subject stated that

he experienced increased foot drop and difficulty in lifting his left foot, both of which impeded his walking and caused him tiredness. He also mentioned having lower back pain, speed limitation during walking and a sense of pessimism. During section I of the NS, which lasted approximately 30 min, the subject presented spasticity; more precisely, on a grading scale of 0 - 2, he scored a 1 (moderate). In addition, he exhibited intense neuralgia (on a grading scale of 0 - 10, he scored a 4), but also fatigue and limb weakness (he scored 5 and 3, respectively). Other indicators, such as Babinski sign, hyperreflexia, tingling sensations and numbness, were characterized as Off or scored as 0 (absent). During section II of the NS, which lasted approximately 30 min, the subject was unable to orient himself. His cognitive ability to perceive time and change rhythm during action was uncoordinated. In terms of exhibiting confusion during action (sadness, anger, etc.), the subject was evaluated as impeded. He was also unable to coordinate visual, auditory and motor cues, showed inhibited movement (INH MOV) in terms of tactile perception and displayed inability to alternate between internal and external attention circuits. He also presented limited proprioceptive ability. His basic functional organization was uncontrolled, especially in terms of side bending, rotation and counter rotation. Moreover, holding patterns during inhalation/exhalation/pauses were found to be impeded. He was also unable to orbit and move around a support base. During section III, which lasted 19 - 29 min, the subject covered a 10 m distance in 11.2 s. Additionally, in terms of swing time dynamics, the subject was found to be unstable. Furthermore, in terms of counterbalance (evaluated in minutes of side-by-side standing), the subject was found to last 2 min, whereas, in terms of tandem stand, the subject was unable to perform all standing combinations. Lastly, the subject was given a final task: to learn and perform a short choreography, guided by the practitioner; his performance was characterized by instability in his stepping and general movement flow, as well as ataxia, spasticity, imbalance and several falls. Of note, a complete list of the subject's results is given in table 1 for all examined indicators.

Intervention week 1

After one week of home training, the subject came in for the first cycle of intervention, already showing some signs of improvement (Table 1, week 1). During self-reporting, he expressed feeling improvement in visuospatial awareness; he also mentioned that all throughout the previous week he had started imagining his midline and feeling its transition from left to right, and vice-versa, during movement. He specifically stated: "I felt my midline being closer to my left, so I adjusted my movement accordingly. I felt that the foam-roller movement protocol stimulated sensorily my left foot". During section I, his fatigue and spasticity showed no change, but his neuralgia did present a small decrease (he scored a 3 – one grade lower than the previous week). He also showed improvement in some of the indicators evaluated within section II: He was able to spatially orient himself, to coordinate visual, auditory and motor cues, to alternate between internal/external attention circuits (on) and to use internal maps to simulate movement without execution (on). Finally, during section III, a slight improvement was seen in his walking speed (he covered a 10 meter distance in 10.69 s, compared to 11.2 s during the previous week); he was also able to orbit and move around a support base (he couldn't do so during week 0), he showed no shortening of his stepping length and was able to support himself on one foot in order to move the other. During choreography training, the subject was able to stand with his legs closed and crossed; he was also able to spatially orient his left-right side. In addition, he was stable while rotating the pelvis and started being aware of his breathing in the left abdominal side.

Intervention week 2

During self-reporting, the subject mentioned that in his home-training he had felt able to terminate or control his actions in a well-timed manner. During section I of the NS, the subject showed, for the first time, a slight amelioration in his spasticity and limb weakness (Table 1, week 2). His neuralgia continued to decrease. During section II, the subject showed the ability to perceive time and change rhythm during action in a coordinated manner. More importantly, for the first time, he displayed no confusion during action; he was found to perform fluid actions. All basic functional organization indicators were also found to be clearly improved for the first time: his flexion, extension, side-bending rotation and counter-rotation were all controlled. In addition, the subject's holding patterns during breathing were improved for the first time. During section III, the subject continued showing improvement in his walking speed (he covered 10 meters in 8.61 s), and for the first time he showed stability in terms of his swing time dynamics, his actions and especially his performance during choreography.

Intervention week 3

During self-reporting, the subject mentioned that over his home training he had gained foot border perception, especially in the toes of his left foot; in fact, he mentioned feeling emotional after moving his left foot toes for the first time. He also reported that he had been able to walk more than 20 min, had better motor control and did not get dizzy when flexing his cervical spine during dancing. During section I, the subject continued to show slightly decreased spasticity, but for the first time he also showed significantly less fatigue (Table 1, week 3). His limb weakness showed further reduction compared to week 2, whereas his neuralgia remained steadily lowered. In section II, the subject's cognitive ability to perceive time and change rhythm during action remained improved; he was found to be coordinated. His improvement in terms of confusion during action also continued; he performed fluid actions, an improvement which, importantly, was maintained thereafter all throughout the procedure. Moreover, the subject continued to be able to coordinate visual, auditory and motor cues. With respect to his basic functional organization, the subject's performance continued to show improvement for all indicators. Further amelioration was also seen during section III: The subject was able to cover a 10 m distance in 8.54 s, continuing to show a small, yet steady, gradual decrease in the time required to complete this specific task. He was also able to perform side-by-side standing that lasted more than 1 min.

Intervention week 4

During self-reporting, the subject mentioned that, over the previous week, he had been able to increase the time he

Table 1: Results during baseline evaluation (week 0) and all throughout intervention weeks (weeks 1 - 6).

Weeks	Week 0	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Section I: Exploratory manipulation during FI							
Babinski sign	Off	Off	Off	Off	Off	Off	Off
Spasticity	1	1	0 - 1	0 - 1	0 - 1	0	0
Sensory disturbances							
Fatigue	5	5	5	3	2	0	0
Tingling sensations	0	0	0	0	0	0	0
Numbness	0	0	0	0	0	0	0
Limb weakness	3	3	2	1	1	0	0
Other	4	3	2	2	1	0	0
Hypperrflexia	Off	Off	Off	Off	Off	Off	Off
Section II: ATM sequences							
Perception/action							
Spatial orientation	Unable	Able	Able	Able	Able	Able	Able
Cognitive ability to perceive time and change rhythm during action	Uncoordinated	Moderately coordinated	Coordinated	Coordinated	Coordinated	Movement viscosity	Movement viscosity
Confusion during action (sadness, anger, fear, doubt, discomfort, and body parts recognition)	Impeded	Impeded	Fluid action	Fluid action	Fluid action	Fluid action	Fluid action
Coordination of visual, auditory, and motor cues	Unable	Able	Able	Able	Able	Able	Able
Tactile perception	INH MOV	FMTA	FMTA	FMTA	FMTA	FMTA	FMTA
Alternation between internal-external attention circuits	Off	On	On	On	On	On	On
Scanning measurement							
Using internal maps to simulate movement without execution	Off	On	On	On	On	On	On
Sensing tonus, and asymmetries	Unable	Able	Able	Able	Able	Able	Able
Basic functional organization							
Flexion	Uncontrolled	Uncontrolled	Controlled	Controlled	Controlled	Controlled	Controlled
Extension	Uncontrolled	Uncontrolled	Controlled	Controlled	Controlled	Controlled	Controlled
Side-bending	Uncontrolled	Uncontrolled	Controlled	Controlled	Controlled	Controlled	Controlled
Rotation	Uncontrolled	Uncontrolled	Controlled	Controlled	Controlled	Controlled	Controlled
Counter rotation	Uncontrolled	Uncontrolled	Controlled	Controlled	Controlled	Controlled	Controlled
Signs of optic neuritis							
Eye fatigue/pain during movement	Off	Off	Off	Off	Off	Off	Off
Reduction of visual acuity/visual field	On	Off	Off	Off	Off	Off	Off
Eye movement difficulties	Moderately controlled	Moderately controlled	Eyeball coordinated movement	Eyeball coordinated movement	Eyeball coordinated movement	Eyeball coordinated movement	Eyeball coordinated movement
Respiration							
Breathing rate	Increased	Decreased	Decreased	Decreased	Decreased	Decreased	Decreased
Holding patterns during inhalation/exhalation/pauses	Impeded	Impeded	Improved	Improved	Improved	Improved	Improved
Swallowing activation	Off	Off	Off	Off	Off	On	On
Section III: Reference actions (Walking, standing, and sitting)							
Walking speed	11.2 s	10.69 s	8.61 s	8.54 s	8.2 s	7.8 s	7.47 s
Shortening length of stepping	On	Off	Off	Off	Off	Off	Off
Increasing of double leg support	Off	Off	Off	Off	Off	Off	Off
Decreasing of single leg support	On	Off	Off	Off	Off	Off	Off
Swing time dynamics	Unstable	Unstable	Stable	Stable	Stable	Stable	Stable
Counterbalance							
Time of standing position	2 min	2 min	2 min	3 min	3 min	3 min	3 min
Side by side stand	< 1min	1 min	> 1 min	> 1 min	> 1 min	> 1 min	2 min
Tandem stand	Unable in all combinations	Rl for 5 s; Lr, rL, lR unable	Lr, rL, Rl for 5 s; lR unable	Lr, rL for > 10 s (not easy); Rl for 10 s (moderately comfortable); lR for 5 s (not easy)	Lr, for > 10 s (moderately comfortable); rL for > 10 s (not easy, with 2 trials); Rl for 10 s (with difficulty); lR for 10 s	Lr and Rl for > 10 s (with lots of trials); rL for > 5 s); lR for 10 s (not easy)	Lr, Rl, lR for 10 s (with 2 trials); rL for > 10 s (with 2 trials)

Dynamic sitting position							
Orbiting and moving around a base of support	Unable	Able	Able	Able	Able	Able	Able

Note: The Babinski sign is evaluated as either on or off; spasticity is evaluated as on (2), moderate (1) or off (0); sensory disturbances are measured on a 0 - 10 scale; hyperreflexia is measured as on or off; spatial orientation is evaluated as able or unable; cognitive ability to perceive time and change rhythm during action is evaluated as uncoordinated, moderately coordinated, coordinated or movement viscosity; confusion during action is evaluated as impeded or fluid action; coordination of visual, auditory, and motor cues is evaluated as able or unable; tactile perception is evaluated as INH MOV (inhibited movement) or FMTA (facilitated movement through attention); alternation between internal/external circuits and use of internal maps to simulate movement without execution are evaluated as on or off; sensing tonus, and asymmetries is evaluated as able or unable; all basic functional organization indicators are evaluated as controlled or uncontrolled; eye fatigue and reduction of visual acuity are evaluated as on or off; eye movement difficulties are evaluated as lack of eyeball rotation, moderately controlled or eyeball coordinated movement; breathing rate is assessed as increased or decreased; holding breathing patterns are assessed as impeded or improved; swallowing activation is evaluated as on or off; shortening of stepping length, increase of double leg support, and decrease in single leg support are evaluated as on or off; swing time dynamics is evaluated as stable or unstable; time of standing position as well as side-by-side standing are evaluated in minutes; tandem stand is evaluated in terms of standing ability for several seconds, with one foot in front of the other (Lr: left foot stable/right foot in front, rL: left foot stable/right foot back, Rl: right foot stable/left foot in front, lR: right foot stable/left foot back); orbiting and moving around a support base is evaluated as able or unable.

spent mounting on a climbing wall and to feel his midline as a cross-section of his right eye; furthermore, he said that he had felt able to perceive movement according to his new kinesthetic information, while also realizing that he still had difficulties in emotional processing (he specifically stated: "I feel emotionally confused and distracted"). Finally, he mentioned being able to monitor himself spatially, predict errors and make corrections on downhill and narrow roads. During section I, he continued to show decreased fatigue and decreased neuralgia signs (Table 1, week 4). In section II, no significant change was seen compared to week 3; improvement in all examined indicators was steadily maintained. The same applied for section III; a slight further amelioration, though, was seen in the subject's walking speed: He was able to cover a 10 m distance in 8.2 s. During choreography, he was able to easily coordinate movement while performing the set of prelearned sequences.

Intervention week 5

During self-reporting, the subject mentioned that he had been able to lengthen his exhalation, stay balanced with his eyes closed and move his midline according to the movement. Importantly, he mentioned that he had started socializing, using public transportation and predicting behavior. During section I, the subject showed improvement in general (Table 1, week 5): He showed no fatigue, no spasticity, no limb weakness and no neuralgia signs. During section II, he finally showed movement viscosity in terms of cognitive ability to perceive time and change rhythm during action; improvement in all other examined indicators was steadily maintained. During section III he continued to show further amelioration in terms of his walking speed: He was able to cover a 10 m distance in 7.8 s. All other indicators steadily maintained an improvement.

Intervention week 6

During last week's session, the subject came in expressing straightaway tremendous enthusiasm. Therefore, following his strongly motivated mood, self-reporting was omitted. During section I, the subject's improved performance was maintained; his spasticity, as well as all his sensory disturbances, were absent (score = 0). During section II, his cognitive ability to perceive time and change rhythm during action remained improved; he exhibited clear movement viscosity. He also remained free from any confusion during action, showing clear action fluidity. In addition, he was still able to coordinate all visual, auditory and motor cues. In terms of basic functional organization, the subject continued to show clear control. During section III, the subject continued to show an improved performance: He was able to cover a 10 m distance in just 7.47 s and to maintain his balance while swinging. In addition, he was able to effortlessly stand side-by-side for 2 whole min. In fact, the subject stated that it was now easy for him to perform this movement protocol and that he felt comfortable executing it. Additionally, when assessed in terms of tandem stand ability, he could stand for 10 s with his right foot stable and his left foot either in front or back, as well as with his left foot stable and his right foot in front. Surprisingly, with his left foot stable and his right foot back, he managed to stand for more than 10 s. Finally, the subject showed clear improvement in performing his short choreography while listening to his music of choice.

Discussion

We recently described the design of a novel tool, the NS, which enables practitioners and MS patients alike to assess changes in sensory-motor and cognitive processes during action; our tool includes specific repetitive movement patterns and intensive home-training, aiming at achieving targeted intervention [25]. In the work, we applied the NS to a single female MS patient, to establish a proof-of-concept study [25]. Here, we have moved forward, by applying the NS to a male MS patient with severe ataxia, to further solidify the efficiency of our approach and gain insight into the usefulness of the NS in the context of MS ataxia.

The NS is essentially a rehabilitative protocol; it is based on the FM, a neurodevelopmental approach that focuses on internal and external integration, while experiencing and directing movement [37]. Our method incorporates both hands-on (FI) and verbally guided (ATM) movement components, which aim specifically at altering cortical, sensory and motor maps through experience and training [38].

We applied our NS approach to the selected subject, for a total of seven weeks, one week of baseline evaluation and six weeks of intervention. We found that the NS contributed significantly to the individual's improvement in terms of motor coordination, static and dynamic balance, gait ataxia, spasticity, sensory awareness and embodied cognition. Namely, his fatigue levels had decreased already by week 3 and were completely absent by the end of week 6. His spasticity started showing signs of decreasing by week 2 and was completely

eliminated by week 5. With respect to his perception/action, the subject also showed great amelioration: Already by Week 1, he was able to spatially orient himself, to perceive time and change rhythm during action in a moderately coordinated manner, and to coordinate visual, auditory and motor cues. Several indicators that were evaluated in the context of his basic functional organization, such as his flexion, extension, side-bending, rotation and counter-rotation, showed improvement one week later by week 2. Of note, the subject's walking speed showed a small, yet steady, increase all throughout the procedure: He started off covering a 10 m distance within 11.2 s at week 0 and ended up covering the same distance within 7.47 s by the end of week 6.

It is worth further elaborating here on two specific parameters in the subject's performance that showed improvement: First, already after one week of intervention, the subject came in mentioning that he had felt able to terminate or control his actions in a well-timed manner-an aspect controlled by the left dorsolateral prefrontal cortex and the dorsal anterior cingulate cortex, which are important for developing adjustment mechanisms during exercise [39]. Second, his performance in the counterbalance movement test was largely impressive: In this sort of test, what is usually assessed is whether the individual can last standing for 10 s; however, this time duration is adjusted, according to the abilities of each subject. In our study, at baseline evaluation, the subject was able to stand for more than 10 s; therefore, we changed the time scale according to his potential and made assessments on a minutes' scale, rather than a seconds' scale. Importantly, this further showcases the personalized profile of our NS approach.

It is also worthwhile commenting on the subject's performance in dance. When the subject came in for his baseline evaluation at week 0, he showed evident difficulties in performing a rather simple choreographic syllabus. However, by the end of week 6, the subject's ability to perform the choreography showed obvious improvement. Dancing involves balance and motor coordination associated with the step-by-step control of goal-directed movements; it can improve an individual's balance, postural control and stability, functional mobility and rigidity [40], and it is for this reason that we chose to incorporate it in our NS approach. In fact, it has been shown that dance training leads to structural brain changes, primarily in the sensory and motor regions, as well as in the connections between them, providing faster conduction and enhanced coordination between these areas, both of which are crucial for the expression of dance [27].

It should be stressed at this point that the subject was asked to select his favorite song to which he would perform his choreography as part of home-training. He chose "Epirotica", a music style originating from Epirus, a region in the northwestern part of Greece, where his family roots are based. The subject mentioned was that this music had a great impact on him; and being able to dance at his village's festivals seemed to work as a significant incentive for him. The rationale behind encouraging our subject to choose music that would evoke positive feelings and/or memories was that, when dancing, the brain's motor and auditory regions are both activated, since dancing requires motor coordination and synchronization with music. These regions are linked to the brain's emotional processing centers [41-43]; therefore, an emotional reaction to music and movement is also involved. In fact, emotional detection, integration and evolution in an individual have been linked to enhanced theta and gamma synchronization in brain regions, such as the orbitofrontal cortex, superior temporal sulcus and amygdala [27].

The uniqueness of our NS approach lies in the fact that the subject is given the ability to assess his own performance, both during home training and while going through each section with the practitioner's guidance. Moreover, the subject could express questions and comments, both in terms of the scale and of the process itself. Most importantly, because of the subject's dynamic participation, the practitioner can monitor his/her responsiveness and alteration capacity through brain learning. During the entire procedure, the subject in our study was encouraged to express his feelings in relation to the NS. His feedback ("I have better connection with my left side, this is huge" (week 1), "I understand and monitor my improvement" and "I was able to grab a cup from the kitchen table, whereas in the past I used to drop it" (week 2), "Thank you so much, I have no words" and "I want to strengthen my leg, let's find a movement protocol" (week 3), "I reached 6.7 s of exhalation" (week 5), "I can recognize my improvement; I managed standing on my own on the subway platform" (week 6)) was not only used by the practitioner on a weekly basis, in order to modify movement patterns based on the subject's progress, but it also promoted a sense of self-awareness that, in turn, led to a sense of agency (that is, an ability to control his own actions and, through them, events in the external world). Importantly, connectivity between the frontal cortex areas, which develop motor plans for voluntary action, and the parietal areas, which monitor outcomes, plays an essential role in the successful computation of agency, which ultimately helps develop motor control, timing and planning of action [44]. Obviously, such dynamic participation helps build confidence and achieve better results.

Nonetheless, our study presents several limitations, which are worth noting: First, our protocol was implemented on a single individual, as a case-study for MS ataxia. We therefore recognize that more conclusive results about its efficiency can only be drawn upon its implementation on a larger number of patients. Secondly, our approach is only empirical; ideally, it should be combined with imaging analysis and other technical and/or clinical applications, to obtain a fuller, more detailed image of the patient's progress.

Our methodology highlights the need to redefine therapeutic approaches under the scope of a body-in-the-brain model [45]. According to this model, the body responds to temporary coherent settings, depending on the information it perceives through constructive neural maps, to facilitate the development of individualized adaptations to environmental cues, as well as its own biological regulation and the maintenance of vital processes [45]. Contextualizing the environmental influence through an individual's experience can form the basis of a novel approach for improving ataxia symptoms in MS patients.

Conclusion

Overall, our results show that, with further refinement, the NS protocol can provide important insights about brain learning and motor-cognitive regulation, in the context of therapeutic interventions for mild and progressive MS-related ataxia.

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None.

Conflict of Interest

None.

References

1. Kutzelnigg A, Lassmann H. 2014. Pathology of multiple sclerosis and related inflammatory demyelinating diseases. *Handb Clin Neurol* 122: 15-58. https://doi.org/10.1016/B978-0-444-52001-2.00002-9
2. Brodal P. 2016. The Central Nervous System. Fifth edition. New York, Oxford Univeristy Press.
3. Noseworthy JH, Lucchinetti C, Rodriguez M, Weinshenker BG. 2000. Multiple sclerosis. *N Engl J Med* 343(13): 938-52. https://doi.org/10.1056/NEJM200009283431307
4. Dutta R, Trapp BD. 2011. Mechanisms of neuronal dysfunction and degeneration in multiple sclerosis. *Prog Neurobiol* 93(1): 1-12. https://doi.org/10.1016/j.pneurobio.2010.09.005
5. Buckley E, Mazzà C, McNeill A. 2018. A systematic review of the gait characteristics associated with cerebellar ataxia. *Gait Posture* 60: 154-163. https://doi.org/10.1016/j.gaitpost.2017.11.024
6. Olgiati R, Burgunder JM, Mumenthaler M. 1988. Increased energy cost of walking in multiple sclerosis: effect of spasticity, ataxia, and weakness. *Arch Phys Med Rehabil* 69(10): 846-849.
7. El-Mansoury B, Laadraoui J, El Khiat A, El Hiba O, Jayakumar AR, et al. 2023. Ataxia in Multiple Sclerosis: From Current Understanding to Therapy. In Ataxia - Practice Essentials and Interventions. IntechOpen.
8. Plotas P, Nanousi V, Kantanis A, Tsiamaki E, Papadopoulos A, et al. 2023. Speech deficits in multiple sclerosis: a narrative review of the existing literature. *Eur J Med Res* 28: 252. https://doi.org/10.1186/s40001-023-01230-3
9. Tsai PF, Chen YJ. 2023. Case report: multiple sclerosis presenting as unilateral gaze-evoked nystagmus. *Optom Vis Sci* 100(6): 419-421. https://doi.org/10.1097/OPX.0000000000002027
10. Iandolo R, Bommarito G, Falcitano L, Schiavi S, Piaggio N, et al. 2020. Position sense deficits at the lower limbs in early multiple sclerosis: clinical and neural correlates. *Neurorehabil Neural Repair* 34(3): 260-270. https://doi.org/10.1177/1545968320902126
11. Wilkins A. 2017. Cerebellar dysfunction in multiple sclerosis. *Front Neurol* 8: 312. https://doi.org/10.3389/fneur.2017.00312
12. Kenyon KH, Boonstra F, Noffs G, Butzkueven H, Vogel AP, et al. 2023. An update on the measurement of motor cerebellar dysfunction in multiple sclerosis. *Cerebellum* 22(4): 761-775. https://doi.org/10.1007/s12311-022-01435-y
13. O'Reilly JX, Beckmann CF, Tomassini V, Ramnani N, Johansen-Berg H. 2010. Distinct and overlapping functional zones in the cerebellum defined by resting state functional connectivity. *Cereb Cortex* 20(4): 953-965. https://doi.org/10.1093/cercor/bhp157
14. Parmar K, Stadelmann C, Rocca MA, Langdon D, D'Angelo E, et al. 2018. The role of the cerebellum in multiple sclerosis-150 years after Charcot. *Neurosci Biobehav Rev* 89: 85-98. https://doi.org/10.1016/j.neubiorev.2018.02.012
15. Tedesco AM, Chiricozzi FR, Clausi S, Lupo M, Molinari M, et al. 2011. The cerebellar cognitive profile. *Brain* 134(12): 3672-3686. https://doi.org/10.1093/brain/awr266
16. Weier K, Till C, Fonov V, Yeh EA, Arnold DL, et al. 2016. Contribution of the cerebellum to cognitive performance in children and adolescents with multiple sclerosis. *Mult Scler* 22(5): 599-607. https://doi.org/10.1177/1352458515595132
17. Tahedl M, Levine SM, Greenlee MW, Weissert R, Schwarzbach JV. 2018. Functional connectivity in multiple sclerosis: recent findings and future directions. *Front Neurol* 9: 828. https://doi.org/10.3389/fneur.2018.00828
18. Ilg W, Timmann D. 2021. General Management of Cerebellar Disorders: An Overview. In Manto M, Schmahmann JD, Rossi F, Gruol DL, Koibuchi N. (eds) Handbook of the Cerebellum and Cerebellar Disorders. Dordrecht, Springer, pp 2639-2666.
19. Asonitou K, Koutsouki D. 2023. Adapted Physical Activity and Ataxia. In Ataxia Practice Essentials and Interventions. Intech Open.
20. Petzinger GM, Fisher BE, McEwen S, Beeler JA, Walsh JP, et al. 2013. Exercise-enhanced neuroplasticity targeting motor and cognitive circuitry in Parkinson's disease. *Lancet Neurol* 12(7): 716-726. https://doi.org/10.1016/S1474-4422(13)70123-6
21. Ma CL, Ma XT, Wang JJ, Liu H, Chen YF, et al. 2017. Physical exercise induces hippocampal neurogenesis and prevents cognitive decline. *Behav Brain Res* 317: 332-339. https://doi.org/10.1016/j.bbr.2016.09.067
22. Cotman CW, Berchtold NC, Christie L. 2007. Exercise builds brain health: key roles of growth factor cascades and inflammation. *Trends Neurosci* 30(9): 464-472. https://doi.org/10.1016/j.tins.2007.06.011
23. Dobryakova E, Genova HM, DeLuca J. 2015. The dopamine imbalance hypothesis of fatigue in multiple sclerosis and other neurological disorders. *Front Neurol* 6: 52. https://doi.org/10.3389/fneur.2015.00052
24. Kondo M, Shimada S. 2015. Serotonin and exercise-induced brain plasticity. *Neurotransmitter* 2(e793): 1-6.
25. Reziti T. 2023. An individualized intervention, based on the feldenkrais method, for multiple sclerosis symptoms: the neuroplasticity scale assessment. *J Neurol Exp Neurosci* 9(1): 7-17. https://doi.org/10.17756/jnen.2023-102
26. Feldenkrais M. 2009. Awareness Through Movement. Harper Collins.
27. Basso J, Satyal M, Rugh R. 2021. Dance on the brain: enhancing intra- and inter-brain synchrony. *Front Hum Neurosci* 14: 584312. https://doi.org/10.3389/fnhum.2020.584312
28. The Trilogy. Postgraduate Seminar. [https://mindinmotion-online.com/teach/] [Accessed on May 30, 2024]
29. Feldenkrais M, Yanai A. 1994. The Feldenkrais Method Awareness Through Movement Lessons. ATM Lesson #21: Contracting the Abdomen While Exhaling. Paris: International Feldenkrais Federation.
30. Feldenkrais M, Yanai A. 2001. The Feldenkrais Method Awareness Through Movement Lessons. ATM Lesson #421: Toes and Stepping. Volume 9, Part A. Paris: International Feldenkrais Federation.
31. Feldenkrais M, Yanai A, 1994. The Feldenkrais Method Awareness Through Movement Lessons. ATM Lesson #17: Breathing. Volume 1, Part 1. Paris: International Feldenkrais Federation.
32. Feldenkrais M, Yanai A, 1994. The Feldenkrais Method Awareness Through Movement Lessons. ATM Lesson #19: Preparation for a Clock. Volume 1, Part 1. Paris: International Feldenkrais Federation.
33. Feldenkrais M. Yanai A. 1994. The Feldenkrais Method Awareness Through Movement Lessons. ATM Lesson #23: Palate, Mouth and Teeth. Volume 1, Part 1. Paris: International Feldenkrais Federation.
34. Salgado R, Vasconcelos LAP. 2010. The use of dance in the rehabilitation of a patient with multiple sclerosis. *Am J Dance Ther* 32: 53-63. https://doi.org/10.1007/s10465-010-9087-x
35. Foreman N. 2007. Spatial Cognition and Its Facilitation in Special Populations. In Applied Spatial Cognition. Psychology Press, pp 129-178.

36. Davis E, Webster A, Whiteside B, Paul L. 2023. Dance for multiple sclerosis: a systematic review. *Int J MS Care* 25(4): 176-185. https://doi.org/10.7224/1537-2073.2022-088
37. Feldenkreis M. 1972. Awareness Through Movement: Health Exercises for Personal Growth. New York, Harper & Row.
38. Connors K, Campbell L, Svendsen D. 2009. The Feldenkrais Method (Chapter 25). In Selvaratnam P, Niere K, Zuluaga M, Friedman S, Sloan C, et al. (eds) Headache, Orofacial Pain and Bruxism. Churchill Livingstone, pp 339-346.
39. Silton RL, Heller W, Towers DN, Engels AS, Spielberg, et al. 2010. The time course of activity in dorsolateral prefrontal cortex and anterior cingulate cortex during top-down attentional control. *Neuroimage* 50(3): 1292-1302. https://doi.org/10.1016/j.neuroimage.2009.12.061
40. Scheidler AM, Kinnett-Hopkins D, Learmonth YC, Motl R, López-Ortiz C. 2018. Targeted ballet program mitigates ataxia and improves balance in females with mild-to-moderate multiple sclerosis. *PLoS One* 13(10): e0205382. https://doi.org/10.1371/journal.pone.0205382
41. Earhart GM. 2009. Dance as therapy for individuals with Parkinson disease. *Eur J Phys Rehabil Med* 45(2): 231-238.
42. Young H, Yang H, Lee Y. 2021. Effect of dance on balance, mobility, and activities of daily living in adults with cerebral palsy: a pilot study. *Front Neurol* 12: 663060. https://doi.org/10.3389/fneur.2021.663060
43. Hackney ME, Earhart GM. 2010. Effects of dance on balance and gait in severe Parkinson disease: a case study. *Disabil Rehabil* 32(8): 679-684. https://doi.org/10.3109/09638280903247905
44. Haggard P. 2017. Sense of agency in the human brain. *Nat Rev Neurosci* 18: 196-207. https://doi.org/10.1038/nrn.2017.14
45. Damasio A. 2000. The Feeling of What Happens. In Mariner Books.