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A novel robotic walker for gait training in cerebellar ataxia: crossover design with treadmill therapy

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ABSTRACT

Background: Cerebellar Ataxia (CA) is a condition that impairs motor control, leading to difficulties in gait and balance. Robot-Assisted Gait Training (RAGT) has been used for rehabilitation, but most studies focus on wearable devices and are retrospective, single-arm studies, or case reports. This study evaluates the rehabilitative effects of WALKit Smart Walker, a multifunctional robotic assistive device, compared to Treadmill-Assisted Gait Training (TAGT) in CA patients.

Methods: A crossover study was conducted with seven participants diagnosed with acquired or hereditary CA, out of nine assessed for eligibility. Two blocks of 15 sessions (30 min each) were completed. Functional assessments, namely SARA, 10-MWT, and TUG, were performed before and after each block. Spatiotemporal gait parameters and inter-limb symmetry ratios were analyzed in four participants.

Results: Six participants completed the study. While SARA scale alone was insufficient to compare both interventions, improvements in 10-MWT, TUG, and gait speed were observed for both treatments, with slightly better and more consistent results after RAGT, especially in TUG test. WALKit Smart Walker may enhance gait quality, as most participants improved or maintained inter-limb symmetry ratio of step excursion and time while increasing gait speed. Stance and swing inter-limb symmetry ratio did not benefit from increased speed in either intervention. Usability of WALKit Smart Walker was rated favorably (average SUS $>$ 75 points), indicating technology acceptance.

Conclusion: WALKit Smart Walker shows potential for improving gait speed and inter-limb symmetry ratio of step excursion and time compared to TAGT. Further research with a larger, more homogeneous sample is needed to confirm these findings.

1. Introduction

Cerebellar Ataxia (CA) consists of a heterogeneous group of movement disorders originating on the cerebellum that can affect postural control, balance, and gait coordination [1,2]. These can be acquired due to other conditions (*e.g.*, stroke, cerebral palsy, multiple sclerosis, or tumors, affecting the cerebellum), inherited, with several identified genetic causes, or idiopathic for reasons that are unclear [2,3]. The prevalence of hereditary ataxia varies around the globe and depends on the population's genetics [3]. A systematic review conducted by Ruano et al. [4] reported an average prevalence of 2.7 per 100,000 for autosomal dominant hereditary ataxia and an average of 3.3 per 100,000 for autosomal recessive ataxia. However, regardless of its etiology, CA is a rare and particularly debilitating condition.

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CA is characterized by incoordination of the lower limbs, gait variability, and postural instability, leading to loss of balance and reduced mobility [5]. Ataxic gait is characterized by variable foot placement, decreased step length and gait speed, increased step width, and postural sway [1,6,7]. The latter is particularly present when standing considering both anteroposterior and mediolateral axes [8]. In fact, the literature shows that the increased step width is considered a compensatory mechanism of patients to increase the limits of their base of support, and the reduced step length may be related to another compensatory mechanism to reduce the time of single support [9]. These patients additionally report an increased fear of falling, which contributes to a progressive immobilization [10]. Furthermore, in hereditary and degenerative conditions, gait impairment tends to progress over time, eventually leading to permanent disability [4]. Consequently, the patients' quality of life is highly impacted, affecting their daily life activities and social well-being [7,11].

Given that pharmacological options are limited [1,2,12], rehabilitation becomes the mainstay of treatment. Evidence-based recommendations suggest an intensive rehabilitation program to alleviate their symptoms [1,12]. Additionally, interventions should be personalized and designed to challenge balance while also being engaging and motivating [1]. This in turn requires a great deal of effort and commitment from therapists [13]. Given the growing pressure on healthcare services, these requirements are hard to meet since therapists simultaneously attend to several patients in a constrained time.

Robot-Assisted Gait Training (RAGT) has been growing significantly and playing a pivotal role not only in enhancing the rehabilitation effectiveness but also alleviating the therapists' burden by offering a collaborative and supportive approach [13]. As with other conditions [13,14], RAGT is being introduced in the rehabilitation of patients with ataxia, mainly with the use of wearable devices, such as UAN.GO® [15], Lokomat® [16], Angel Legs M20 [17,18], and curara® [19]. The results have been promising across various studies. Lamberti et al. [15] reported improvements in Scale for the Assessment and Rating of Ataxia (SARA), the Berg Balance Scale (BBS), the 6-Minute Walk Test, and spatiotemporal gait parameters in an adult patient. Belas dos Santos et al. [16] found significant improvements in balance and independence, measured by BBS, the Timed Up and Go (TUG) test, the Functional Independence Measure (FIM), and SARA in cerebellar stroke patients; however, these gains were not significantly different from those achieved with Therapy-Assisted Gait Training. Hong et al. [17] and Yoo et al. [18] reported enhanced gross motor and gait functions in pediatric patients with ataxia. Lastly, Matsushima et al. [19] observed improvements in the 10-Meter Walk Test (10-MWT), 6-Minute Walk Test, and other gait parameters. These results encourage the development and future integration of such devices into health services. However, further studies are still needed to establish RAGT as a complement to conventional therapy in CA, as presented studies are case reports [15,18], single-arm studies [19], or retrospective studies [20]. Thus, controlled studies, as presented in [16], are still needed to reinforce the efficacy of this assisted therapy. Our study aims to address this gap by presenting a crossover study exploring RAGT using a robotic walker designed to address the unique characteristics of gait ataxia.

WALKit Smart Walker, previously known as ASBGo [11,21], is a robotic device under development to address the challenges of ataxic gait variability, trunk instability, and significant loss of balance. Designed for intensive physical rehabilitation, it is adaptable to a wide range of users and rehabilitation stages. Although its development follows a user-centered approach, having been tested on ataxic patients from the very beginning, its validation is still preliminary [21,22]. Therefore, this work presents a crossover study that evaluated the robotic walker considering usability and recovery of motor control in ataxic population, performing benchmark against actual interventions, namely Treadmill-Assisted Gait Training (TAGT). Usability was assessed using the widely recognized System Usability Scale (SUS) [23]. As for motor recovery, this has been evaluated using a standard clinical scale, SARA, functional assessments, namely 10-MWT and TUG tests, which are widely used to verify progress in ataxic population [24,15–20], and by assessing gait quality through a symmetry ratio of gait-related spatiotemporal parameters.

This manuscript is organized as follows: Section 2 presents the materials and methods, briefly presenting the robotic walker, and the methodology followed for its validation with final users; Section 3 presents the results; Section 4 critically discusses these results; and Section 5 presents a brief overview to this manuscript and insights for future research.

2. Materials and methods

This section briefly presents the robotic walker, and the methodology followed to evaluate the effectiveness of this device in gait and balance rehabilitation of patients with CA.

2.1. WALKit smart walker

WALKit Smart Walker is three-wheeled robotic walker designed for gait and balance rehabilitation in patients with balance disorders. Its structure includes a front caster wheel and motorized rear wheels with encoders, offering stability and control. Its mechanical structure features enlarged dimensions to cope with gait variability, while robust materials ensure patient safety and enhance gait stability. The device also includes an ergonomically designed, curved wooden platform to ensure an ergonomic posture and comfort and providing non-adaptive body-weight support, being, therefore, suitable for patients with marked loss of balance. Additionally, the platform is equipped with an electric lift system for easy height adjustment, allowing customization to each patient. Lastly, it is a multifunctional device since it allows: i) assistance in sitting and standing through a remote-controlled electric platform; ii) walking assistance using a mobile platform, which can be operated in manual control, using an ergonomic and user-friendly handlebar, remote control by the physiotherapist when patients lack sufficient dexterity, and autonomous navigation; iii) gait, posture, and balance rehabilitation through repetitive training with possibility to adapt speed in real time; and iv) real-time monitoring through integrated sensors, enabling human–machine interaction strategies such as audiovisual biofeedback and exergames. The device is equipped with a range of sensors, as illustrated in Fig. 1, which can be grouped into three main categories: i) navigation and safety: 9 ultrasonic sensors, an infrared user detector, emergency stop button, and a laser range finder for obstacle detection and autonomous navigation; ii) monitoring: an Inertial Measurement Unit (IMU), placed at L3–L5 level, for trunk sway and postural control, two load cells for posture analysis, and two RGB-D cameras for gait and posture monitoring [25]; and iii) control: a handlebar-mounted IMU to detect user intent and rear-wheel encoders to monitor speed.

2.2. Interventional study

This subsection presents the methodology used to conduct an interventional study with patients diagnosed with CA, both inherited and acquired. The interventional study was performed at 2CA-Braga and involved participants from the Hospital of Braga. The study was approved by the Ethics Committee of the Braga Hospital under reference CESHB-135/2016 (in its final form CEHB 216/2023), according to the Declaration of Helsinki and the Oviedo Convention. All participants provided informed consent to participate in this study.

2.3. Participants

Nine participants were assessed for eligibility. From these, seven (3 males, 4 females) agreed to participate in this study. At the start of the study, the participants had a mean age of 59.3 ± 14.1 years, with ages



Fig. 1. Robotic device used in this study and respective sensors and actuators.

ranging from 37 to 80 years, an average height of 161.9 ± 7.3 cm, and a mean body mass of 66.2 ± 9.1 kg (average Body Mass Index of 25.3 ± 3.7 kg/m^2).

The study was presented to all participants by the medical team. Patients were identified based on the inclusion criteria, namely i) having been diagnosed with CA for more than 3 months; ii) having gait ataxia; and iii) having muscle strength of at least 3 according to the Medical Research Council scale in the hip flexor, knee extensor and ankle dorsiflexor muscles. Patients were excluded if: i) they were unable to understand or cooperate in the study; ii) they had other orthopedic or neurological pathologies that affected their gait; iii) they had cardiovascular or respiratory pathologies that contraindicated physical exercise; and iv) they were unable to maintain the orthostatic position or gait.

Table 1 presents a brief report of all participants that enrolled in the interventional study. In accordance with ethical considerations, participants were not required to suspend their usual treatments.

2.3.1. Clinical protocol

Participants were enrolled in an AB/BA crossover design (see Fig. S1 of Supporting Data), chosen due to the rarity of CA and associated recruitment challenges. This design allowed a controlled trial to be conducted with fewer participants, enabling individual response assessments. Table S1 of Supporting Data presents the sequence of interventions that each participant received.

The protocol consisted of two phases, each including a 15-day intervention period using either the robotic walker or a treadmill, with a washout period of at least three consecutive weeks between phases to minimize potential carry-over effects [26]. Robotic-walker sessions were conducted in the corridor of 2CA-Braga along a predefined U-shaped circuit, while treadmill sessions were performed in manual mode without elevation. All training sessions were standardized by duration, consisting of 30 min of gait therapy.

Walking speed was individually adapted for each participant during every session, with the supervising physiotherapist adjusting speed based on performance and fatigue. For the robotic walker, speed was additionally limited by the device's maximum of 3.5 km/h. Table S2 of Supporting Data summarizes the range of walking speeds applied to each participant throughout the study phases. All participants were able to operate the robotic walker manually using the handlebar.

Lastly, assessment sessions were conducted at the start and end of each 15-day intervention block, *i.e.*, day 0 and day 16, including clinical scale evaluations and gait data acquisition.

2.3.2. Participant instrumentation

Before and after each block of sessions, participants were instrumented with an inertial motion capture system, the Xsens Awinda (Movella, USA, validated in [27]), in a full-body configuration with seventeen IMUs placed on the head, both shoulders, sternum, upper arms, forearms, wrist, pelvis, thigh, shin, and feet. Each of these sensors was positioned according to the manufacturer's guidelines [28], and were always placed by the same researcher, ensuring repeatability. Data

Table 1
General overview of all participants of this interventional study. CIS: Cerebellar Ischemic Stroke; MSA-C: Multiple System Atrophy - Cerebellar type, CPA: Cerebellar Pilocytic Astrocytoma; SCA8: SpinoCerebellar Ataxia Type 8; MC: Mitochondrial Cytopathy; TBI: Traumatic Brain Injury; SCI: Spinal Cord Injury.

Characteristic	Participants							Mean (±std)
	P1	P2	P3	P4	P5	P6	P7	
Gender	Male	Female	Female	Male	Female	Female	Male	–
Age	59	66	37	80	55	49	69	59.29 ± 14.08
Body height (cm)	169	158	160	164	160	150	172	161.86 ± 7.31
Body mass (kg)	69	50	72	68	79	61	64.4	66.20 ± 9.14
BMI (kg/m^2)	24.2	20	28.1	25.3	30.9	27.1	21.8	25.34 ± 3.74
Diagnose	CIS	MSA-C	CPA	Cerebellar Atrophy	SC8	CA caused by MC	CA caused by TBI and SCI	–

collection was performed at 60 Hz.

2.3.3. Data collection

Participants were evaluated before and after each intervention (pre/post) of each intervention using a clinical scale, functional assessments, and gait-related spatiotemporal parameters.

Regarding the clinical scale, the SARA score was used [29], which was administered by blind residents from the Physical Medicine and Rehabilitation Department of Hospital of Braga. This scale covers gait, stance, sitting, speech, finger chase, nose-finger test, rapid alternating hand movements, and heel-shin exercise [30]. This study specifically examined the gait, stance, and sitting sub-scores, each with a maximum score of 8, 6, and 4 points, respectively, as these are key indicators for assessing the impact of both RAGT and TAGT. Higher values reflect greater severity of ataxia.

Functional assessments included the 10-MWT and TUG test, following [31,32], conducted by the same researcher with therapist support. Each participant performed three trials at a comfortable speed using their walking aids if needed. The 10-MWT assessed gait speed and spatiotemporal parameters using floor markings at 0, 2, 8, and 10 m, with timing between 2 and 8 m. The TUG test, based on [33], involved standing from a chair, walking 3 m, turning, returning, and sitting, while time was recorded by the researcher. This is a reliable scale for assessing mobility and measuring fall risk [34].

Gait-related spatiotemporal parameters, including stride and step excursion, stride and step time, and stance and swing time, were calculated on both assessment days. An inter-limb symmetry ratio was calculated and evaluated on both assessment days, as presented in studies [35,36].

Lastly, to validate the robotic walker regarding easy-of-use, participants were asked to evaluate give their perception by answering the SUS questionnaire [23], translated into Portuguese language [37].

2.3.4. Data processing and analysis

Clinical scale sub-scores were compared between days 0 and 16. For the 10-MWT, walking speed (m/s) was calculated using the central 6 m, as described in [31]. Mean and standard deviation of three trials were computed for 10-MWT and TUG times and gait speed. To reduce the effect of population heterogeneity, post-training data were normalized to pre-training (baseline = 1.0): value equal to 1.0 indicate no change; <1.0, a decrease; >1.0, an increase.

Gait spatiotemporal data were collected using Xsens Awinda. Due to possible electromagnetic interference that could affect absolute spatial positions, which sometimes causes cumulative horizontal drift, system calibration was always performed in the evaluation environment, and both stride and step excursions were computed as Euclidean distances to account for sagittal and frontal plane movement, minimizing drift effects. Step width was indirectly included in step excursion. Temporal parameters, which were unaffected by interference, were calculated from segmented gait cycles using heel-strike and toe-off events.

Gait symmetry was assessed using the inter-limb symmetry ratio [35,36]. To standardize interpretation, symmetry ratio was calculated considering the technique proposed by Patterson et al. [36], using the higher limb value as the numerator and a sign indicating which of the measures is higher (right foot: positive sign; left foot: negative sign). In this work, only the absolute value was used. A value of 1.0 reflects perfect symmetry; much higher values indicate asymmetry.

All data were processed in MATLAB R2023b (MathWorks®, California, USA) and analyzed using GraphPad Prism 8.4 (GraphPad Software, Inc., Massachusetts, USA). Statistical tests were not applied due to the heterogeneity of the population and the limited number of participants.

3. Results

Fig. 2 presents the flow chart of this study. Of the nine patients assessed for eligibility, seven agreed to enroll. Of these, six completed successfully the study, while one (P2) was excluded due to behavioral changes caused by the progression of her condition, which at times prevented her from cooperating effectively. This section outlines the key results of this study, organized by each rehabilitation outcome.

3.1. Scale for the assessment and rating of ataxia (SARA)

Table 2 presents the SARA specific sub-scores obtained for the six participants considering both assessment days and for both RAGT and

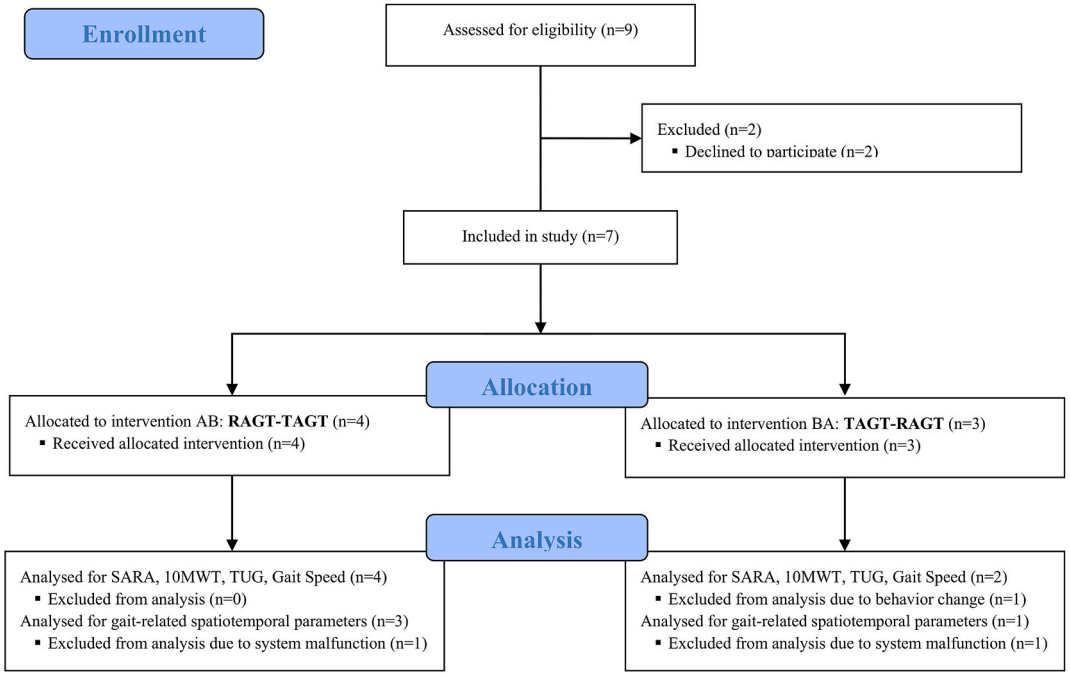

Fig. 2. Flow chart of the crossover study.

Table 2
SARA sub-scores of gait, stance, and sitting balance for both RAGT and TAGT. A negative post-training variation represents improvement, a positive variation represents deterioration, and a zero value represents no change.

Participant	Intervention	Gait		Variation	Stance		Variation	Sitting		Variation
		Pre	Post		Pre	Post		Pre	Post	
P1	RAGT	4	4	0	2	2	0	0	0	0
	TAGT	3	2	−1	2	2	0	0	0	0
P3	RAGT	6	6	0	4	5	1	0	0	0
	TAGT	6	6	0	2	3	1	1	0	−1
P4	RAGT	6	6	0	2	2	0	0	1	1
	TAGT	6	6	0	4	4	0	0	0	0
P5	RAGT	2	3	1	1	1	0	0	0	0
	TAGT	2	2	0	1	1	0	0	0	0
P6	RAGT	6	5	−1	4	3	−1	1	0	−1
	TAGT	6	6	0	1	3	2	1	0	−1
P7	RAGT	6	5	−1	3	3	0	0	0	0
	TAGT	6	6	0	2	3	1	0	0	0

TAGT. To further clarify the findings, the table displays the changes observed between assessment days. A negative variation represents a post-training improvement.

Regarding RAGT, most participants showed minimal changes in SARA sub-scores, with improvements noted primarily in P6 and P7, who each demonstrated a 1-point decrease in gait sub-score, suggesting enhanced mobility. P6 also improved in stance and sitting sub-scores, while P7 maintained these scores. Other participants either showed no change (P1, P3, P4) or a 1-point increase in sub-scores. Regarding TAGT, this type of intervention appeared to be benefic for P1 considering gait sub-score, and P3 and P6 considering sitting sub-score. However, P3 reported an increase of 1 point in stance sub-score, from 2 to 3 points, and P6 presented an increase of 2 points on stance sub-score. Finally, P7 maintained his score of gait and sitting, but an increase of 1 point was observed in stance sub-score.

3.2. 10-meter walk test and gait speed

To further evaluate motor outcomes from RAGT and TAGT, all participants completed the 10-MWT, though some required assistive devices on both assessment days for both interventions. P3 used crutches, P4 used a standard walker, and P6 used her usual four-wheeled walker.

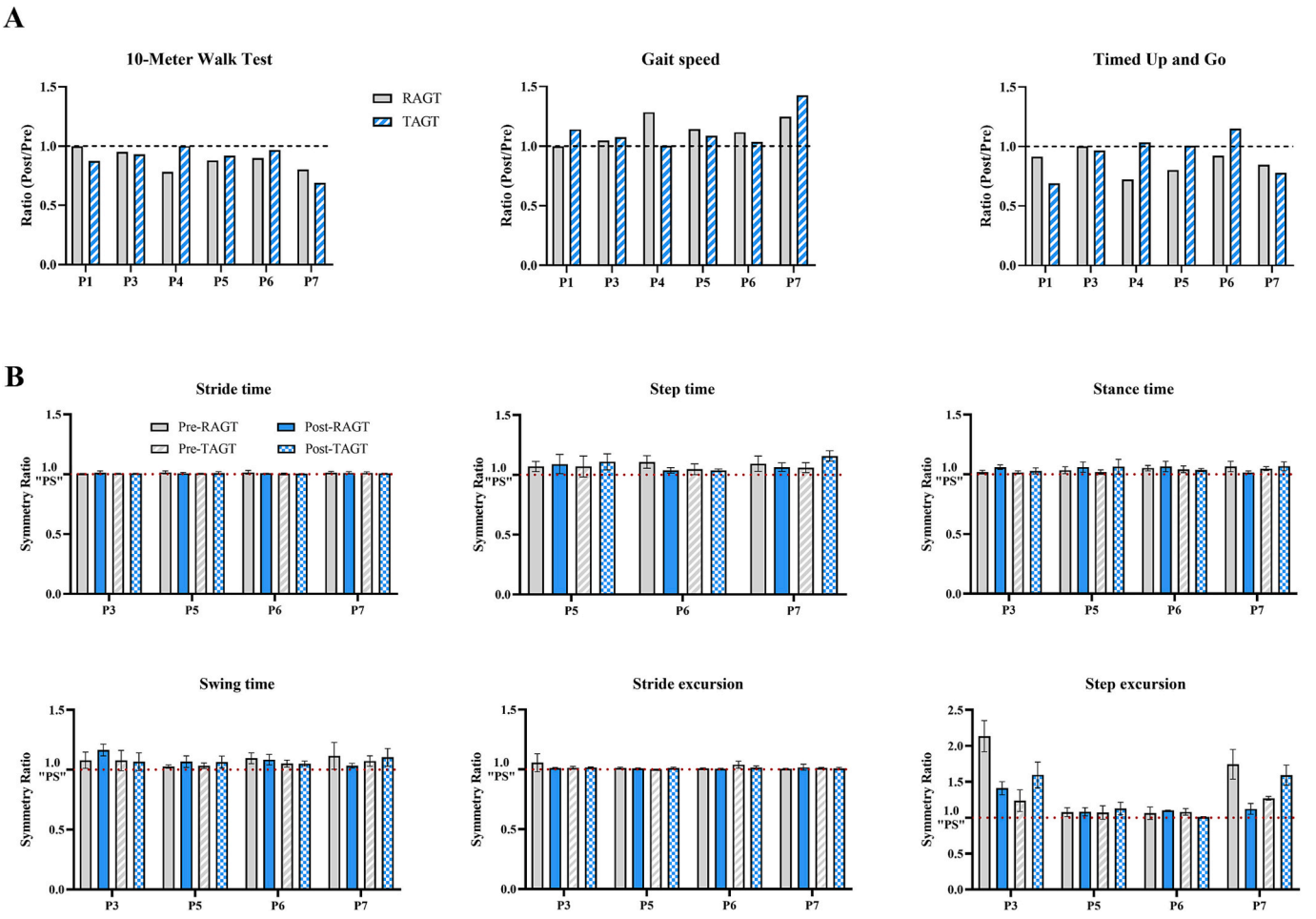

Fig. 3. Comparison between RAGT and TAGT: A. ratio obtained for 10-MWT, gait speed, and TUG; B. ratio obtained for each gait-related spatiotemporal parameter.

P1, who normally uses a two-wheeled walker, completed the test without assistance. P7 completed the test without a device but received light arm support from the therapist, who remained on the side so as not to interfere with the participant's cadence.

Post-training results have been normalized to pre-training, expressing a ratio. A ratio lower than 1.0 for the time needed to complete the test indicates that participants were able to complete the test more quickly, thus increasing their walking speed (considering the same six meters). Fig. 3A presents the 10-MWT and the gait speed ratios obtained for each participant and considering both RAGT and TAGT. Absolute average values can be found in Supporting Data, Table S3.

Both interventions led to improved 10-MWT completion times. For RAGT, most participants showed ratios below 1.0 (mean 0.88 ± 0.08), indicating faster performance. P1 showed no change (1.00), while the greatest improvement was seen in P4 (0.78); P3, P5, P6, and P7 had ratios of 0.95, 0.88, 0.90, and 0.80, respectively. TAGT also yielded improvements for all but P4 (1.00), with P1, P3, P5, P6, and P7 showing ratios of 0.87, 0.93, 0.92, 0.97, and 0.69.

Improvements in 10-MWT times corresponded to increased gait speed. RAGT led to a notable average speed gain (1.14 ± 0.11), presented in Fig. 3A, with all participants except P1 exceeding a 5% increase. P3 to P7 showed ratios of 1.05, 1.28, 1.14, 1.12, and 1.25. TAGT also improved gait speed (1.13 ± 0.15), though only P1 (1.14) and P7 (1.43) surpassed considerable their RAGT gains. The remaining participants, namely P3, P4, P5, and P6 reported ratios of 1.08, 1.00, 1.09, and 1.03, respectively.

3.3. Timed up and go

Similar to the 10-MWT and gait speed, the pos-training time of TUG test was normalized to pre-training. Therefore, a value below 1.0 after training represents an improvement in mobility and functionality. Fig. 3A also illustrates the gain in TUG observed after RAGT and TAGT. Absolute average values can be found in Supporting Data, Table S3.

Most participants reported an improvement in TUG after RAGT, with improvements that range from 8% to 28%, except for P3, who maintained her time. Participants P1, P4, P5, P6, and P7 presented ratios of 0.91, 0.72, 0.80, 0.92, and 0.85. As for TAGT, participants P1 and P7 showed higher improvements, similarly to what has been observed in gait speed, presenting ratios of 0.69 and 0.78, respectively. Moreover, P3 also reported a slight improvement, with a ratio of 0.97. As for participants P4 and P5, these reported a slight increase in ratio (1.03 and 1.01, respectively), while P6 reported a more evident increase (1.15).

3.4. Gait quality

Although improvements were seen in gait speed, inter-limb gait symmetry should be analyzed, as it is considered an indicator of gait quality [38]. A symmetry ratio was calculated following study [36]. A perfect symmetry ratio is obtained when the ratio is 1.0, but not even healthy individuals present this value [39]. Patterson et al. [36] defined normative values by considering the 95% confidence interval for each metric calculated for a healthy group: 1.08 was defined for step length, and 1.05 and 1.06 for stance and swing phase durations, respectively [36,39].

Fig. 3B summarizes the overall results regarding both spatial and temporal parameters. Although participants P1 and P4 completed the interventional study, technical issues were identified with the data from at least one intervention period, so these patients were not included in this analysis. The mean and standard deviation values are presented in Supporting Data, Table S5.

3.4.1. Temporal parameters

Regarding stride time, the results show a symmetry between the right and left foot at both assessment days, and this was consistent across participants. Moreover, this conclusion is valid for either RAGT (pre-training: 1.01 ± 0.005, post-training: 1.01 ± 0.003) and TAGT (pre- and post-training: 1.01 ± 0.002). All participants reported similar stride times for both feet, as also can be observed in Table S5 of Supporting Data. In terms of absolute values, all participants, except for P7, presented decreases in stride time, ranging from 1% to 7%, that are consistent with the observed increase in gait speed. This result suggests that stride length probably increased or was maintained over a shorter period.

The same analysis was performed for step time. However, for this analysis, only participants P5, P6, and P7 were included. P3 was not included because the step time of the right foot is influenced by the time required to move the crutches forward. This participant advanced the crutches one at a time before initiating gait with her right foot. Therefore, considering this time for the symmetry analysis would affect the results and would always indicate an asymmetric time, visible in Table S5 of Supporting Data. Although this is a systematic factor, the time needed to project the crutches forward is variable, thus removing this time would introduce additional error. Regarding the remaining participants, P6 and P7 showed improvements in the symmetry ratio after training with the robotic walker: i) P6 presented a decrease from 1.11 ± 0.04 to 1.04 ± 0.02, and ii) P7 presented a decrease from 1.09 ± 0.05 to 1.06 ± 0.03. As for P5, a slight increase of the symmetry ratio was observed, from 1.07 ± 0.03 to 1.09 ± 0.07. However, if one examines the average step time presented in Table S5 of Supporting Data, the values became more consistent after RAGT.

Regarding TAGT, two participants (P5 and P7) reported an increase in the symmetry ratio. P5 presented an increase of symmetry ratio from 1.07 ± 0.07 to 1.11 ± 0.06. As for P7, a more notorious increase from 1.06 ± 0.03 to 1.16 ± 0.04 was observed. Finally, for P6, the symmetry ratio was practically maintained. These results suggest that the robotic walker was more effective in terms of improving the step time symmetry ratio for P6 and P7. As for P5, both interventions appeared to worsen the symmetry ratio, but this was more evident for TAGT.

Regarding the stance time, all participants, except for P7, increased slightly their symmetry ratio to close to 1.06/1.07 after RAGT. P3 reported an increase in her symmetry ratio from 1.02 ± 0.01 to 1.06 ± 0.02, P5 from 1.03 ± 0.02 to 1.06 ± 0.02, and P6 from 1.05 ± 0.02 to 1.07 ± 0.04. On average, the value remains close to the threshold for symmetry (1.05), though it is unclear whether this slight deviation holds clinical significance. Table S5 of Supporting Data shows a generalized decrease in stance time after training, which aligns with the observed increase in gait speed but may have contributed to unexpected variations in the symmetry ratio. On the other hand, P7 revealed an improvement in stance time symmetry ratio, from 1.07 ± 0.04 to 1.02 ± 0.01.

Regarding TAGT, P5 and P7 reported an increase of stance time symmetry ratio, from 1.02 ± 0.01 to 1.06 ± 0.05 for P5, and 1.05 ± 0.01 to 1.07 ± 0.03 for P7. The remaining participants maintained their inter-limb symmetry ratio for this specific temporal parameter.

As for the swing time symmetry ratio, the results show that RAGT was beneficial for participants P6 and P7, since both decreased their symmetry ratio. However, for P6, swing time remained asymmetric (pre-training: 1.10 ± 0.04, post-training: 1.08 ± 0.04) considering the threshold proposed in [36], although close to be considered symmetric (1.06). As for P7, swing symmetry ratio improved from 1.12 ± 0.09 to 1.03 ± 0.02, becoming symmetric. On the other hand, P3 and P5 revealed increases in the swing time SR: P3 revealed a more expressive increase, from 1.08 ± 0.06 to 1.16 ± 0.04, and P5 reported an increase from 1.03 ± 0.01 to 1.07 ± 0.04.

The results obtained for TAGT reveal that P3 registered practically no change in the swing time symmetry ratio (pre-training: 1.08 ± 0.07, post-training: 1.07 ± 0.06), P5 slightly increased the symmetry ratio (pre-training: 1.03 ± 0.02, post-training: 1.06 ± 0.04), similarly to what was found after RAGT, P6 maintained her symmetry ratio (pre-training: 1.05 ± 0.02, post-training: 1.05 ± 0.02), and P7 slightly increased the symmetry ratio that was already above the limit (pre-training: 1.07 ±

0.04, post-training: 1.10 ± 0.06).

3.4.2. Spatial parameters

Gait symmetry was also evaluated considering spatial metrics, namely stride and step excursion. As shown in Fig. 3B, stride excursion was considered symmetrical, and this result is consistent for all participants. An average symmetry ratio of 1.02 ± 0.02 and 1.01 ± 0.01 were found for pre- and post-training, respectively, considering RAGT. A careful analysis to Fig. 3B reveals that the very slight decrease was motivated by an improvement observed for P3 who presented a pre-training symmetry ratio of 1.06 ± 0.06 and 1.01 ± 0.003 post-training. As for TAGT, the symmetry ratio of stride excursion was also similar between assessment days, except for P6 who decreased her symmetry ratio from 1.04 ± 0.02 to 1.02 ± 0.01.

Step excursion was also evaluated for both interventions. P3 revealed an expressive improvement of step excursion symmetry ratio after RAGT (pre-training: 2.13 ± 0.18, post-training: 1.41 ± 0.08). P7 also revealed an important improvement in step excursion after training (pre-training: 1.74 ± 0.17, post-training: 1.12 ± 0.06). As for participants P5 and P6, P5 revealed no change (pre-training: 1.08 ± 0.05, post-training: 1.08 ± 0.05) and P6 revealed a slight increase after training (pre-training: 1.06 ± 0.07, post-training: 1.10).

Regarding TAGT, there was an overall increase in the SR. In fact, only P6 revealed a decrease in the symmetry ratio and for a value very close to 1.0 (pre-training: 1.08 ± 0.04; post-training: 1.01 ± 0.01).

3.5. Usability and acceptability

In addition to assessing the potential gain in motor rehabilitation, the device was evaluated for its usability and acceptability using the SUS questionnaire [23,37]. Fig. 4 shows a radar graph with the average score for each question. A positive score of 5 points is expected for the odd-numbered questions, while a score close to 1 point is expected for the even-numbered questions, indicating that a star-shaped radar graph would reflect an excellent usability assessment. SUS results per question and participants are presented in Supporting Data, Table S6.

The results reveal that participants felt confident using the system (Q9: 4.5 points), and they found it easy to use and well-integrated (Q3: 4.5 points, Q7: 4.33 points). However, users tended to be neutral when asked if the system was more complex than necessary (Q2: 2.83 points), if they would need help from a technician to use the system (Q4: 3.33 points), or if they had to learn a lot before being able to handle the system (Q10: 2.5 points). Overall, patients consider the device functional, with scores ranging from 57.5 points to 90 points, as presented in Table S6. The average score was 75.42 ± 11.00 points, classifying the device as good and acceptable (maximum of the acceptability grade), considering the acceptability scale proposed in [40].

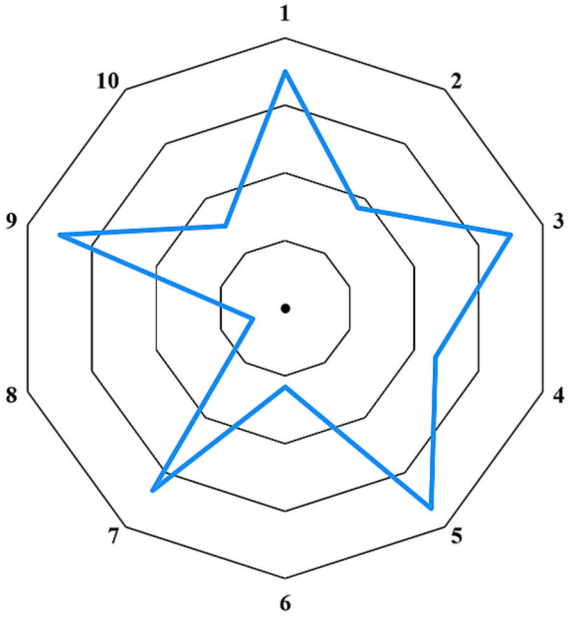

Fig. 4. Average score per question on the SUS questionnaire, based on responses from the six participants. The scale ranges from 1 to 5, represented from the center outward.

4. Discussion

The use of RAGT in the rehabilitation of patients with impaired mobility is still an active area of research. RAGT has been investigated in the rehabilitation of individuals with mobility impairments resulting from various neurological conditions, including stroke, Parkinson's disease, spinal cord injury, and cerebral palsy [19]. In the context of stroke rehabilitation, the literature has demonstrated significant improvements in gait performance and functional capacity, but a clear consensus regarding its implementation in clinical practice has yet to be established [41]. Its application in the rehabilitation of patients with CA has also been investigated [15–19], but current evidence remains limited [42]. Despite this, the available evidence suggests that RAGT may provide beneficial effects on gait performance, particularly with respect to gait, mobility, and balance.

This study presents a crossover intervention study using WALKit Smart Walker, a robotic walker specifically developed to support motor rehabilitation in individuals with ataxia. To the best of the authors' knowledge, this is the first crossover study investigating a robotic walker-based intervention specifically designed for individuals with CA, while also directly comparing its effects with treadmill-based gait training. Due to the low number of participants and their heterogeneity, a patient-by-patient analysis was deemed appropriate to interpret the results and draw overall conclusions.

Considering the SARA scale, the findings suggest broadly comparable effects between RAGT and TAGT on SARA outcomes. The results suggest that the robotic walker appeared to be more effective than the treadmill only for participants P6 and P7 regarding gait sub-score. Still, in cases where an improvement or no change was found in stance sub-score after RAGT (P6 and P7), these patients presented a deterioration in TAGT. As for sitting sub-score, the results suggest that TAGT appeared to be slightly better than RAGT. However, the reported differences were not so pronounced (typically 1 point), which may represent clinically meaningful changes, but could also be influenced by inter-rater variability, as different evaluators assessed participants at each time point. Ideally, multiple blinded assessors should provide average SARA scores. Furthermore, patient fluctuations may also be related to the symptomatic variability shown on different days, which is influenced by the patients' state of mind or tiredness. To mitigate this issue, future studies should include intermediate (*e.g.*, day 8) and daily assessments to better track progress and reduce variability.

The SARA scale alone was insufficient to fully characterize the effects of the interventions. To complement it, 10-MWT, TUG, gait speed, and inter-limb symmetry ratio were assessed. Some participants showed greater improvements when using the robotic walker, while others responded better to treadmill training. Despite this variability, both interventions generally led to improvements in the 10-MWT, indicating an overall enhancement in gait speed. In addition, both treatments were associated with improvements in TUG, which assesses functional mobility, including standing, walking, and turning. Notably, the robotic walker appeared to provide greater improvements in TUG performance, suggesting that it may offer additional benefits in transitional movements.

These findings may be related to the specific characteristics of overground robotic walker-assisted training. Unlike treadmill-based interventions, the proposed robotic walker allows patients to perform gait initiation, stopping, turning, and transitional movements within a

more ecological environment. In addition, the continuous physical support provided by the walker may enhance postural stability and increase patients' confidence during locomotion, potentially reducing fear of falling and encouraging more symmetrical and functional gait patterns. Furthermore, the overground nature of the intervention may promote greater variability and adaptability of gait compared to treadmill-based training, which typically constrains gait speed and movement patterns. This may be particularly relevant in CA, where deficits in motor coordination and dynamic balance strongly affect gait adaptability during real-world locomotion. This may be particularly important for translating rehabilitation gains into activities of daily living, where patients must continuously adapt gait patterns to variable environmental demands.

In addition to these findings, it is important to analyze changes in the symmetry ratio alongside improvements in gait speed, as this provides a more comprehensive indication of overall gait quality. Clinically, increases in gait speed may be particularly meaningful when accompanied by improvements in gait symmetry. Achieving this combination, however, can be particularly challenging for patients with CA, due to their characteristic gait incoordination and difficulty in maintaining balanced and coordinated movements. Based on the results, there is an overall tendency toward a reduction in the symmetry ratio of step excursion after RAGT, mainly driven by improvements in P3 and P7, and a relative stabilization in P5 and P6. Although P6 showed a slight increase in the ratio, its clinical relevance remains uncertain. Regarding P3, although improvements were observed, gait asymmetry remained pronounced, likely reflecting the persistence of compensatory gait strategies associated with assistive-device use and underlying postural instability. This highlights the complexity of gait rehabilitation in CA, where increases in gait speed do not necessarily translate into fully normalized gait patterns. In terms of symmetry ratio of step time, a tendency for improvement was also observed after training with the robotic walker, particularly for P6 and P7, who showed improvements in this outcome. Moreover, regarding P7, although a substantial improvement in gait speed was observed after treadmill training, this was accompanied by increased asymmetry in step excursion and step time, indicating reduced gait quality. In contrast, RAGT resulted in a smaller yet substantial speed increase and improved inter-limb symmetry of both step excursion and step time. Although the latter improvement is small, the average step times became more balanced, as presented in Table S5 of Supporting Data. Considering the symmetry ratio obtained by the average step times, the gait could be considered closer to symmetrical; thus, the overall average symmetry ratio might also be close to the threshold for being considered symmetrical. Additionally, improvements in stance and swing symmetry ratios after RAGT further support enhanced gait quality.

Our findings align closely with the existing literature supporting the use of RAGT in individuals with ataxia. In particular, our results are consistent with those reported by Belas dos Santos et al. [16], who evaluated Lokomat-based RAGT in individuals with post-stroke ataxia and observed improvements in clinical and functional outcomes. Similarly, Son et al. [20] performed a retrospective study investigating exoskeleton-based RAGT in patients with ataxic and hemiplegic stroke, reporting overall improvements in gait and functional outcomes, further supporting the potential utility of robotic interventions in post-stroke ataxia.

Additional evidence from wearable robotic systems also corroborates our findings. Matsushima et al. [19] reported that training with the curara wearable robot was associated with improvements in gait performance in individuals with degenerative CA, highlighting the feasibility of non-exoskeletal assistive technologies in this population. Likewise, case-based reports further reinforce these observations. Lamberti et al. [15] described improvements in gait and functional mobility following robot-assisted gait training in a patient with ataxia, while Yoo et al. [18] reported functional gains after overground robot-assisted gait training in a child with ataxic cerebral palsy. Although our findings are generally aligned with previous studies reporting improvements following robotic gait interventions in ataxia populations [15,16,18–20], important differences between the proposed approach and previous systems should be considered. Most previous studies focused either on treadmill-based robotic systems, such as Lokomat, or wearable exoskeletons designed primarily for lower-limb actuation, frequently in post-stroke or pediatric ataxic populations. In contrast, the proposed robotic walker provides overground assistance combined with continuous upper-limb support and dynamic stabilization, potentially offering a rehabilitation environment that more closely resembles daily-life locomotion and that is specifically tailored to the instability and variability associated with *CA*.

Collectively, these findings indicate that our results are aligned with the emerging evidence supporting the use of robotic gait interventions to improve gait performance, mobility, and functional capacity across different ataxia populations. Our study further extends the current evidence by evaluating a novel robotic walker specifically designed to accommodate the instability and variability of ataxic gait. Although the sample size was limited, most participants showed functional gains, with some responding better to RAGT than treadmill training. These preliminary results support the potential clinical utility of the proposed robotic walker, though larger and more homogeneous studies are still needed to confirm efficacy. Moreover, direct comparisons across studies remain challenging due to differences in patient populations, intervention protocols, robotic technologies, and outcome measures.

Lastly, regarding the usability scores, the results with users with CA reveal high levels of usability and technology acceptability, with an average score of 75 points (out of 100) on the SUS scale. This result classifies the device as “Good” and “Acceptable” [40]. Patients reported, however, some shortcomings, namely: i) the elbow pads that they found to be very hard, causing discomfort with prolonged use, and ii) they considered that the handlebar occasionally began to cause discomfort to the hands. Future work should consider improving these aspects to achieve usability levels above 85 points, translating to excellent usability. Despite these minor limitations, patients reported a high level of satisfaction with the treatment, as reflected in the first item of the SUS. The responses indicate that patients were generally satisfied and expressed a willingness to use the device regularly, likely because it enhanced their sense of safety while walking.

Overall, although preliminary and limited by the small heterogeneous sample, the present findings support the feasibility, usability, and potential clinical relevance of robotic walker-assisted gait training for individuals with CA, while reinforcing the need for larger controlled studies to establish efficacy and identify patient profiles most likely to benefit from this intervention.

5. Conclusion

This work presents the first crossover interventional study using WALKit Smart Walker, a multifunctional robotic device for gait and balance rehabilitation in *CA*. The aim of this study was to use RAGT in patients with CA, and to further compare the rehabilitative gain with that obtained with TAGT. Therefore, a total of six participants diagnosed with CA agreed to participate in and completed this intervention study, which included two blocks of 15 daily sessions with a maximum of 30 min of RAGT or TAGT. The SARA sub-scales of gait, stance, and sitting were assessed, and the 10-MWT and TUG tests were used. From the 10-MWT, gait-related spatiotemporal parameters were extracted, and an inter-limb symmetry ratio was calculated for a total of four of the six patients. The results from SARA suggest improvements in gait for two participants and practically no change in stance and sitting sub-scores for RAGT. However, SARA scale alone revealed insufficient to conclude if RAGT is comparable, superior, or inferior to TAGT. Regarding 10-MWT and TUG, improvements were observed post-training for both interventions, but this was slightly more evident after RAGT for TUG test. Moreover, the robotic walker generally

provided an improvement in gait quality in terms of inter-limb symmetry ratio of step excursion and time, while increasing gait speed, which was not fully observed with TAGT. Finally, six participants evaluated the robotic device for ease of use and functionality, and an overall score of 75 points was reported. Overall, these results suggest that WALKit Smart Walker may be effective for gait rehabilitation and may promote a more physiological improvement of gait speed.

5.1. Limitation and future research insights

This study has some limitations that should be considered in future research. An attempt should be made to increase the number of participants in the study and to create more homogeneous groups. In addition, it would be interesting to evaluate the effects of the robotic walker on the hereditary and acquired ataxia groups separately. As the number of participants increases and more homogeneous groups are considered, statistical tests could be applied to verify the significance of the gain in rehabilitation. Finally, interim assessments should be considered throughout the study, as well as short daily assessments, to increase the power of the results.

CRediT authorship contribution statement

João M. Lopes: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Catarina Matias:** Writing – review & editing, Validation, Methodology, Conceptualization. **Cristina Cruz:** Writing – review & editing, Validation, Supervision, Methodology. **Tânia Pereira:** Writing – review & editing, Investigation. **João Cerqueira:** Writing – review & editing, Validation, Methodology, Conceptualization. **Cristina P. Santos:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial or personal relationships that could be viewed as influencing the work reported in this paper.

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Appendix A. Supplementary data

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