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Augmented reality active video game for gait rehabilitation after surgery in adolescents with cerebral palsy: A randomized controlled trial

Anne-Laure Guinet

anne-laure.guinet@univ-grenoble-alpes.fr

Université Grenoble Alpes

Guillaume Bouyer

Université d'Évry Val-d'Essonne

Samir Otmane

Université d'Évry Val-d'Essonne

Neijib Khouri

Hôpital Necker-Enfants Malades

Farah Ayoubi

Fondation Ellen Poidatz

Eric Desailly

Fondation Ellen Poidatz

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Augmented reality active video game for gait rehabilitation after surgery in adolescents with cerebral palsy: A randomized controlled trial

Anne-Laure Guinet, Guillaume Bouyer, Samir Otmane, Neijib Khouri, Farah Ayoubi, Eric Desailly

***Abstract*—Rehabilitation after single-event multilevel surgery (SEMLS) in children with cerebral palsy (CP) is heterogeneous, and treadmill training, although standard, often lacks enjoyment. We compared ARRoW-CP, an augmented reality active video game for overground gait training, with treadmill training in adolescents with CP after SEMLS. In this randomized controlled trial, participants aged 12–18 years (Gross Motor Function Classification System levels I–III) completed three sessions per week for four weeks in addition to usual rehabilitation. Outcomes were the 6-Minute Walk Test (6MWT), the Muscle Power Sprint Test (MPST), and enjoyment (Physical Activity Enjoyment Scale, PACES). Equivalence was assessed with analysis of covariance and Two One-Sided Tests using predefined clinical margins. Twenty-five participants completed the study (ARRoW-CP, n = 13; Control, n = 12). The 6MWT distance increased by 102.4 ± 77.8 m with ARRoW-CP and 90.8 ± 93.4 m with treadmill training (adjusted difference −16.1 m; 95% CI −87.2 to 55.1), and more than 80% of participants in each group exceeded the minimal clinically important difference. Formal equivalence was shown for MPST best speed but not for the 6MWT or MPST mean speed (adjusted difference 0.102 m/s; 95% CI −0.037 to 0.241), mainly because of wide confidence intervals. Enjoyment was significantly higher with ARRoW-CP (PACES 66.1 ± 9.2 vs 55.6 ± 7.9; p = 0.008; Cohen's d = 1.21). ARRoW-CP produced improvements in walking capacity and sprint performance comparable to treadmill training while being substantially more enjoyable, supporting augmented reality overground training as an engaging option for adolescents with CP.**

***Index Terms*—Active video games, augmented reality, cerebral palsy, gait rehabilitation, randomized controlled trial, single-event multilevel surgery, treadmill training**

I. Introduction

Cerebral palsy (CP) is the leading cause of motor disability in childhood and often results in persistent limitations in walking capacity, contributing to restrictions in daily participation [1]–[3]. Among the available therapeutic strategies, single-event multilevel surgery (SEMLS) is recognized as an effective intervention to improve musculoskeletal alignment, gait kinematics, and functional outcomes [4], [5]. However, postoperative improvements in gross motor function and participation remain heterogeneous, particularly when rehabilitation is not delivered through a structured and sufficiently intensive approach [6], [7].

A recent systematic review shows that rehabilitation following SEMLS in individuals with cerebral palsy is disparate, with considerable variability in rehabilitation modalities, content, and intensity, as well as several practical challenges, including postoperative pain [8]. Postoperative rehabilitation lasts on average 4.5 months, typically involves four sessions per week, and most often occurs in rehabilitation centers. The authors emphasize the importance of incorporating structured strength training and intensive gait training in such postoperative protocols. In particular, therapies integrating high-intensity functional gait training demonstrate benefits for improving walking speed, physical fitness, and global motor performance [9], [10].

Treadmill gait training is a standard to improve walking capacity and endurance [11]. It is a well-established post-SEMLS rehabilitation approach to improve 6-minute walking test distances. For example, Grecco et al. demonstrated an improvement from 227.4 ± 49.4 m to 377.2 ± 93.0 m [12]. However, limitations are reported concerning its ecological validity, the constrained nature of treadmill walking, and the generally low motivation and enjoyment observed among adolescents [13].

In recent years, other methods have been explored to tackle these limitations. In particular, interventions based on active video games (AVGs) or immersive technologies like virtual and augmented reality are gaining increasing interest [14] and show benefits for lower limb rehabilitation in elderly adults, stroke, and Parkinson populations [15], [16] and patients with CP [17]. These interactive systems typically provide visual cues such as virtual footprints, obstacles, or avatars to guide walking patterns. They address the problems of low enjoyment, limited engagement, and reduced motivation reported with conventional training [18]. They are also more suited than treadmills to allow task-oriented interventions in ecological situations, incorporate variable practice, and provide augmented feedback on the results or the performance [19]. All these components are known to be essential for motor learning and for supporting adherence to therapy and recovery in young patients [20]–[22].

Despite growing interest in these systems, to our knowledge, no AR-based active video game has yet been designed specifically for overground, high-intensity gait training with augmented feedback in the context of post-SEMLS rehabilitation of children. To address this gap, we develop ARRoW-CP, an augmented reality active video game (AR-AVG) for children with CP, providing overground gait training

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with audio and visual feedback based on the patient's performance. ARRoW-CP has been developed through a user-centered design process involving therapists and patients [23]. After several preliminary trials that demonstrated the system's feasibility and clinical potential and helped us identify the most relevant augmented feedback [24], [25], we evaluated the impact of ARRoW-CP through a randomized controlled trial (RCT).

The full protocol of this RCT has been published previously [26]. This study compares overground gait training using ARRoW-CP to treadmill training in adolescents with CP following SEMLS. Treadmill training was chosen as the control because it is a well-established and validated approach to rehabilitation after SEMLS [12]. The AR-AVG ARRoW-CP incorporates intensive gait training adapted from a previously validated protocol for this population [10]. The measured outcomes are walking capacity with the 6-minute walking test (6MWT) [27], anaerobic performance with the Muscle Power Sprint Test (MPST) [28], and enjoyment using the Physical Activity Enjoyment Scale (PACES) [29].

The hypothesis is that AR-AVG ARRoW-CP would be at least as effective as treadmill training, while providing a more joyful experience. This article presents the complete results of the RCT.

II. Methods

A. The ARRoW-CP Active Video Game

ARRoW-CP is developed for the Microsoft HoloLens augmented reality headset, which allows overground walking with direct vision of the real environment while superimposing virtual elements. Using the head pose estimation provided by the headset sensors, we have developed a real-time gait analysis algorithm that detects heel-strikes and computes walking parameters (speed, cadence, and step length). It has been validated for children with CP [30].

The ARRoW-CP game includes narrative elements. It immerses the child in a cartoon-style samurai world (Fig. 1). The objective is to protect a village and get progressively stronger through walking training. The game has been primarily built upon augmented feedback mechanisms, specifically designed to help participants improve their walking speed [25]. The main source of feedback is a talking virtual dragon that moves at the target speed, which children must follow. It triggers visual effects and verbal encouragement based on performance. Terminal feedback after sprints includes advice and scores.



Fig. 1. Illustrations of ARRoW-CP. *Top left: the dragon, flying in front of the patient at the target walking speed, and delivering colored feedback; top center: performance graphs for the therapists; top right: an animated ninja demonstrating the correct gait pattern; bottom left: samurai master narrating the story; bottom center and right: teenagers testing the system.*

B. Study Design

Participants were allocated randomly to the ARRoW-CP group, receiving overground gait training with the AR-AVG, or to the Control group, receiving treadmill training. During the four-week intervention, all participants continued their usual post-SEMLS rehabilitation program, consisting of five 45-minute sessions per week, including stretching, strengthening, and functional exercises (sit-to-stand, transfers, balance, walking, and stairs). The interventions were designed to deliver high-intensity, task-oriented gait training during the fourth phase of post-SEMLS rehabilitation, in accordance with current recommendations. All details are available in the published study protocol [26].

C. Participants

Eligible participants were aged 12–18 years, functioning preoperatively at GMFCS I–III, and able to walk at least 50 meters with or without an assistive device. All participants received a SEMLS intervention at least 4 weeks before inclusion. Exclusion criteria included photosensitive epilepsy, visual, cognitive, or auditory impairments interfering with game participation, or a history of seizures triggered by video games. Written informed consent was obtained from all participants and/or their parents. The study was approved by the French Ethical Committee Sud-Est (IRB/IORG 0009918; national number 2020-A00675-34 approved June 2020) and registered on ClinicalTrials.gov (Identifier: NCT04837105).

D. Interventions

1) ARRoW-CP Group

All sessions were standardized through therapist training before the study, including familiarization with the ARRoW-CP active video game. Participants trained with ARRoW-CP using the Microsoft HoloLens AR headset, supervised by physiotherapy staff, assistant physiotherapists, or research staff. Training involved walking sprints at a designated target gait speed, conducted three times per week over four weeks. The target speed was determined at the start of each week using the MPST as a calibration with the AR headset, with no feedback provided to the participant. The intervention integrates

overground walking sprints with audio and visual feedback based on the patient's performance. The gait training protocol was adapted from Zwinkels et al. [10], specifying session intensity, volume, and duration. A video trailer of ARRoW-CP is available online at https://www.youtube.com/watch?v=BbmniiiJuaA.

2) Control Group

The Control group trained on a treadmill three times per week for four weeks, with sessions lasting up to 30 minutes. Target velocity was estimated from a treadmill speed test using the Borg Rating of Perceived Exertion Scale, and participants walked at 80% of their maximum speed for up to 20 minutes, including gradual warm-up and cool-down periods. Sessions were supervised by physiotherapy staff or assistants. This protocol was adapted from Grecco et al. [12].

E. Outcome Measures

Assessments were performed the day before the first session (T0: pre-intervention) and the day after the last session (T1: post-intervention).

6-Minute Walk Test (6MWT): In children with CP, 6MWT evaluates walking capabilities rather than the submaximal aerobic capacity [31]. In this study, the main outcome is the distance walked in six minutes. MCID range for the CP population outside the postoperative context is 6-23 m, with subgroup ranges of 4-28 m for GMFCS I-II and 9-19 m for GMFCS III [32].

Muscle Power Sprint Test (MPST): Assesses anaerobic performance over six 10-meter sprints, calculating peak and mean power, speed, acceleration, and force. In this study, two outcomes are the average of the 6 mean speeds ("MPST mean") and the highest of the 6 mean speeds ("MPST best") [33].

Physical Activity Enjoyment Scale (PACES): The 16-item PACES questionnaire [34] was used to assess children's pleasure and satisfaction. It was completed after the final session by the children themselves or with minimal assistance from the therapist (such as reading the items aloud). The outcomes are positive/negative items and the global score.

F. Statistical Analysis

The primary objective was to determine whether the ARRoW-CP intervention produced functional outcomes equivalent to those of a control intervention with established efficacy, within predefined clinical margins. For each functional outcome, an equivalence margin (Δ) was defined a priori, based on published minimal clinically important difference (MCID) or minimal detectable change (MDC) values. These margins represent the largest difference between interventions that would still be considered clinically negligible in either direction.

For the 6MWT, the equivalence margin was set at ±23 m, corresponding to the upper bound of the MCID reported in children with cerebral palsy. For the MPST, margins were derived from published MDC values for peak (38.5 W) and mean (25.0 W) power. These were converted into equivalent velocity thresholds using the inverse cubic relationship between power and velocity ($P = m \times v^3$), based on the mean body mass and baseline velocities of the study sample. The resulting equivalence margins were ±0.29 m/s for peak speed and ±0.21 m/s for mean speed, and should be considered as an empirical approximation.

Equivalence was evaluated by estimating the baseline-adjusted between-group difference in change and its associated uncertainty. Adjusted mean differences were obtained using analysis of covariance (ANCOVA) models, with the change score (post minus pre) as the dependent variable, treatment group (ARRoW-CP vs. Control) as the main factor, and the baseline value of the outcome as a covariate. Adjusting for baseline reduces potential bias due to baseline imbalance, limits regression to the mean, and increases statistical precision. The coefficient associated with the group term represents the adjusted mean difference in improvement between groups, that is, the expected difference attributable to ARRoW-CP for participants with the same baseline level.

For each outcome, a two-sided 95% confidence interval was constructed for the adjusted between-group difference. Formal equivalence testing was conducted using the Two One-Sided Tests (TOST) procedure [35], which simultaneously tests whether the adjusted difference exceeds $-\Delta$ and falls below $+\Delta$. Equivalence was concluded when both one-sided tests were significant at $\alpha = 0.025$, corresponding to a global α level of 0.05. This approach estimates whether the observed difference is compatible with clinical equivalence in both directions; if the confidence interval falls entirely within $[-\Delta; +\Delta]$, a clinically meaningful difference between interventions can be excluded. Effect sizes were quantified using Cohen's d for all functional outcomes.

A responder analysis was additionally performed to estimate the proportion of participants achieving a clinically meaningful improvement, defined according to established MCID or MDC thresholds. Between-group differences in responder rates were assessed using Fisher's exact test. All analyses were conducted on the per-protocol population ($n = 25$) as the primary analysis, with an ITT sensitivity analysis performed for the primary outcome.

Patient enjoyment was analyzed post-intervention as a superiority outcome (PACES-16). Negatively worded items were reverse-scored, and a total enjoyment score was computed by summing all 16 items (total range 16–80). Between-group comparisons were conducted using Welch's t-test or Mann–Whitney U test, depending on normality assessed via the Shapiro–Wilk test. Effect sizes were quantified using Cohen's d.

G. Theory

Postoperative gait recovery in adolescents with CP relies on high-intensity, task-specific practice and augmented feedback to promote motor (re)learning. Overground gait training with real-time performance feedback is expected to enhance neural adaptation, functional walking capacity, and patient engagement more effectively than conventional treadmill training. Motivation and enjoyment are considered key mediators of motor performance and adherence in this population. The ARRoW-CP AR-AVG was designed to

integrate these principles by providing individualized speed targets, audio-visual feedback, and interactive challenges.

H. Calculation

Training intensity for each participant was determined objectively. In the ARRoW-CP group, weekly target walking speed was set using the MPST, with the highest velocity over six 10-meter sprints defining the training speed objective. In the Control group, treadmill target speed was set at 80% of the maximum achieved during a progressive treadmill test using the Borg scale. Outcomes were calculated directly from these measures: 6MWT distance, MPST best and mean speed, and PACES global and subscale scores. These outcomes provide clinically relevant measures of walking capacity, anaerobic performance, and patient enjoyment, which are directly linked to functional mobility and participation in daily life activities.

III. Results

A. Characteristics of Participants

A total of 31 children and adolescents with CP were enrolled (16 males, 15 females; mean age 14.8 ± 2.1 years). Six participants did not complete the study (four early discharges, one withdrawal after a fall outside the intervention, and one due to knee pain), leaving 25 participants for per-protocol analyses. Among these, 13 were allocated to the ARRoW-CP group and 12 to the Control group.

In the per-protocol cohort, the mean age was 14.8 ± 1.8 years, 16 participants (64%) were male, and GMFCS levels I, II, and III were represented in 12 (48%), 9 (36%), and 4 (16%) participants, respectively. Baseline 6MWT distance was 240.9 ± 79.4 m in ARRoW-CP versus 312.6 ± 106.2 m in Control, with walking speeds of 0.67 ± 0.22 and 0.87 ± 0.29 m/s, respectively. MPST best and mean sprint speeds were 1.02 ± 0.28 and 0.94 ± 0.26 m/s in ARRoW-CP versus 1.20 ± 0.43 and 1.10 ± 0.39 m/s in Control. Between-group differences at baseline were not statistically significant, indicating comparable demographic and functional profiles before the intervention (Table I).

TABLE I
PATIENT CHARACTERISTICS (PER-PROTOCOL POPULATION)

	All patients (N=25)	ARRoW-CP (N=13)	Control (N=12)
Age	14.8 (SD 1.8)	14.9 (SD 1.3)	14.8 (SD 2.2)
Sex	M: 16 (64%); F: 9 (36%)	M: 10 (77%); F: 3 (23%)	M: 6 (50%); F: 6 (50%)
GMFCS level	1: 12 (48%) 2: 9 (36%) 3: 4 (16%)	1: 6 (46%) 2: 4 (31%) 3: 3 (23%)	1: 6 (50%) 2: 5 (42%) 3: 1 (8%)
6MWT pre-intervention, distance (m)	275.28 (SD 98.28) (MIN/MAX 91.0/480.0)	240.85 (SD 79.38) (MIN/MAX 91.0/370.0)	312.58 (SD 106.22) (MIN/MAX 135.0/480.0)
6MWT pre-intervention, speed (m/s)	0.77 (SD 0.27) (MIN/MAX 0.25/1.33)	0.67 (SD 0.22) (MIN/MAX 0.25/1.03)	0.87 (SD 0.29) (MIN/MAX 0.37/1.33)
MPST pre-intervention, speed best sprint (m/s)	1.11 (SD 0.36) (MIN/MAX 0.34/1.90)	1.023 (SD 0.28) (MIN/MAX 0.33/1.34)	1.20 (SD 0.43) (MIN/MAX 0.54/1.90)
MPST pre-intervention, speed mean sprint (m/s)	1.02 (SD 0.33) (MIN/MAX 0.32/1.79)	0.94 (SD 0.26) (MIN/MAX 0.32/1.31)	1.10 (SD 0.39) (MIN/MAX 0.50/1.79)

A total of 31 children were enrolled, and 25 completed the per-protocol assessment. SD: standard deviation; GMFCS: Gross Motor Function Classification System; 6MWT: 6-Minute Walk Test; MPST: Muscle Power Sprint Test.

B. Primary Outcome: 6MWT

Participants (n = 25) walked an average of 275 ± 98 m during the 6MWT at baseline (mean speed 0.77 ± 0.27 m/s). Following the intervention, mean distance increased to 372 ± 99 m (mean speed 1.03 ± 0.28 m/s), corresponding to an average pre–post change of 96.8 ± 84.0 m (+0.27 ± 0.23 m/s). Both groups showed substantial improvements: in the ARRoW-CP group (n = 13), the mean increase in 6MWT distance was 102.4 ± 77.8 m (from 241 ± 79 m to 343 ± 101 m); in the Control group (n = 12), the mean increase was 90.8 ± 93.4 m (from 313 ± 106 m to 403 ± 92 m).

After adjusting for baseline 6MWT distance, the estimated difference between groups was small (−16.1 m in favor of Control), with a 95% confidence interval spanning from −87.2 m to +55.1 m (Cohen's d = +0.13). The TOST equivalence analysis did not demonstrate formal equivalence within the predefined clinical margin of ±23 m (TOST p = 0.421), primarily due to the width of the confidence interval rather than to a clinically meaningful difference between interventions (Fig. 2).

The sensitivity analysis conducted on the ITT population (n = 31) yielded identical point estimates and confidence intervals, confirming the robustness of the per-protocol findings.

To complement the group-level analysis, the proportion of participants achieving the MCID for the 6MWT (≥23 m) was 84.6% in the ARRoW-CP group and 83.3% in the Control group (Fisher's exact p = 1.000), indicating a high and comparable rate of clinically meaningful responders in both groups (Fig. 3).

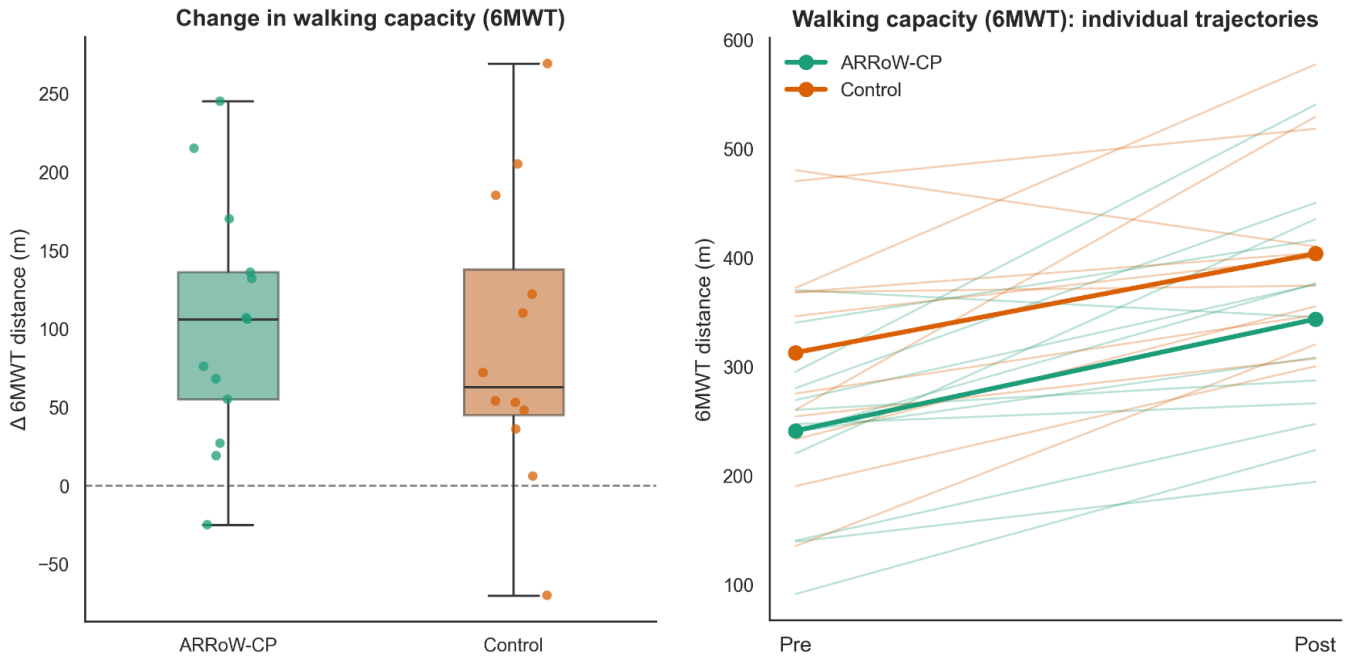


Fig. 2. (On the left) Box plot of the 6MWT difference pre-post intervention (distance in meters). (On the right) Evolution of the 6MWT among participants (distance in meters). *Both groups improved, with slightly greater mean gains in the ARRoW-CP group for distance and walking speed.*

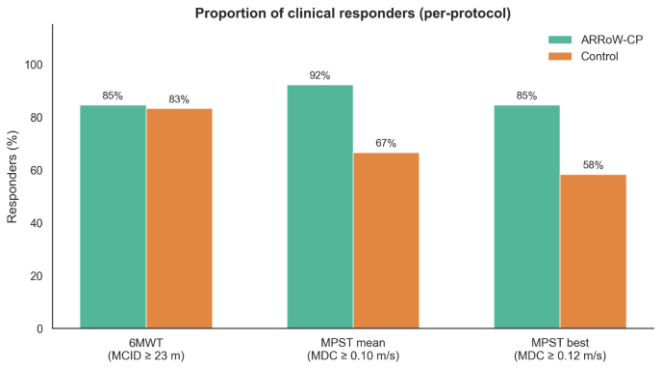


Fig. 3. The proportion of participants achieving the MCID for the 6MWT and MPST.

C. Secondary Outcome: MPST Mean and Best

For MPST mean speed, the overall cohort improved from 1.02 ± 0.33 m/s at baseline to 1.24 ± 0.36 m/s post-intervention (+0.23 ± 0.16 m/s). In the ARRoW-CP group, mean speed increased from 0.94 ± 0.26 to 1.22 ± 0.27 m/s (+0.28 ± 0.16 m/s), and in the Control group from 1.10 ± 0.39 to 1.27 ± 0.44 m/s (+0.18 ± 0.16 m/s).

For MPST best speed, the overall cohort improved from 1.11 ± 0.36 m/s to 1.37 ± 0.44 m/s (+0.26 ± 0.22 m/s). In the ARRoW-CP group, best speed increased from 1.02 ± 0.28 to 1.31 ± 0.29 m/s (+0.29 ± 0.16 m/s), and in the Control group from 1.20 ± 0.43 to 1.43 ± 0.57 m/s (+0.23 ± 0.28 m/s).

The ANCOVA + TOST analysis demonstrated that ARRoW-CP was equivalent to the control intervention for MPST best speed within the predefined clinical margin of ±0.29 m/s (adjusted difference: +0.069 m/s; 95% CI [−0.127; +0.265] m/s; TOST p = 0.015; Cohen's d = +0.25). For MPST mean speed, the adjusted difference was +0.102 m/s (95% CI [−0.037; +0.241] m/s; TOST p = 0.061; Cohen's d = +0.64), and narrowly missed the formal equivalence threshold within the ±0.21 m/s margin. As the confidence interval slightly exceeded the predefined upper equivalence margin, the observed effect slightly favored ARRoW-CP. (Fig. 4)..

Responder analyses further supported these findings. For mean MPST speed, 92.3% of ARRoW-CP participants exceeded the MDC threshold (≥0.10 m/s) compared with 66.7% of Control participants (Fisher's exact p = 0.160). For best MPST speed, 84.6% of ARRoW-CP participants versus 58.3% of Control participants achieved clinically meaningful improvements (Fisher's exact p = 0.202). While these between-group differences did not reach statistical significance, the consistently higher responder rates in the ARRoW-CP group suggest a favorable trend for sprint performance in this group.

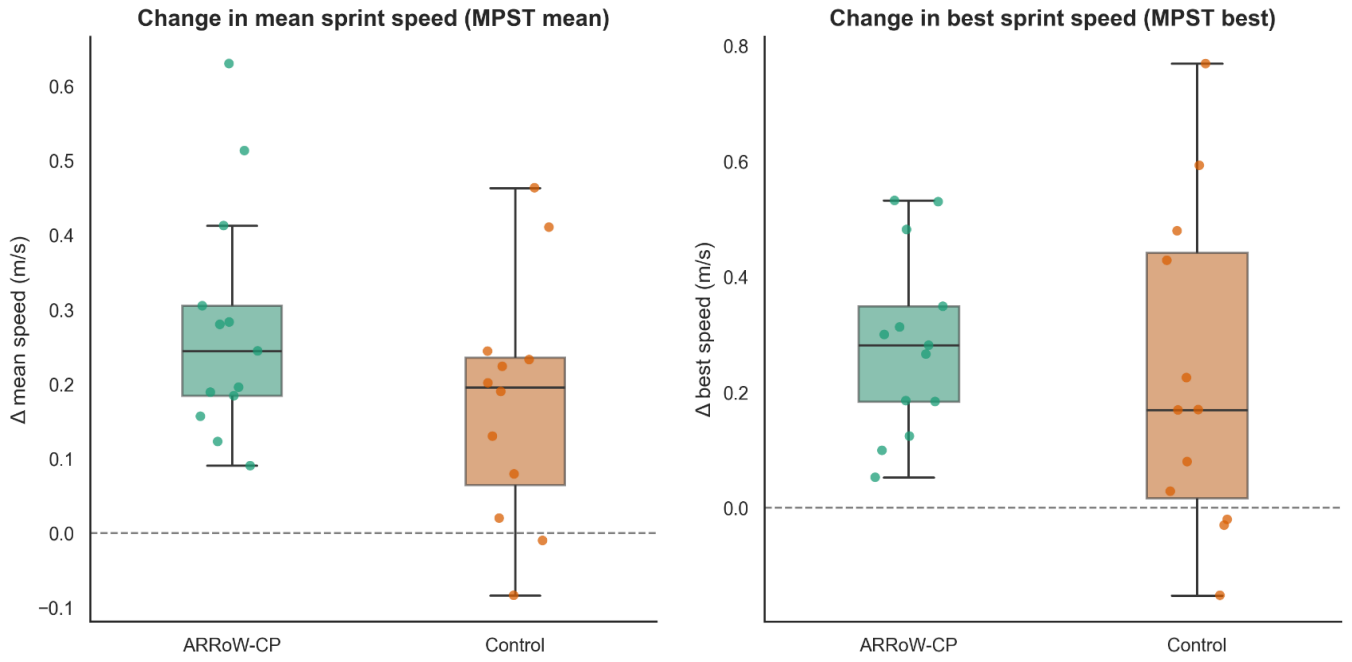


Fig. 4. (On the left) Box plot of the "MPST mean" difference pre-post intervention (speed in m/s). (On the right) Box-plot of the "MPST best" difference pre-post intervention (speed in m/s).

D. Patient Enjoyment: PACES

The mean PACES-16 total score was 66.1 ± 9.2 in the ARRoW-CP group (12 responses) versus 55.6 ± 7.9 in the Control group (11 responses) (Fig. 5(a)). Welch's t-test showed a significantly greater enjoyment in favor of ARRoW-CP ($t = 2.93$, $p = 0.008$, 95% CI [3.0; 17.9]) with a large effect size (Cohen's $d = 1.21$).

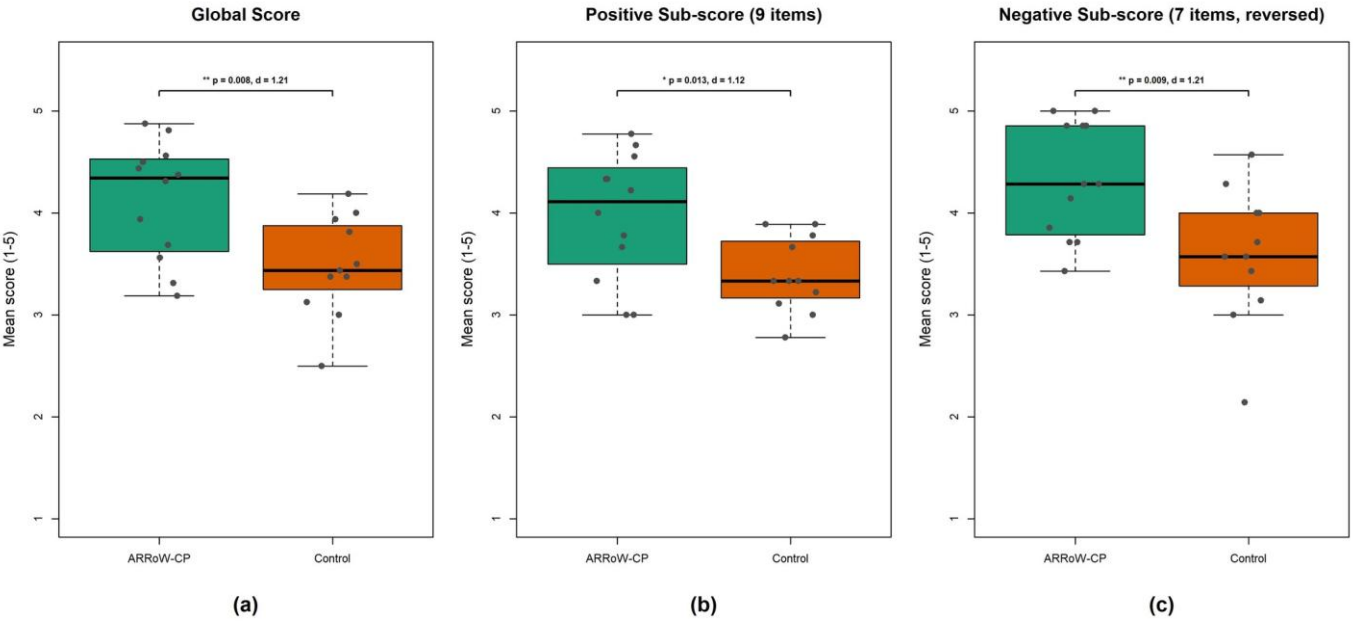


Fig. 5. (a) PACES-16 total sum scores for the ARRoW-CP and control groups, (b) positive and (c) negative (reversed) sub-scores for the ARRoW-CP and control groups. *Individual data points are shown. Higher scores indicate greater enjoyment.*

This difference was consistent across both the positive items sub-score (35.8 ± 5.6 vs 30.5 ± 3.3, $p = 0.013$, $d = 1.12$) and the negative items sub-score after reversal (30.3 ± 4.0 vs 25.1 ± 4.7, $p = 0.009$, $d = 1.21$) (Figs. 5(b) and 5(c)).

Exploratory item-level comparisons identified four items with between-group differences at $p < 0.05$ (Fig. 6), with the item "It wasn't fun" showing the strongest effect ($p < 0.001$). These item-level results were not corrected for multiple comparisons and should be interpreted with caution.

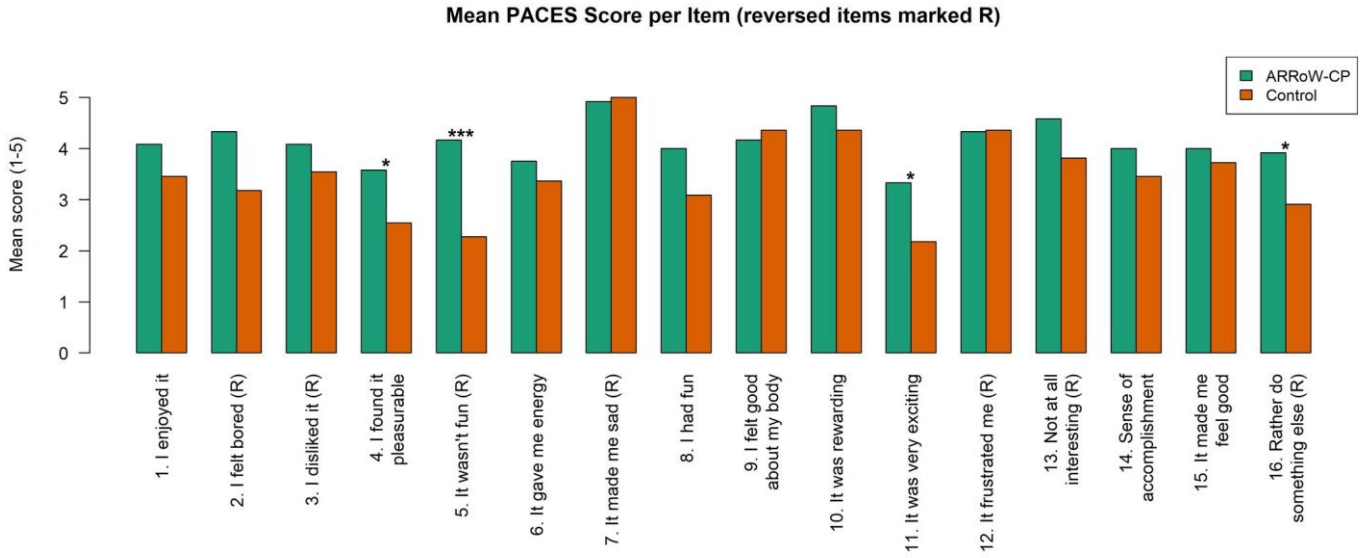


Fig. 6. Mean PACES score per item for the ARRoW-CP and control groups. *Negatively worded items are reverse-scored and marked with (R). Higher bars indicate greater enjoyment. Significance markers from exploratory Mann–Whitney U tests, uncorrected for multiple comparisons: *p < 0.05, **p < 0.01, ***p < 0.001.*

IV. Discussion

Our study aimed to compare overground gait training using ARRoW-CP active video game to treadmill training in adolescents with CP following SEMLS. Our results showed that both interventions produced walking capacity gains. For the 6MWT, large and clinically meaningful improvements were observed in both groups, with more than 80% of participants exceeding the MCID after 4 weeks. For the MPST outcomes, non-inferiority was demonstrated for best sprint speed, indicating that ARRoW-CP improved anaerobic performance without any clinically meaningful loss compared with the control intervention.

Both groups demonstrated clinically meaningful improvements in walking capacity, with a mean gain of 97 meters on the 6MWT — well above the established MCID of 23 m — and no between-group difference. The proportion of participants achieving the MCID was 84.6% in the ARRoW-CP group and 83.3% in the Control group, reflecting a high and comparable rate of clinically meaningful responders across both conditions. This convergence further supports the notion that the two interventions are clinically equivalent in their effects on walking capacity.

Baseline 6MWT distances in our cohort (275 ± 98 m) are consistent with normative data reported in the literature for ambulant individuals with CP, ranging from 305 ± 67 m at GMFCS level III to 440 ± 50 m at GMFCS level I [36]. The mean gain of 97 m observed in the present study exceeds improvements typically reported in gait rehabilitation studies in children with CP. In a recent multicenter observational study of 135 participants with CP or acquired brain injury, treadmill-based virtual reality biofeedback training yielded a mean 6MWT improvement of +27.2 m (95% CI: 20–41 m), rising to +45 m among participants whose primary rehabilitation goal was gait function improvement [37]. In the context of robotic-assisted gait training, a randomized controlled trial comparing robotic training to conventional physical therapy in an inpatient setting found no significant between-group difference on the 6MWT ($p = 0.8$), with both conditions producing only modest gains [38]. The substantially larger gains observed in the present study may be attributed to several factors, including intervention intensity, session frequency, and the motivational effects inherent to participation in a clinical trial. It should also be noted that a proportion of the observed gains likely reflects the natural postoperative recovery trajectory following SEMLS, an intervention known to produce a transient functional decline followed by progressive recovery extending over 12 to 24 months [6], such that improvements in 6MWT performance cannot be attributed exclusively to the rehabilitation protocols under investigation.

The absence of a clinically meaningful between-group difference is consistent with a broader pattern of findings in the literature. Multiple studies comparing different gait training modalities — including partial body weight-supported versus unsupported treadmill training, overground versus treadmill-based approaches, and technology-assisted versus conventional protocols — have consistently reported significant within-group improvements without significant between-group differences [9], [39]. Similarly, a network meta-analysis comparing five rehabilitation modalities (robotic-assisted gait training, treadmill training, overground gait training, conventional physical therapy, and BWSTT) found no statistically significant difference between any two interventions for gross motor function as assessed by the GMFM (dimensions D and E) [40]. More specifically, while some meta-analyses report superior outcomes with robotic-assisted training over conventional physical therapy for gait

speed and walking distance, no differences are found between robotic training and treadmill training across the majority of outcomes [41]. Taken together, these findings support the interpretation that the primary drivers of functional improvement are the general principles of motor learning — task repetition, training intensity, and task specificity — rather than the specific technological medium through which training is delivered [19], [21].

The equivalence testing analysis did not yield formal statistical equivalence within the predefined margin of ±23 m. This result should be interpreted with caution: the failure to demonstrate equivalence reflects primarily the width of the confidence interval (−87.2 m to +55.1 m), which is a direct consequence of the limited sample size (n = 25), rather than the presence of a clinically meaningful difference between interventions. The estimated between-group difference was −16.1 m in favor of the Control group, with a Cohen's d of +0.13, indicating a negligible effect size. This pattern is not uncommon in the literature: trials comparing innovative technology-based protocols to active control conditions frequently report non-significant between-group differences, yet rarely achieve the statistical power required to formally conclude equivalence [42].

For anaerobic sprint performance, ARRoW-CP demonstrated formal equivalence to treadmill training for MPST best speed within the predefined margin. For MPST mean speed, the adjusted difference favored ARRoW-CP (+0.102 m/s). Formal equivalence was not demonstrated because the upper bound of the confidence interval (+0.241 m/s) slightly exceeded the predefined equivalence margin (+0.21 m/s), leaving open the possibility of a small advantage for ARRoW-CP rather than indicating a clinically meaningful disadvantage. Responder analyses reinforced this pattern: a numerically higher proportion of ARRoW-CP participants exceeded the MDC for both mean and best sprint speed, although these between-group differences did not reach statistical significance given the limited sample size. The 8-month training programme reported in [43] resulted in a significant improvement in MPST mean power. Gillett et al. reported a significant increase in MPST peak power but not in mean power after a 12-week combined functional anaerobic and strength-training programme [44]. The present study and Gillett et al. [44] involved shorter interventions. This difference in training duration may partly explain why mean performance did not reach statistical significance in these studies, while peak performance appeared more responsive. Taken together, both studies suggest that peak, single-effort measures may be more sensitive to a training effect than measures averaged across repeated sprints, and that mean anaerobic gains in CP are attainable but often modest in absolute terms.

As expected, ARRoW-CP produced significantly higher enjoyment scores than control training on treadmill, with a large effect size. Other studies have shown similar effects of technology or gaming on enjoyment during physical activity, whether in healthy or clinical populations [18].

This improvement in the overall PACES score is driven evenly by positive and negative sub-items. Looking at the significant sub-items, the most discriminating negative ones ("*It wasn't fun*," "*I'd rather do something else")* show that our AR AVG reduces boredom compared to the treadmill; while the positive items ("*I found it pleasurable*," "*It was very exciting*") indicate that the solution also actively provides enjoyment.

Since the walking exercise is similar in both groups (walking in a straight line at maximum speed), the difference likely stems from the gamification elements (a friendly character to follow, audiovisual feedback during the sprint, end-of-session star ratings, and narration) and the novelty effect of the technology, which remain effective at least for the duration of the 12 sessions in the protocol. It could also be due to the relative freedom of walking overground and moving naturally through the hallways, rather than walking in place on a treadmill.

Enjoyment is considered a predictor of adherence to physical activity in adolescents, though direct evidence in rehabilitation settings remains limited [45]. The superior enjoyment, combined with the fact that it is no less effective in terms of walking performance, suggests that ARRoW-CP could be a preferable alternative to the treadmill in terms of the patient experience, which could lead to better adherence in longer protocols.

Our measure of enjoyment is, however, limited. PACES was measured only once after the intervention (12 sessions). We do not know whether this enjoyment will persist over time. Furthermore, while it might help predict rehabilitation adherence, it does not measure it. Finally, our analysis of the PACES items is purely exploratory and has not been adjusted. With respect to enjoyment difference, even if ARRoW-CP and control groups were randomized, the trial was not blinded: it is possible that the patients were influenced by the fact that the trial was about to assess the effects of an innovative rehabilitation technology.

A. Strengths

This study has several strengths. It was designed as a randomized controlled trial. The interventions were standardized and aligned with post-SEMLS rehabilitation recommendations. A combination of objective quantitative measures (6MWT, MPST) and subjective assessment (PACES) was used to provide a comprehensive evaluation of outcomes. The ARRoW-CP system was developed following the PROGame framework, supporting its clinical relevance and acceptability, and the protocol was grounded in prior literature, including the selection of appropriate outcome measures such as those proposed by Zwinkels [10]. In addition, the treadmill intervention was based on a previously validated and effective post-surgical protocol Grecco et al. [12], ensuring a strong and clinically relevant control condition. This design allows us to demonstrate that the improvements observed with ARRoW-CP are at least comparable to an established standard of care, while offering additional benefits in terms of motivation and anaerobic performance. Notably, these effects were achieved with a shorter intervention duration (4 weeks) and fewer sessions than in prior studies, highlighting the efficiency of the proposed approach.

B. Limitations

The sample size remained limited, an inherent challenge in clinical trials conducted in pediatric postoperative rehabilitation settings. Nevertheless, the number of participants included in the present study is comparable to that reported in several randomized controlled trials investigating gait training interventions in children with CP. In their systematic review and meta-analysis, Moreau et al. reported a mean sample size of 25 participants across eight randomized controlled trials, with individual studies ranging from 14 to 35 participants [46]. Moreover, the sample size calculation was based on our previously published preliminary work, which relied on the results reported by Grecco et al [12]. Another limitation of this study is that long-term effects were not assessed, preventing conclusions about the sustainability of the observed improvements. Finally, both the therapeutic mechanics and the gameplay are generic and repetitive. Virtual and game-like elements such as storytelling and rewards compensate for this during much of the 12 sessions of the RCT, but this would not be sufficient in the long term, particularly for adolescents.

V. Perspectives

Future research should involve longer study durations and larger, more diverse samples, including other clinical populations, to better evaluate the effects on gait, aerobic performance, social participation, and additional functional outcomes. Developing personalized goal-setting and automated monitoring systems may further enhance motivation and adherence. Expanding ARRoW-CP into a home-based version also represents a relevant perspective, increasing accessibility and continuity of care. Overall, ARRoW-CP may serve as a motivating and effective alternative to treadmill-based rehabilitation, with specific advantages including improvements in anaerobic performance (e.g., sprint capacity), increased enjoyment and engagement, and strong potential for further integration of personalized feedback and gamification strategies.

VI. Conclusion

ARRoW-CP was developed to provide overground gait training with audio and visual feedback based on the patient's performance. This device was proposed to address several limitations reported while conducting high-intensity functional gait training, mainly low enjoyment, limited engagement, and reduced motivation. Through interactive feedback, ARRoW-CP aims to enhance the training experience and promote greater participation and adherence to rehabilitation programs. The results of the RCT suggest that ARRoW-CP provides functional benefits comparable to established treadmill-based rehabilitation while offering a more engaging therapeutic experience.

Declarations

Ethics approval and consent to participate: Written informed consent was obtained from all participants and/or their parents. The study was approved by the French Ethical Committee Sud-Est (IRB/IORG 0009918; national number 2020-A00675-34 approved June 2020) and registered on ClinicalTrials.gov (Identifier: NCT04837105).
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