ORIGINAL REPORT

VIRTUAL REALITY FOR ENHANCEMENT OF ROBOT-ASSISTED GAIT TRAINING IN CHILDREN WITH NEUROLOGICAL GAIT DISORDERS

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Objective: To examine the effect of various forms of training interventions, with and without virtual reality, on the initiation and maintenance of active participation during robot-assisted gait training.

Design: Intervention study at the Rehabilitation Centre Affoltern a. A., University Children's Hospital, Zurich.

Subjects: Ten patients (5 males, mean age 12.47 years, standard deviation 1.84 years) with different neurological gait disorders and 14 healthy children (7 males, mean age 11.76 years, standard deviation 2.75 years).

Methods: All participants walked in the driven gait orthosis Lokomat® in 4 different randomly-assigned conditions. Biofeedback values calculated during swing phases were the primary outcome measure and secondary outcomes were derived from a questionnaire assessing the participant's motivation.

Results: Findings revealed a significant main effect for training condition in all participants ($p<0.001$), for patients ($p<0.05$) and for healthy controls ($p<0.01$). Overall, both virtual reality-assisted therapy approaches were equally the most effective in initiating the desired active participation in all children, compared with conventional training conditions. Motivation was very high and differed between the groups only in the virtual navigation condition.

Conclusion: Novel virtual reality-based training conditions represent a valuable approach to enhance active participation during robot-assisted gait training in patients and healthy controls.

Key words: virtual reality; rehabilitation; robot-assisted gait training; motivation; children, neurological gait disorders.

INTRODUCTION

Over the past decade, robotic devices have become increasingly established for gait training in patients with neurological gait disorders. Several studies have demonstrated improvements in locomotor ability in different patient populations receiving robot-assisted gait training (RAGT) (1–6). However, the evidence so far is controversial. Randomized controlled trials have shown the effectiveness of RAGT and promising effects on functional and motor outcomes in patients after stroke (4, 7). In contrast, a multicentre randomized clinical trial found that conventional gait training appeared to be more effective for stroke patients than RAGT (8). There is also a growing body of literature showing that RAGT is feasible for use with children with cerebral palsy and can be considered a safe treatment method with beneficial effects on the standing and walking sections of the gross motor function measurement (GMFM) (9, 10). Explanations for the controversial results might, on the one hand, be due to different patient populations and, on the other hand, be due to different methods for enhancing activity during training interventions and protocols (e.g. reducing body-weight support, increasing gait speed, reducing guidance force). Overall, training efficacy depends on a number of different parameters. Findings of RAGT need to be interpreted cautiously and examined in greater detail in order to exploit its beneficial effect fully in each specific patient population.

Another possible explanation for the limited effectiveness of robotic devices might be the patient's passivity in the driven gait orthosis (DGO). Studies have shown that active involvement in the production of a motor pattern resulted in greater motor learning and retention than did passive movement (11–13). Comparison of RAGT with manually assisted treadmill training has shown that muscular activity in patients and healthy controls were reduced when walking with a robotic device (14, 15). An important issue in RAGT might be preventing passivity and improving active performance in the rehabilitation training of patients. A prerequisite for achieving these targets is the appropriate feedback of patient performance. Virtual reality (VR) offers a novel possibility to provide feedback to patients about their performance and the opportunity to directly interlink the patient's motor performance during RAGT with actions in a computer game-like virtual world. In paediatric rehabilitation in particular, the need for diversification, fun and motivation have been demonstrated in several investigations (16, 17). Previous studies have indicated that VR offers powerful options to

Table I. *Characteristics of participants*

ID	Age years/sex	Height cm	Weight kg	Lokomat®'s Legs	Disease	GMFCS level	Mobility aids
01	13/F	149	41.4	T	BS-CP	II	None
02	13/M	154	53.0	T	TBI	–	AFOs
03	16/F	164	56.4	T	SLE	–	None
04	9/M	133	21.7	K	BS-CP	III	AFOs
05	11/F	142	38.0	T	BS-CP	III	AFOs
06	13/F	153	58.0	T	MMC	–	KAFOs
07	12/F	160	48.0	T	MMC	–	KAFOs, post walker
08	11/M	152	40.0	T	TBI	–	Wheelchair
09	10/M	140	37.0	K	BS-CP	IV	Wheelchair, AFO
10	14/M	144	29.0	K	BS-CP	II	Insoles
11	15/F	169	58.5	T	Healthy	–	None
12	14/F	169	49.0	T	Healthy	–	None
13	14/F	166	60.0	T	Healthy	–	None
14	11/M	135	34.0	K	Healthy	–	None
15	11/M	140	31.0	K	Healthy	–	None
16	6/F	125	28.0	K	Healthy	–	None
17	15/F	174	65.0	T	Healthy	–	None
18	10/M	146	37.0	K	Healthy	–	None
19	10/M	148	39.8	K	Healthy	–	None
20	10/M	144	33.7	K	Healthy	–	None
21	10/M	139	30.5	K	Healthy	–	None
22	10/M	146	34.2	K	Healthy	–	None
23	15/F	158	50.4	T	Healthy	–	None
24	14/F	164	57.6	T	Healthy	–	None

GMFCS-level: Gross Motor Function Classification System; BS-CP: bilateral spastic cerebral palsy; MMC: meningomyelocele; TBI: traumatic brain injury; SLE: systemic lupus erythematodes; AFOs: ankle-foot orthosis; KAFOs: knee-ankle foot orthosis; M: male; F: female; K: kids; T: teens; Mobility aids: over ground mobility aids.

provide therapy within a functional, purposeful and motivating context (18–20). The effectiveness of RAGT in children might be influenced strongly by their motivational state during the intervention. Motivation involves an interaction between a person's motives and the incentives associated with a situation (21). Since changing a person's motive is difficult, a solution could be to influence and provide incentives during RAGT.

Given that the motivational state is a precondition for the success of such an approach, we sought to ascertain whether VR-based therapy in patients more easily induces an appropriate response during RAGT compared with conventional training interventions without VR. The purpose of this study was to examine the differential effect of various VR scenarios as well as verbal encouragement on the induction and maintenance of active participation during RAGT. We assume that, in paediatric rehabilitation, competitive situations and augmented feedback could serve as additional motivational factors, and therefore will lead to higher active participation and maintenance during conditions with VR, compared with other conventional interventions without VR.

METHODS

Participants

The study was approved by the local ethics committee and conformed to standards set by the Declaration of Helsinki. Written informed consent was obtained from the legal guardians of all participants before inclusion in the study. A total of 24 participants met the inclusion criteria and were enrolled in the study. Ten patients (5 males, mean age 12.2 years, standard deviation (SD) 2.04 years) with various neurological gait disorders were referred to the Rehabilitation Centre Affoltern am Albis of the University Children's Hospital Zurich. Additionally, 14 healthy children (7 males, mean age 11.78 years, SD 2.72 years) from the soccer club Affoltern am Albis, Switzerland, were included. The demographic characterization of the participants is shown in Table I.

All participants were naive to the purpose of the study and were eligible for the study if they met the following inclusion criteria: (*i*) aged 4–18 years, with a femur length between 21 and 47 cm; (*ii*) minimal voluntary control (i.e. the ability voluntarily to initiate a step movement) of their lower-extremity muscles to ensure that they had the ability to respond and adapt their walking pattern and could follow different walking instructions; (*iii*) ability to signal pain, fear, discomfort; and (*iv*) willingness to meet the study requirements for training with the DGO Lokomat® (Hocoma AG, Volketswil, Switzerland).

Interventions

All measurements were conducted at the Rehabilitation Centre Affoltern a. A. of the University Children's Hospital Zurich, Switzerland. Prior to the measurements, the participants became familiarized with the Lokomat. For clinical use, the Lokomat is normally position-controlled with 100% guidance force. The intervention protocol was held constant and each child was unloaded with 30% of their individual body-weight with 100% guidance force and foot-lifting straps, which assisted ankle dorsiflexion for adequate toe-clearance during the swing phase. Participants had a velocity of 1.8 km/h, except for 1 patient (ID 07) who had a reduced speed of 1.6 km/h.

All participants were then randomly assigned to 1 of the 2 test schedules. Measurements consisted of 2 parts. First, participants were instructed to walk at 3 different activity levels for 30 s each, to ascertain the individual degree of active involvement (Validation): (*i*) *passive*: participants should behave completely passively; (*ii*) *active*: participants should walk with the same pattern as the Lokomat; (*iii*) *strongly active*: participants should exaggerate their walking with maximal force. All instructions for the validation were standardized. The second part consisted of 4 pseudo-randomly presented conditions: (*i*) use of a VR soccer game as a motivating tool to walk actively (VR soccer); (*ii*) with therapist's standardized instructions to promote active walking (Therapist); (*iii*) watching a movie (DVD); and (*iv*) use of the VR navigation game as a motivating tool to walk actively (VR navigation) (Fig. 1). Instructions for the second part were kept as standardized as possible during all 7-min conditions.
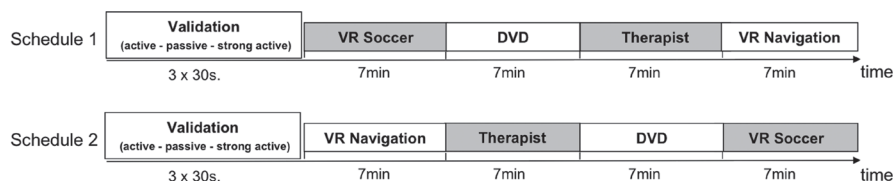

Fig. 1. Measurement schedules for the two parts of the study. Participants were randomly assigned to either of the schedules. VR: virtual reality.
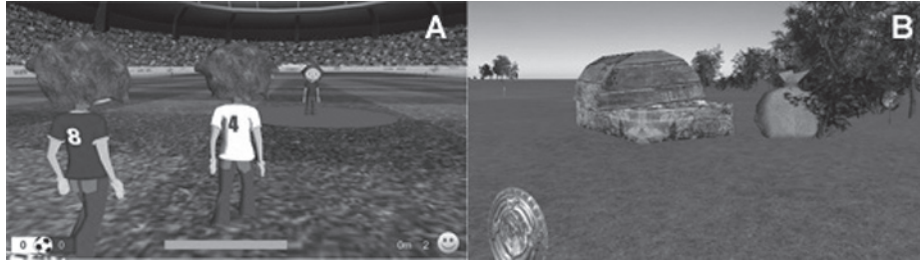
Fig. 2. Both virtual reality (VR) games used in this study. (A) VR soccer game with two opponents; (B) VR navigation game.

Virtual environment system set-up

Both VR scenarios have been developed especially to increase motivational aspects for RAGT in paediatric rehabilitation. The VR set-up consisted of a 42-inch flat screen placed in front of the Lokomat and a 7.1 Dolby surround system. The Lokomat system was used as a multimodal feedback system: the human-machine interaction forces measured from the Lokomat are used as an input device for the patient's movements into the VR. Furthermore, the Lokomat served as a haptic display that reflects interactions with objects, such as a soccer ball, represented in the virtual environment, with the purpose of providing haptic feedback to the participant. The haptic contact forces when kicking the ball were modelled as a spring damper system.

The VR soccer game made it possible for participants to kick a ball in competition against two virtual opponents (Fig. 2A). One was waiting in front of the participant, who had to kick the ball past his or her opponent; otherwise he or she had to start from the previous kick position. The second opponent would approach from behind, taking over the soccer ball when the opponent outpaced the participant. This second opponent was configured to walk faster and take over the ball from the participant if the exertion of the participant was weak. The opponent walked slower when the child participated actively.

The VR navigation game used asymmetrical physical activity of the legs to induce turning in the virtual environment (Fig. 2B). Specifically, turning right and left can be induced by increasing activity of the contralateral leg of the desired direction, and decreasing activity of the ipsilateral leg, respectively.

Outcome measures

The biofeedback of the Lokomat gait orthosis is based on the interaction torques between the participant and the orthosis. For this reason, the hip and knee linear drives are equipped with force sensors that measure the human-machine interaction forces that are required to keep the participant on a predefined gait trajectory. The biofeedback values are unit-less and weighted averages of the measured human-machine interaction forces at the hip and knee joints for stance and swing phase. The weighting functions were defined for each part of the gait cycle, such that the resulting biofeedback values increase for therapeutically desirable movements, e.g. knee flexion for early swing. Thus, the biofeedback levels are positive when the patient is actively participating and negative for passive behaviour or when inappropriate involuntary muscle activations, such as caused by spasms, would interfere with the gait cycle. The so-called biofeedback values are unit-less and are weighted averages of the measured man-machine interaction forces at the hip and knee joints for stance and swing phase separated. For the present study, it was assumed that the force level represents the physical activity of the participants (22, 23).

Eight biofeedback values (bilateral hip and knee joints) were recorded separately for swing- and stance-phases during all conditions. The mean biofeedback value of the swing- and stance phase for hip and knee joints was calculated separately during each condition. This provided 4 overall biofeedback values for hip and knee joints and for swing- and stance phases in each condition (i.e. VR soccer, VR navigation, Therapist, DVD) separately.

To assess subjective aspects of the RAGT with and without VR, a self-designed motivational questionnaire was used. Patients and healthy controls were asked to rate on a visual analogue scale (VAS) the extent to which they had liked the different training conditions, from 0 ("not at all") to 10 ("very much").

Statistical analysis

Individual "involvement" was analysed using Spearman's correlation, because non-linear relations were predicted. Biofeedback values for all 4 joints in the 2 gait phases swing and stance during approximately 580 strides for each subject were correlated to the level of activity that each subject was instructed to perform (1 = passive, 2 = active, 3 = strongly active). Other settings (body weight support, treadmill speed, patient coefficient) that might have influenced the biofeedback values were kept constant.

Biofeedback values were examined for normality. As the assumption for normally distributed data was not met, a non-parametric Friedman's test was performed to detect differences among the conditions, while *post-hoc* analysis was performed using Wilcoxon signed-rank for comparisons between the conditions (24). In general, effects were considered statistically significant when falling below $p < 0.05$. Since *p*-values depend strongly on sample sizes, we additionally calculated the effect size measure Cohen's *d* to obtain information on how strong an effect was (24, 25). In this study we decided to rely on strong effect sizes for our interpretation. In terms of Cohen's terminology $d \geq 0.5$ can be considered as medium effect, while $d \geq 0.8$ can be considered as large effect.

With respect to the questionnaire, mean values (SD) for the motivation scores were calculated and differences between the conditions (within each group) were analysed with Friedman's test. Pair-wise comparisons between the conditions were additionally analysed with the Wilcoxon signed-rank test. Furthermore, motivational scores for each individual condition were compared between the two groups and analysed using the Mann-Whitney *U* test. All statistical analyses were performed using the statistical software package SPSS 16 for Mac, release 16.0.1.

RESULTS

The two groups assessed in this study did not differ significantly in age ($p = 0.689$), gender ($p = 0.735$), height ($p = 0.812$), and weight ($p = 0.852$) from each other for the demographic characteristics given in Table I.

The recorded biofeedback values were correlated to the level of activity each subject was instructed to perform ("passive" = 1, "active" = 2, "strongly active" = 3). Fig. 3 shows the absolute biofeedback values of hip swing for the instructed activity using clustered bars. The mean biofeedback activity for the passive condition was 11.20 (SD 18.91) and 4.17 (SD 7.52) for patients and healthy children, respectively. During the active condition the values were 20.60 (SD 10.32) (patients) and 34.71 (SD 16.65) (healthy children). For the strongly active condition the values were 54.96 (SD 20.22) (patients) and 65.36 (SD 25.27) (healthy children).
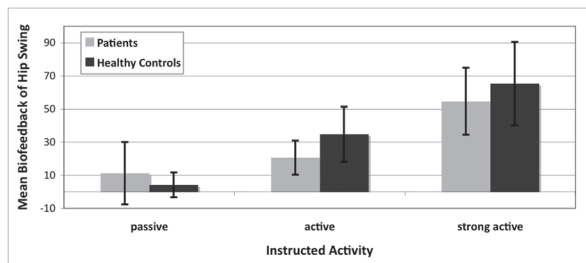
Fig. 3. Differences between the mean biofeedback values of hip swing phase broken down separately for instructed activity for patients and healthy control children.

The biofeedback values of the hip torques correlated moderately with the instructed activity during swing phases, whereas there was no correlation of hip and knee torques and activity during stance phases. The results are illustrated in Table II. Based on the results from the correlation between instructed activity and biofeedback values (Table II), further analyses were carried out for the biofeedback values during the hip swing phase only.

Significant differences in biofeedback values were found both for the patient group and for the healthy controls (Table III).

In addition, Table III shows the differences in the absolute biofeedback values during the 4 conditions. Patients reached the highest biofeedback values (mean, SD) in the two VR conditions and the lowest values for the DVD condition, whereas healthy children reached the maximum biofeedback value for the condition VR soccer and the lowest values for the DVD condition.

A *post-hoc* analysis was performed to determine differences between the conditions (Fig. 4). Statistical comparisons of both VR conditions with DVD revealed significant results in both groups (for VR soccer: $p < 0.001$, $p < 0.05$ for patients, respectively; VR navigation: $p < 0.05$). Comparisons of VR conditions with therapist showed a significant difference only in the healthy control group for VR soccer ($p < 0.05$). Similarly, for the comparisons of therapist condition compared with DVD: only healthy controls ($p < 0.05$) showed significantly more active performance in the therapist condition.

Effect sizes for patients for the comparison of both VR conditions with DVD (for VR soccer: Cohen's $d = 0.86$ and VR navigation: $d = 1.03$) were considered as large and VR with therapist (VR soccer: $d = 0.58$ and VR navigation: $d = 0.80$) were considered as medium and large, respectively. Only the effect size for the comparison of therapist with DVD ($d = 0.33$) must be considered small. A similar pattern appeared for healthy

Table II. *Correlation of biofeedback and participant's instructed activity*

Joint	Hip right		Knee right		Hip left		Knee left	
	Stance	Swing	Stance	Swing	Stance	Swing	Stance	Swing
Spearman's rho	0.135	0.560	0.145	0.217	0.200	0.654	0.098	0.142
Sig. (2-tailed)	0.258	0.001*	0.225	0.067	0.093	0.001*	0.412	0.233

*$p < 0.001$.

Table III. *Analysis of the biofeedback values of the hip swing phase*

	Biofeedback values of the hip swing phase				
Group	VR Soccer Mean (SD)	VR Navigation Mean (SD)	Therapist Mean (SD)	DVD Mean (SD)	Within-group differences
Patients	18.96 (15.97)	24.90 (21.97)	10.52 (12.80)	6.12 (13.79)	$\chi^2 = 8.76$, $p = 0.033$**
Healthy controls	43.73 (24.51)	31.51 (22.49)	30.63 (24.80)	23.03 (22.39)	$\chi^2 = 15.00$, $p = 0.002$
Between-group differences	$z = -2.635$, $p = 0.008$**	$z = -1.23$, $p = 0.219$	$z = -2.459$, $p = 0.014$*	$z = -1.932$, $p = 0.053$	

*$p < 0.05$; **$p < 0.01$.
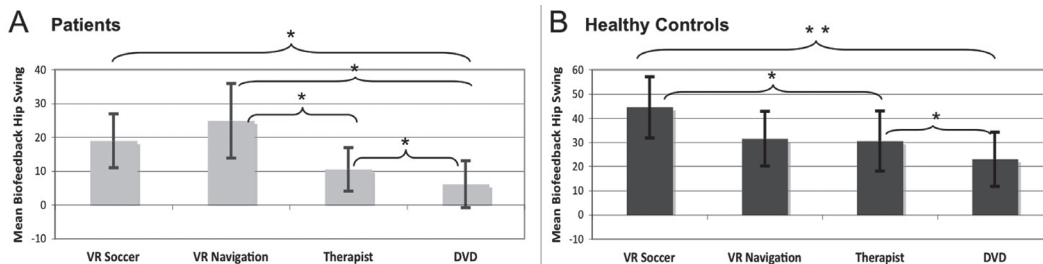SD: standard deviation; VR: virtual reality.

Fig. 4. Comparison (mean and standard deviation) of hip swing phase in all 4 conditions separately for (A) patients (1-tailed) and (B) healthy control children. Asterisks above the columns define the level of significance of within-group comparisons (**$p < 0.001$; *$p < 0.05$).

children: the effect size for VR soccer compared with DVD ($d=0.88$) was large. Effect sizes for all other within-group comparisons were considered medium, and the comparison of therapist with DVD ($d=0.32$) was considered small.

The analysis of this motivation questionnaire revealed that during each condition all participants had fun. The Friedman's test showed only a significant difference between the conditions for the healthy control group. Pair-wise comparisons showed that the healthy children rated the VR soccer ($p=0.012$) and watching a DVD ($p=0.042$) significantly higher than the instructions by the therapist. We found only one significant difference between the groups for the VR navigation condition (Table IV). With regard to generalization of the preferred conditions, 70.4% of all participants reported that they would prefer the VR for the next training sessions, while only 29.6% preferred watching a DVD.

DISCUSSION

Active participation is an important prerequisite for motor learning and improving functional and motor outcomes. To assess participation during RAGT and to find the most effective and most strongly motivational interventions in paediatric rehabilitation is of interest to both therapists and clinicians. In the present study, VR-based training was implemented for RAGT in children. The overall aim of the present study was to investigate the effect of different supportive conditions on active participation and maintenance in children during RAGT. The two VR-assisted therapy forms resulted equally in the desired response in both patients and healthy controls. The between-group analyses showed that the effects were equal between healthy subjects and patients. Furthermore, in this study we were able to extend recent observations (26) that VR-based RAGT has an advantage over other conventional training sessions, especially in longer lasting conditions of 7 min.

Biofeedback of the hip swing phase correlated moderately with the instructed activity in all participants. There was no correlation for the knee swing phase and for the hip and knee stance phases. Despite the fact that variables were kept constant, the relatively low correlations might have been caused partially by difficulties in the exact synchronization of the exoskeleton and the treadmill and the contact of the foot with the treadmill during stance phase. These findings are in line with those of Lünenburger et al. and Banz et al. (22, 23, 27).

For these reasons further calculations were based on hip swing phases only.

The results reported here support our earlier findings that RAGT coupled with VR can improve active participation in children (26). We extended these findings by demonstrating that VR during RAGT was also able to maintain the enhanced active participation level during prolonged training conditions of 7 min. In particular, both VR conditions (soccer game and navigation game) reached higher participation levels compared with normally applied training conditions, such as therapist instructions or watching a DVD in both patients and healthy children. The lowest biofeedback values were revealed in the condition DVD, although children reported that they liked watching a DVD very much (as reported in the motivation questionnaire). The reason for this discrepancy may be that children fully immersed themselves in watching a DVD, but were not concentrating on their walking behaviour and "let themselves go" in the Lokomat instead of performing actively. This might be one of the main advantages of coupling VR with RAGT. The question arises as to the possible aspects/mechanisms involved in imparting the beneficial effects of VR-supported RAGT to children.

Although motivation has long been suspected to play an important role in determining the outcome of therapy, a clear definition of this phenomenon has not yet been drawn up (28). Motivation is usually not a constant factor, but a dynamic process that is dependent on many external and internal factors. Awareness of all the factors impinging on motivation for rehabilitation will also foster a better understanding of the phenomenon of patient disengagement in rehabilitation (28). In particular, active engagement towards a training intervention is usually equated with motivation, and similarly passivity with the lack of motivation (29). Several studies have demonstrated that virtual environments are challenging to children and help them to be creative, which proved motivating (16, 26) and helped patients with cerebral palsy to develop a more positive self-image (17, 30, 31). A recently published review concluded that due to the engaging and challenging character of VR, it seems to be an effective rehabilitation tool in paediatric rehabilitation, as it allows children to participate in activities that would otherwise not be possible (32).

Although little is known about the neural mechanisms of locomotor recovery, VR might target brain networks, speeding up the recovery process (33, 34). Indeed, using functional magnetic resonance imaging, You et al (35). demonstrated

Table IV. *Analysis of the motivation questionnaire*

Group	Motivation scores				Within-group differences
	VR Soccer Mean (SD)	VR Navigation Mean (SD)	Therapist Mean (SD)	DVD Mean (SD)	
Patients	8.78 (1.59)	6.97 (3.12)	7.80 (3.06)	9.25 (2.37)	$\chi^2=5.548, p=0.136$
Healthy controls	9.71 (0.47)	9.36 (0.89)	7.71 (3.45)	9.54 (0.80)	$\chi^2=9.434, p=0.024*$
Between-group differences	$z=-1.568, p=0.117$	$z=-2.020, p=0.043*$	$z=-0.030, p=0.976$	$z=-0.907, p=0.364$	

*$p < 0.05$.
SD: standard deviation; VR: virtual reality.

that VR induced cortical reorganization in the lower extremity of patients with chronic stroke. These findings suggest that VR may have attributed to positive changes in neural reorganization.

In our previous study (26), we were able to show that a VR-based soccer scenario induced an immediate effect on motor output that was of similar magnitude to the effect resulting from verbal instructions issued by the therapist. However, one has to be aware that each given condition in this study lasted for approximately 2 min. While an average normal training period lasts for approximately 30–40 min, a 2-min experimental condition is not likely to be representative. Therefore, we extended the duration of the conditions up to 7 min, which was the longest possible duration to compare several conditions within a single therapy session.

While the current study provides findings about improvements in active participation of VR-based RAGT in children, this study clearly has potential shortcomings. First, as previously mentioned, each condition lasted 7 min, while patients walk up to 45 minutes during a normal RAGT session. To the best of our knowledge, it has not yet been shown whether this enhanced active performance can also appear during a whole training session and whether this leads to a more effective rehabilitation process for patients. Secondly, patients were heterogeneous with respect to age and diagnosis. However, this reflects a normal paediatric neurorehabilitation clinic population and the healthy control group was matched for age and gender. Thirdly, unfortunately, the two game scenarios provided suspense for only 15 min, after which the children lost interest in the game. Indeed, emphasis should be placed on the development of engaging and immersive game designs, which allow and even promote human gait variability and various degrees of difficulty in performance levels. These variables must be optimized in order to keep children attentive during consecutive training sessions of 30–40 min. Furthermore, cognitive and spatial aspects could be implemented in serious games designs to increase the therapeutic value of such VR games.

In conclusion, VR-based scenarios were implemented for RAGT in children. The results have demonstrated that patients with neurological gait disorders and healthy controls participated more actively with VR-based RAGT than with other interventions. The VR scenarios in this study were designed to challenge children's abilities and provided interactive elements to engage them during Lokomat therapy. Further research should reveal whether an increase in active participation leads to a better functional outcome, as a result of patient cooperative strategies such as VR. However, to enable this kind of research, visionary and thoughtful game designs first need to be developed.

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