Visual Feedback in Augmented Reality to Walk at Predefined Speed Cross-Sectional Study Including Children With Cerebral Palsy

Anne-Laure Guinet, Guillaume Bouyer, Samir Otmane, and Eric Desailly

***Abstract*—In an augmented reality environment, the range of possible real-time visual feedback is extensive. This study aimed to compare the impact of six *scenarios* in augmented reality combining four visual feedback characteristics on achieving a target walking speed. The six *scenarios* have been developed for Microsoft Hololens augmented reality headset. The four feedback characteristics that we have varied were: Color; Spatial anchoring; Speed of the feedback, and Persistence. Each characteristic could have different values (for example, the color could be unicolor, bicolor, or gradient). Participants had to walk for two consecutive walking trials for each *scenario*: at their maximal speed and an intermediate speed. Mean speed, percentage of time spent above or around target speed, and time to reach target speed were compared between *scenarios* using mixed linear models. A total of 25 children with disabilities have been included. The feasibility and user experience were excellent. Mean speed during *scenario* 6, which displayed feedback with gradient color, attached to the world, with a speed relative to the player equal to his speed, and that disappeared over time, was significantly higher than other *scenarios* and control (p =0.003). Participants spent 80.98% of time above target speed during *scenario* 6. This *scenario* mixed the best combination of feedback characteristics to exceed the target walking speed (p=0.0058). *Scenarios* 5 and 6, which shared the same feedback characteristics for spatial anchoring (world-locked) and feedback speed (equal to the player speed), decreased the time to reach the target speed (p=0.019). Delivering multi-modal feedback has been recognized as more effective for improving motor performance. Therefore, our results showed that not all visual feedback had the same impact on performance. Further studies are required to test the weight of each feedback characteristic and their possible interactions inside each *scenario*. This study was registered in the ClinicalTrials.gov database (NCT04460833).**

***Index Terms*—Augmented reality, assistive technology, feedback, gait disorders, patient rehabilitation.**

Manuscript received 14 June 2022; revised 21 July 2022; accepted 29 July 2022. Date of publication 11 August 2022; date of current version 22 August 2022. This work was supported by the ARRoW-CP Project through Ellen Poidatz and Association Nationale Recherche et Technologie (ANRT), in collaboration with Université Paris-Saclay, Université Evry, IBISC, équipe IRA2, Paris, France. *(Corresponding author: Anne-Laure Guinet.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board (or Ethics Committee) of Comité de Protection des Personnes Ile de France I under Application No. IRB/IORG 0009918 and National No. 2020-A00675-34, in June 2020.

Anne-Laure Guinet is with the Université Paris-Saclay, Univ Evry, IBISC, 91020 Evry-Courcouronnes, France, also with the IBISC, Université Evry, 91020 Evry-Courcouronnes, France, and also with Fondation Ellen Poidatz, Pole Recherche & Innovation, 77310 Saint-Fargeau-Ponthierry, France (e-mail: anne-laure.guinet@fondationpoidatz.com).

Guillaume Bouyer and Samir Otmane are with the Université Paris-Saclay, Univ Evry, IBISC, 91020 Evry-Courcouronnes, France, and also with the IBISC, Université Evry, 91020 Evry-Courcouronnes, France.

Eric Desailly is with Fondation Ellen Poidatz, Pole Recherche & Innovation, 77310 Saint-Fargeau-Ponthierry, France.

This article has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2022.3198243, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2022.3198243

I. Introduction

Cerebral palsy (CP) describes "a group of permanent disorders of the development of movement and posture, causing activity limitation, which is attributed to non-progressive disturbances that occurred in the developing fetal or infant brain" [39]. It is the most common cause of childhood disability, affecting 17 million people worldwide [20], [41]. Gait pattern functions are often altered (spastic, stiff, or/and hemiplegic gait), causing mobility restriction. The natural history in people with CP is a gradual decline in ambulatory function as children grow and age [5], [35]. One effective approach to reverse this tendency is gait training (GT), showing beneficial effects on walking speed, endurance, and other gait-related outcomes, with positive long-term effects [8], [48]. In order to optimize motor recovery, current motor learning theories recommend task-specific, variable and high intensity of practice but also the use of augmented feedback during therapy sessions [11], [32], [36], [44]. In pediatric rehabilitation, fun and motivation are also critical keys to successful therapy [37]. To this end, studies have demonstrated high level of interest, compliance and engagement with game-based intervention and virtual rehabilitation [10], [24], [29]. Virtual rehabilitation, defined as "interventions that are built on virtual reality platforms to meet rehabilitation goals" are very efficient to provide concurrent feedback in real-time [27]. But active video games developed for these systems do not always integrate motor learning principles, including optimal feedback [15]. The feedback retraining paradigm is based on the conversion, supplementation, and augmentation of sensory information that are usually accessible only by an internal focus of attention into accessible information [27], [34]. Augmented feedback is defined as augmented sensory information provided by an external resource (therapist or display) to the patient. The information provided to the user could refer to the movement's pattern itself or result on the environment, or the outcome of a movement concerning the goal [42]. Sensory channels usually used to deliver information are visual, auditory, or haptic and the proprioceptive channel. The timing of feedback delivery is critical. Concurrent feedback is delivered while the skill is being performed, terminal feedback is delivered after the skill is performed with or without delay [38]. There are many ways to provide augmented feedback when using an augmented reality (AR) or virtual reality (VR) headset. In most studies, even if feedback is effective in improving motor activities, the characteristics applied during interventions were generally inconsistent with motor control feedback theory [17], [30]. Therefore, a recent systematic review highlighted that visual and auditory feedback was provided in all studies as a display of total score and/or reward sounds without any indication about movement characteristics (knowledge of performance) [16]. The objective of this study was to define the most practical combination of visual feedback characteristics delivered in augmented reality to reach, maintain or exceed a target speed for people with cerebral palsy.

II. Preliminary Work

In a previous article, we proposed a model to describe the characteristics of feedback dedicated to the rehabilitation of walking in AR [21]. In an AR environment, feedback takes the form of 3D holograms and sounds, whose spatial location has a considerable impact on their perception by users. The feedback can be attached to the world (i.e., the feedback has its spatial coordinates in the world and stays in its place even if the player moves) or to the player (i.e., when the player moves, the feedback follows her/him). As a consequence, the position and speed of the feedback change: the feedback could translate at a predefined target speed, or the player speed, or be stationary in the world. Our preliminary qualitative study on healthy adults showed that feedback characteristics displayed in an AR game influence the walking speed. Some feedback seemed to help maintain or exceed the target speed, while others resulted in high variability in walking speed compared to the control scene without feedback. These preliminary results on healthy participants helped us to improve our classification of the different feedback characteristics that could affect gait rehabilitation efficiency [21] and to design more carefully the six *scenarios* tested here. Based on these previous results, we have also decided to try two different walking speeds: maximal and intermediate (mid-point between self-selected and maximal). The main reason is that our research on feedback characteristics is part of a global project aiming to improve walking rehabilitation in children with CP using Augmented Reality technology. In this context, therapists need to train the children to exceed their maximum walking speed but also to maintain some specific sub maximal walking speeds.

III. Methods

A. Design Study

This study was a crossover trial with a repeated measures design in which each patient was assigned to a sequence of 7×2 walking trials. Participants played 7 *scenarios*, each twice. Each *scenario* presented visual feedback with different characteristics. One of them was control without visual feedback. Two trials by *scenarios* have been recorded, with two different instructions given to the participant: 1. "Walk as fast as possible for 30 meters" i.e match and exceed maximal walking speed (condition MAX) and 2. "Walk at your intermediate walking speed" i.e match and maintain intermediate walking speed (condition INTER). The target speed was not the same for each condition (MAX and INTER). Each session began with a calibration scene where the child had to walk as fast as possible for 2×15m. This first calibration calculated the MAX target speed used in the study; the maximum average speed among these two sprints was the MAX target speed. Then, the child walked 30 m at self-selected walking speed. The second calibration calculated the INTER target speed; the midpoint between the MAX target speed and the average speed during this self-selected trial was the INTER target speed. The instruction of walking at the "intermediate speed" was given to the participant before starting the first scenario as follows: "Your intermediate speed is the middle between your spontaneous walking speed and your maximal walking speed. You aim to walk as close as possible to this medium-speed". The participant did not know a priori this INTER target speed because it was calculated, not realized by the participant himself. The study coordinator systematically asked the participant if he/she has understood this specific instruction. The objective of the first experimental condition (condition MAX) was to define the most efficient combination of visual feedback characteristics delivered in augmented reality to reach and exceed a target speed; whereas the objective of the second experimental condition (condition INTER) was to reach and maintain a target speed for people with cerebral palsy. To avoid the "order" effects, all participants walked during the same number of walking trials, in random order, and participated for the same number of periods (Figure 1). The instructions were standardized by playing a recorded human voice in the AR application.

B. AR Application: Best-Of ARRoW

1) System Characteristics: The device used was Microsoft Hololens augmented reality headset (Microsoft, US). Microsoft HoloLens (1^{st} generation) is the world's first fully untethered holographic computer, using Gaze tracking, Gesture input, and Voice support to understand user actions (Figure 3). But also, Spatial sound to understand the environment. It's an Augmented Reality Head-Mounted Display of 579 grams, equipped with Processor Intel 32-bit architecture with Trusted Platform Module 2.0 with Custom-built Microsoft Holographic Processing Unit, connected with WiFi and Bluetooth. The Microsoft Hololens headset also included an inertial measurement unit (IMU), four environment understanding cameras, one depth camera, a photo/video camera,

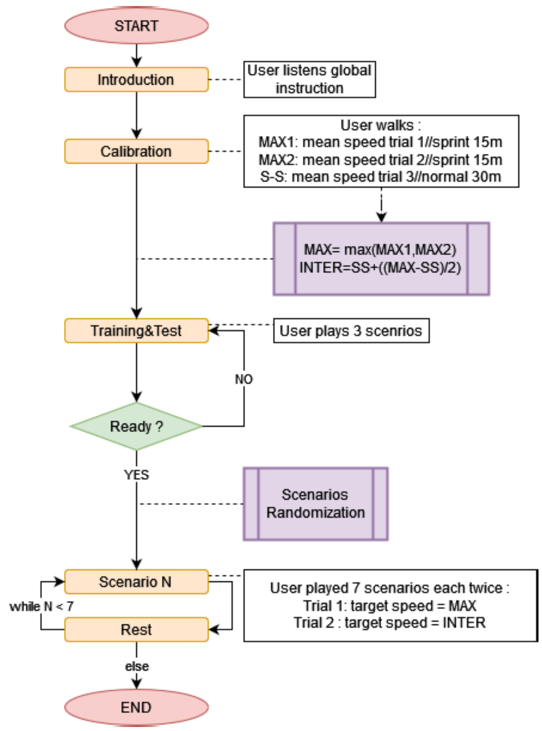

Fig. 1. Software flowchart.

four microphones, one ambient light sensor. Best-Of ARRoW application has been developed with Unity 2019.2.8f1 (64-bit) using Mixed Reality Toolkit version 2. Microsoft Hololens tracking was accurate enough to measure the position of the user without time drift [22]. An algorithm (called HoloStep) was developed specifically for measuring the real-time gait parameters from the head pose of children with CP: walking speed, cadence, step length, and global distance traveled. Metrics such as sensitivity, specificity, accuracy, and precision for step detection with HoloStep were above 96%. The Intra-Class Coefficient between steps length calculated with HoloStep and the reference was 0.92 for children with GMFCS I and 0.86 for children with GMFCS II or III. [23].

2) Development Framework: This work followed the serious game development framework PROGame, proposed by Amenguai Alcover *et al.* [3]. The multidisciplinary team was composed of therapists (3 physiotherapists), researchers (2 in computer science, 1 in rehabilitation science, 1 in movement science), and a software engineer. The six *scenarios* that we have tested were (Table I):

- Scenario 1: A blue round shape (unicolor) moved ahead at the target speed; this shape is attached to the player (body);
- Scenario 2: A round shape moved ahead at the target speed, the color changed if the user succeeded (green) or failed (red) to reach the target speed (bicolor); this shape is attached to the player (body);
- Scenario 3: A round shape moved ahead at the target speed, the color changed with a gradient (green-yellow-orange-red) depending on his speed; this shape is attached to the player (body);

TABLE I

FEEDBACK CHARACTERISTICS FOR EACH SCENARIO. *Feedback Was Given on Current Walking Speed Relative to the Target Speed. Sc: Scenario; TS: Target Speed; PS: Player Speed; Scenario 7 (S7) Was the Control Without Any Feedback*

Sc	Color	Spatial anchor	Speed relative to the player	Speed relative to the world	Persistence
S1	unicolor	Body	$TS - PS$	TS	full
S2	bicolor	Body	$TS - PS$	TS	full
S3	gradient	Body	$TS - PS$	TS	full
S4	bicolor	Body	$null$	PS	full
S5	bicolor	World	PS	$null$	full
S6	gradient	World	PS	$null$	faded
S7	none	none	none	none	none

- Scenario 4: A round shape stayed 1m in front of the user, the color changed if the user succeeded (green) or failed (red) to reach the target speed. His/her perceived speed of the round shape was null relative to him/her while he/she was walking.
- Scenario 5: A round shape stayed at the end of the corridor, the color changed if the user succeeded (green) or failed (red) to reach the target speed; the round shape was placed at a fixed position in the world;
- Scenario 6: Five green round shapes were positioned every 5m, the color changed with a gradient, and the shape disappeared if the user failed to reach them on time; the five round shapes were placed at a fixed position in the world.

For each condition (MAX and INTER), the feedback always displayed the current speed relative to the target speed. The model of feedback used to develop these specific *scenarios* has been inspired by Macintosh *et al.* [30]. We have adapted their model to the AR environment. The visual sensory channel of the feedback could be characterized by the shape, size, persistence, material, shade, and color. We deliberately developed feedback with a simple design using elementary geometric shapes (round shape), with the same size, the same material, and shade properties. We have introduced variations between *scenarios* to test the effect of color, spatial anchor, speed and persistence characteristics. Color could be: unicolor (round shape was blue all the time); bicolor (round shape was green if the child exceeded his/her target speed, red if he/she didn't); or gradient (round shape color changed from green to red, through orange and yellow depending on the distance from the target speed). The persistence characteristic was defined as the shape that was visible for the user over time. Persistence is full for *scenarios* 1 to 5 and faded for *scenario* 7 (the shape disappeared). The spatial representation of the feedback could be characterized by its position, its spatial anchor, and its speed. For spatial anchor characteristic, the feedback could be body-locked (i.e., attached to the gaze user) or world-locked (i.e., relative to the environment). So, feedback characteristics differed only by their color, persistence, spatial anchoring, and relative moving speed. Figure 2 illustrates some feedback used. See also Additional file 1 for a more detailed description of the displayed scenarios.

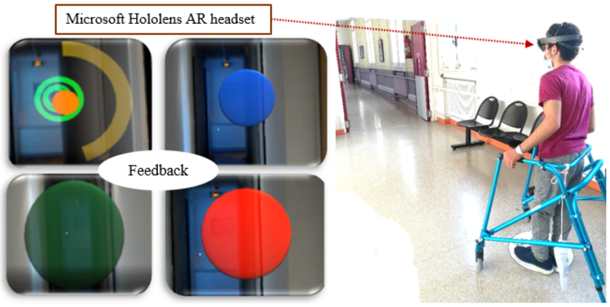

Fig. 2. Application Best-Of ARRoW. *Example of four scenarios played with the Hololens during walking sprints. Top left: Scenario 6; Top right: Scenario 1; Bottom left: Scenario 2; Bottom right: Scenario 4.*

C. Participants and Data Collection

Participants were recruited from a pediatric rehabilitation center (Fondation Ellen Poidatz - Saint Fargeau). The inclusion criteria were: a clinical diagnosis of spastic CP, including hemiplegia, diplegia, and quadriplegia; age between 12 and 18 years; Global Motor Function Classification System (GMFCS) levels I-III; a minimum score of 2 on the Functional Mobility Scale 50m; ability to cooperate, understand and follow simple instructions to play the game; voluntary patient whose parents have given their free and informed written consent for their child's participation in the study. This study occurred between September 2020 and March 2021. Each participant wore the AR headset and followed the instructions given by the application.

D. Outcome Assessment

During the session, raw data were logged (100Hz) in .txt format through the application and were available in the Windows Device Portal. Logfile contained time (s), position x, y, and z of the headset, step length, and distance traveled calculated with HoloStep algorithm [23]. The outcomes were: Mean speed (condition MAX and condition INTER), percentage of time spent above the MAX target speed (condition MAX), percentage of time spent around the INTER target speed ($\pm$ 0.1 m/s) (condition INTER), time to reach the target speed (condition MAX and condition INTER). The target speed was not the same for conditions MAX and INTER (see Design study in section III.A. for more details). The threshold ($\pm$ 0.1 m/s) is the threshold for a change of outcome measure that has a meaningful effect for the patient [33]. The time to reach the target speed was the first time ever above the target speed after the patient's first forward acceleration (acceleration on z axis > 0). At the end, participants completed a questionnaire rating their experience (feasibility and user experience evaluation) [31].

E. Data Analysis

Data analysis was performed using MatLab version 9.6.0.1472908 (R2019a) Update 9. Raw data (time, position, step length) were filtered with Butterworth filter design (Filter order 2, Cutoff frequency 4Hz) using *filtfilt* function. For each participant, trials were cut off three steps before the end, not considering deceleration. The instantaneous walking speed was calculated using position and re-filtered using polynomial curve fitting (order 1, frame length 701). Statistical analysis was performed using R version 4.0.5. Mean speed, mean percentage of time spent above (condition MAX) or around (condition INTER) the target speed (with a cut-off of the three first steps, not considering acceleration), and time to reach the target speed were compared between *scenarios*. Moreover, the percentage of time spent above the target speed was analyzed according to the participant's target speed using generalized linear models (GLM). Thus, Figure 5 was a GLM using linear methods to describe a potentially nonlinear relationship between predictor terms and a response variable. In condition MAX, the mean speed relative to the target speed ($\mu_{Sn'}$) has been calculated for each *Scenario (Sn)*:

$$\mu_{Sn'} = (\mu_{Sn} \times 100)/(\mu_{TS})$$

The different *scenarios* were compared using mixed linear models, including the patients as random effects to take into account the repeated measures. Parametric bootstrap tests based on the likelihood ratio test (LRT) statistic with 1000 iterations were used to perform hypothesis testing on the fixed effects. This strategy was preferred as it introduced less bias. Tests were implemented with the function PBmodcomp in the pbkrtest package (v.0.5.1). Statistical significance was determined at the 0.05 level throughout. Qualitative information was extracted to explore individual responses. Qualitative information was extracted from the user's questionnaire.

F. Ethical Considerations

Ethics approval was granted by the Ethical Committee of Ile-de-France 1 in France (IRB/IORG : IORG0009918). Additionally, all parents and participants from 12 years of age signed the informed consent before study initiation. All participants had a reflection period before the inclusion (minimum 15 days between information and approval). The National Commission guaranteed confidentiality and data access for Data Protection. A Data Protection Officer has been designated for all research studies conducted in the rehabilitation center. He assured that the data protection and the rights of the participants were respected according to the General Data Protection Regulation (European Union) 2016/679. This study was registered in the ClinicalTrials.gov database (NCT04460833).

TABLE II
PRELIMINARY INFORMATION. MAX: CONDITION MAX, INTER: CONDITION INTER

Sample Characteristics	Children (n = 25)
Age (mean (SD))	14.7 (1.6 years))
Sex (F/M)	14/11
GMFCS	I:15 II:10
Calibration Results	**Children (n = 25)**
Speed MAX (mean (SD))	1.48 (0.36m/s)
Speed INTER (mean (SD))	1.30 (0.27m/s)

IV. RESULTS

A total of 25 participants was included. Characteristics of population were detailed in Table II.

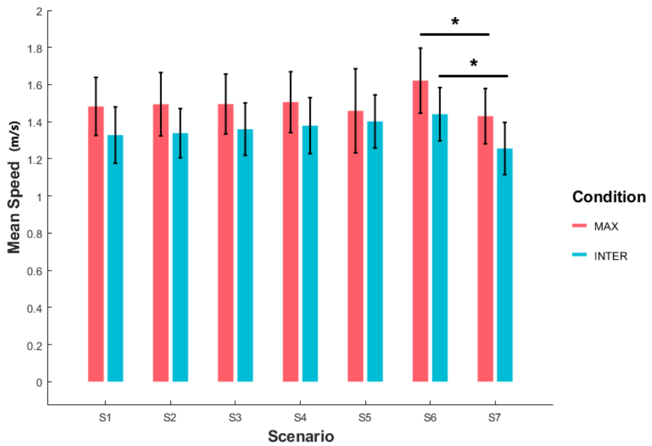

Fig. 3. Mean Speed in m/s for Condition MAX and INTER during the different scenarios including feedback (S1 to S6) and control without feedback (S7). The error bars represent the standard deviation. *Significant difference was observed between S6 and S7 (control) during both condition (MAX and INTER) (p<0.05)*.

TABLE III

The Ranking of Scenarios - Condition MAX. *Mean Speed Relative to TS, Mean Percentage of Time Above TS and Mean Time to Reach TS for Each Scenario: Mean Value and [Ranks]. TS: Target Speed*

Scenario	Mean speed relative to TS (%)	% above TS	Time to reach TS (s)
S1	100.0 [5]	62.9 [3]	2.83 [5]
S2	100.8 [4]	53.9 [7]	2.69 [4]
S3	100.9 [3]	61.7 [4]	2.25 [3]
S4	101.6 [2]	63.9 [2]	2.97 [6]
S5	98.4 [6]	59.5 [5]	1.75 [2]
S6	109.4 [1]	81.0 [1]	1.28 [1]
S7	96.5 [7]	55.6 [6]	3.31 [7]

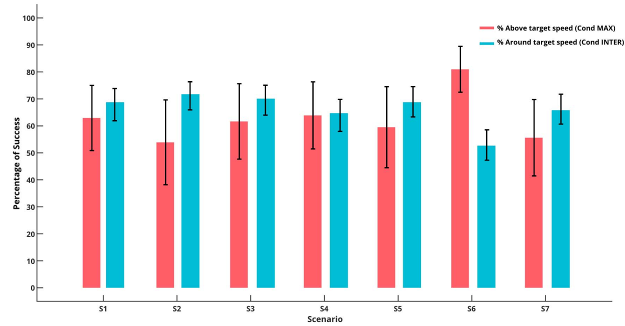

Fig. 4. Percentage of time above the target speed for Condition MAX and Percentage of time around the target speed for Condition INTER during the different scenarios, including feedback (S1 to S6) and control without feedback (S7). *Significant difference was observed between S6 and S7 during condition MAX.*

A. Feasibility and User Experience Evaluation

All participants completed the session. There was no missing data. No adverse effects such as difficulty breathing, discomfort, or cybersickness were observed during trials. None of the participants fell while walking and wearing the AR headset. The user experience questionnaire revealed that all participants correctly understood the game instructions. All participants rated 5/5 on the items "I learned to use the game quickly" and "I understood the walking instructions easily". They thought that the game was immersive, fun, and pleasant (items "The experience was challenging. I found the game stimulating", "The experience was immersive" and "The playing environment was visually appealing" rated 5/5). Some participants mentioned that in some *scenarios* it was less easy to move around because the feedback sometimes disappeared. All participants recognized the value of the game as a tool for learning (item "The game scenario had relevance to the issue of walking skills development" rated 5/5).

B. Mean Speed

The average walking speed (WS) varied according to the *scenario* (Figure 3).

1) Condition MAX: Mean speed during *scenario* 7 (control) was the lowest speed (1.43 SD 0.32 m/s), and was inferior to target walking speed (1.48 SD 0.36m/s). Mean speed for all *scenarios* including feedback was superior to the target walking speed. The mean speed during *scenario* 6 was significantly higher (1.62 SD 0.36m/s) than in the *scenario* control ($p < 0.05$). The first quartile (Q1) for speed during *scenarios* 1-6 was higher than the Q1 for target speed and control. The median showed that 50% of people had a walking speed above 1.56m/s with the help of feedback provided during *scenario* 6 while the median target speed was 1.41m/s. In condition MAX, the mean speed relative to the target speed has been calculated. The higher percentage was in the *scenarios* 6, the mean speed represented 109.4% of the target speed. The lowest was in the *scenario* control (S7), with 96.5% (Table III).

2) Condition INTER: Mean speed during *scenario* 7 (control) was the lowest speed (1.26 SD 0.29m/s), and was inferior to target walking speed (1.30 SD 0.27m/s). All *scenarios* including feedback allowed to achieve the speed objective. The mean speed during *scenario* 6 was significantly higher (1.44 SD 0.27 m/s) than in the *scenario* control ($p < 0.05$). The first quartile (Q1) for speed during *scenarios* 2-6 was higher than the Q1 for target speed and control. The median showed that 50% of people had a walking speed above 1.37m/s with the help of feedback provided during *scenario* 6 while the median target speed was 1.32m/s.

C. Percentage of Success

The percentage of success was the percentage of time above target speed in condition MAX (i.e. exceed) and the percentage of time around target speed in condition INTER (i.e. maintain). The percentage of success varied according to the *scenario* (Figure 4), and the participant target speed (Figure 5).

1) Percentage of Time Above Target Speed in Condition MAX: Participants succeeded significantly more during *scenario* 6 (81% SD 15.5% of time spent above target speed) than in other *scenarios* ($p<0.05$). The qualitative analysis showed a tendency that *scenarios* 1, 3, 4, and 5 helped to achieve speed goal in comparison to the *scenario* 7 (control without feedback) (Figure 4). Particularly, 75% people spent at least 73.1%

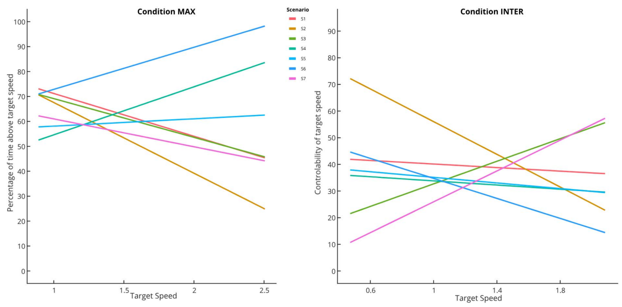

Fig. 5. Percentage of time above target speed in condition MAX and percentage of time around target speed in condition INTER. Data Analysis: Generalized linear model fit.

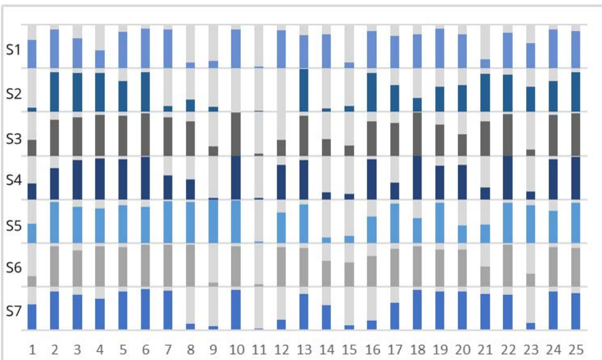

Fig. 6. Percentage of time around target speed in condition INTER. Individual results of the 25 participants.*Each line represents a scenario, each column a participant.*

of time above target speed in *scenario* 6 whereas 75% people spent 20.9% of time above target speed without feedback. 'Faster walkers' (i.e., participants who had a target speed superior to 1.5 m/s from the calibration) responses to *scenarios* were more heterogeneous (Figure 5): their performance were better with *scenarios* 4 and 6. 'Slowers walkers' performance were homogeneous, between 50% to 70%.

2) Percentage of Time Around Target Speed in Condition INTER: The percentage of time around target speed varied according to the *scenario* (Figure 4), and the participant target speed (Figure 5). Maintaining the target speed (i.e controlability) was not significantly impacted by the *scenario* (p=0.07). However, *scenario* 2 was the more effective (mean time spent around target speed was 73.4% SD 23.3) against *scenario* 6 (52.7% SD 32.5) and *scenario* 7 without feedback (66.0% SD 23.4). Particularly, 'Faster walkers' (i.e., participants who had a higher target speed from the calibration) performance was better in the more complex scenario (scenario 3 with gradient color and scenario 6). 'Slower walkers' better succeed to maintain their target speed in scenario 2 (Figure 5). The individual results showed that participants responses according to the *scenario* (Figure 6). Some of them always maintain their target walking speed at the correct value (participants 5 and 25). On the contrary, some participants always failed (participants 11 and 15). Others showed good results according to the scenario (participant 9 succeed only with scenario 5). These individuals results

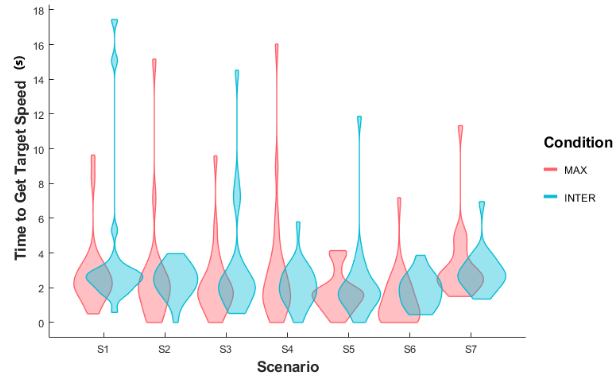

Fig. 7. Time to Reach the Target Speed for Condition MAX and INTER during the different scenarios, including feedback (S1 to S6) and control without feedback (S7). *In condition MAX, Scenarios 5 and 6 significantly decreased the time to reach target speed. Outliers showed people who did not reach their target walking pace quickly.*

highlighted different profiles of responders to the different scenarios.

D. Time to Reach Target Speed

The time to reach target speed varied according to the *scenario* (Figure 7).

1) Condition MAX: The *scenarios* 6 and 5 significantly decreased the time to reach target speed (respectively 1.28s SD 1.11s and 1.75s SD 0.86s) in comparison to the *scenario* 7 (control 3.31s SD 1.35s). Qualitative analysis revealed that in the *scenarios* 2-6, 75% people reached the target speed in less than 2s.

2) Condition INTER: The *scenario* 6 significantly decreased the time to reach target speed (1.86s SD 0.76s) in comparison to the *scenario* 7 (control 2.94s SD 0.82s). Qualitative analysis revealed that in the *scenarios* 2-6, 75% people reached the target speed in less than 2s.

E. The Ranking of Scenarios in Condition MAX

In condition MAX, the objective was to define the most practical combination of visual feedback characteristics delivered in augmented reality to reach and to exceed a target speed for people with cerebral palsy. Comparing the three outcomes (mean speed percentage relative to the target speed, percentage of time above target speed, and time to reach target speed) across *scenarios* during condition MAX, we established a ranking (Table III). All *scenarios* except S5 and control without feedback (S7) had a mean speed above the target speed. The "top 3" *scenarios* to spend more time above the target speed were S6, S4, and S1 (>62% of time above target speed). All *scenarios* helped to improve the performance outcomes in comparison to the control S7.

V. Discussion

This study explored the impact of augmented feedback characteristics to help people with motor disabilities to reach, to maintain and/or to exceed a target walking speed using an AR headset. Several scenarios combining different feedback characteristics were tested based on our theoretical model.

A. Feedback in AR to Improve Gait Parameters

With augmented reality, users can perceive digital objects (or "holograms") that co-exist in space and interact in real-time within physical environments [18]. This core feature allows us to design a walking rehabilitation system for disabled people in a real environment, based on augmented digital feedback. Patients can walk with their natural walking pattern and their walking aids. Augmented feedback characteristics could be multiple. In the rehabilitation context, the feedback content could vary according to the aim of the therapy, for example, improving specific kinematics or kinetics parameters. This study raises the question of the best combination of feedback characteristics to help people reach and maintain a target walking speed. This question has not been sufficiently explored, and the choice of our *scenarios* was based in particular on our previous results on healthy adults [21]. Some feedback characteristics increased walking speed, whereas others had a larger impact on speed variability. Specific recommendations from this previous study included using knowledge of results focusing on the outcome of a movement to create a more challenging task that motivates participants to excel, body-locked holograms that are easier to track and clarifying the game presentation. Previously, Baram *et al.* trained ten patients with CP with visual feedback. They used a display attached to the eyeglasses frame, providing an image of transverse lines, responding dynamically to the patient's motion [4]. They showed that walking speed measured along a straight track of 10 meters improved after 20 minutes of training using elementary visual feedback (+21.70 ± 36.06%). This improvement was greater for participants with baseline walking speed below the median (+35.75 ± ±47.76%). Using our model of feedback, we could classify their feedback as *{color = unicolor, spatial anchor = World-locked, speed relative to the player = player speed, speed relative to the world = null, persistence = full}* which is very close to the *scenario* 6 characteristics. Our results showed that success depends on children's gait speed during calibration and feedback. For percentage spent above target speed, even if it was only qualitative analysis, we observed in Figure 5 that children with baseline walking speed below the median ('slower walkers') presented more homogeneous results than faster walkers. *Scenarios* with feedback helped them, especially in condition MAX, but there was no *scenario* that surpassed the others. By contrast, for faster walkers, the feedback characteristics impacted their performance. In *scenario* 6, percentage spent above target speed is near 100% for these children which barely reached 20% of that amount in *scenario* 3. Providing relevant feedback to improve performance, especially walking speed, is crucial for rehabilitation. In stroke patients, prescriptive feedback (describing the errors and suggesting how to correct them) was found to be more effective than descriptive feedback (just relating the mistakes) [45]. Feedback delivered in real-time with an AR headset could be implicitly prescriptive by playing on challenges, rewards, motivation, and friendliness. In *scenario* 6, if the user doesn't catch the round shape ("the coin") in time, it disappears. So the user can easily understand that she/he is too slow (description of the error), and that she/he should speed up in order to win (suggestion to correct the error). Our results highlighted that the modification of visual aspect (*{color = gradient}*) helped to improve walking speed. The feedback attached to the world with fixed position (*{speed relative to the world = null}*) seemed to be better to minimize visual discomfort and, by extension, fatigue. There was some loss of tracking with movement, conducting to unstable holograms when the device could not locate itself within the real world. A faded persistence of the feedback created a playful challenge, working as a magnet for young people. The impact of augmented feedback on walking speed is explored in other rehabilitation context. For individuals' post-stroke, Alhirsan *et al.* [1] developed a VR exergame (Racing Game) in which the participant tests three experimental conditions with varying levels of augmented feedback. In condition 1, the participant only receives visible real-time display of his/her walking speed; in condition 2, same information than in Condition 1 and a representative avatar walker, using real-time walking speed data in a VR environment; in condition 3, same than Condition 2, and six other racers with pre-set speeds and an audience cheering for the racers. This game has one objective in common with our scenarios (condition MAX) as it aims to enhance the maximum walking speed. They describe "The game provides individuals post-stroke with minimal challenge levels above their attempted performance to win the race game, provide immediate feedback, and make walking tasks more game-like by including avatar competitors with different speeds". If we apply our theoretical model of feedback, condition 3 is similar to our scenario 1 adding a game interface. The results are not already known. This field of research, combining feedback, rehabilitation and VR game is being increasingly popular. Few results are available, but a lot of protocol studies have been published. Even if the literature converges on the positive impact of visual feedback on stability, asymmetry and balance, the precise modalities of feedback are not detailed [46].

B. Individual Responses to the Feedback

The results of this study confirmed that people with CP can adapt their walking speed and that they can positively respond to the real-time AR feedback [25]. However, we have observed that not all patients performed equally well with the scenarios. When we have looked at each participant's responses for each scenario, we have observed some key differences. Some people did not perform better with the feedback; others were helped by a particular scenario but disturbed in another scenario. Some authors highlighted these inter-individual differences. Slaboda *et al.* shown that the effect of continuous visual flow on the ability to regain and maintain postural orientation differed according the age of participants [43]. Recently, Liu *et al.* have underscored different patient profiles: "non-responders" and "responders" to the feedback. In their study, patients were people after stroke. They were instructed to walk on a treadmill while visualizing an avatar replicating their exact walking pattern in real-time on a large screen. Overall, patients improved step length and walking speed when the avatar was displayed on a side view. But results were not the same for all participants; the authors distinguished non-responders and responders to the feedback. They hypothesized that the initial step length ratio could influence the result because patients with a larger paretic step length better responded [136]. This study has shown that specific populations are more sensitive to the virtual environment [28]. Booth *et al.* added that self-perception of walking, preference, cognitive ability and previous experience with feedback could be other factors that influenced the results [7]. In our study, a qualitative distinction has been made between three profiles of participants when confronted with AR feedback (Figure 6). They could be defined as follows:

- "Responders" who had a high performance; i.e., a high mean speed and a high percentage of time above target speed, and who reached the target speed faster with feedback than in the control condition without feedback
- "Non-Responders" who performed equally well whatever the scenario was
- "Disturbed" who had lower performance and a longer time to reach target speed when the spatial anchor characteristic was *Body*, and longer time to reach target speed for other scenarios.

We can only formulate some hypotheses about those observations. After the session, a particular patient reported some bug in scenario 5, that could explain its "Disturbed" profile. Moreover, we observed that one patient did not perform at their best during the calibration, making the task too easy to realize during walking sprints. This too-easy task made the feedback superfluous for performance, which could explain its "Non-Responders" profile. These parameters need to be further explored in future studies evaluating feedback to explain these different profiles of response to AR feedback. Although this is a qualitative analysis, we have observed a low proportion of "Disturbed" patients and a high proportion of "Responders" patients that is very encouraging to develop the potential of AR systems and feedback for gait rehabilitation in children with CP. All these studies, and our results, have shown that specific populations are more susceptible to the virtual environment and respond differently than predicted. The potential of VR/AR systems and feedback is encouraging. More research on these inter-individual differences is required to personalize the VR/AR programs.

C. Gamification for Improved Experience

It is well known that a better-engaged patient performs more and better [1]. Motivation and engagement play a crucial role in the rehabilitation context, [16], especially for children who love playing. *Gamification* is the process that aims to influence the user's behavior and motivation by adding game mechanics, game elements, and game experience design in contexts that are initially utilitarian or serious. Gamification is a solution to improve the game-user (or patient-user) experience. Recently, Sardi *et al.* have identified the game elements employed in the digital healthcare domain (i.e., doing a therapy exercise a serious game): feedback/rewards (94% of studies investigated), progression (43%), social connection (37%), challenges/quests (26%), others (game currency, prizes) [40]. Gamification can also give users a sense of accomplishment and progress [9]. Feedback plays a crucial role to enhance motor learning and motivation level [30]. Use adaptive and mixed feedback modalities depending on the task complexity and patient's profile appear to be a good way to improve rehabilitation protocol [29]. Moreover, gamification should meet specific criteria to be efficient. Recently, inside the NEWTON project (large EU Horizon 2020 Innovation Action project), Zhao *et al.* created a multi-layer integrated framework for gamification. They proposed a combination of 4 layers (L1 to L4) : L1 - gamification layer providing game mechanics and rewarding rules; L2 - game-based learning defining the set of the game contents consuming the mechanics defined in the previous layer; L3 - Profiling and recommendation to personalize and adapt game-based learning according the learner's profile; L4 - Socialization allowing communication and sharing results between students and teachers [47]. Based on this work, we can envisage customizing our game elements according to this framework by implementing new game mechanics and customizing them according to the patients' profiles and interests.

D. Hololens Limitations

The Hololens AR headset presents some technical limitations [13]. First, during trials, children mentioned the restricted field of view (FOV) of the screen used to display the holograms (approximately 30° × 17°). Humans have a general static view of about 135 to 180 degrees horizontally, with about 120 degrees of binocular vision. With eyeball rotation (about 90 degrees), the field of view extends to 270 degrees. In addition, the vertical field of vision for humans is about 50 degrees in the upper visual field and 70 degrees in the lower visual field. Hololens FOV is much smaller and estimated to be about 30 degrees wide and 17.5 degrees high. So, the Hololens has a small portion of human vision, and there is a specific point where objects reach the end of the screen and disappear. Secondly, Coolen *et al.* compared the obstacle-avoidance maneuvers of participants stepping over either natural or holographic obstacles of different heights and depths. They showed that the number of observed obstacle collisions was considerably higher for holographic than natural barriers. They noticed significant, unnatural head adjustments of participants to view the holographic obstacle while crossing [14]. Moreover, wearing a head-mounted display while walking has an impact on kinematics and performance on a standard clinical test of dynamic balance (Time Up and Go Test) [2]. The headset can limit peripheral vision and increase head movement to explore the environment [26]. Finally, children reported that the HoloLens is not very comfortable with a weight of 579g.

E. Clinical Application

New technologies have been introduced in rehabilitation practice in recent years, both for upper and lower limbs therapy. To 'actively practice the task of walking', systems combining treadmill training and exergame delivered through a television screen in a semi-immersive environment have been tested. Results on patients with CP showed good adherence and improvement both in walking speed on the 10-meter walk test and distance traveled in the 2-minute walk test [12]. Recently, an innovative treadmill platform based on immersive virtual reality through a 180° semi-cylindrical screen (GRAIL from Motek) provided promising results both on Gross motor function, endurance, and walking speed on children with CP [6], [19]. Both these systems offer a possibility to provide high-intensity training in a multi-modal environment and variable practice but also to increase motivation level [42]. However, motor learning principles are not always fully integrated into VR/AR systems because of the lack of knowledge about which feedback characteristics and which intensity level should be provided in rehabilitation settings [16]. Only 42% of custom VR systems for rehabilitation delivered multi-sensory feedback that combined visual and auditory and/or haptic feedback [16]. In contrast, a combination of multi-modal feedback is recommended to be more effective for improving motor performance [42]. Our results bring information about effective visual feedback improving gait parameters. The next step of our project is to develop and test an active video game in AR for gait rehabilitation based on these first results, including visual and auditory feedback.

F. Study Limitations

Each session had a limited number of walking trials to ensure maximum quality, so there were a limited number of *scenarios* that have been tested. All participants performed 14*30 meters. It was chosen because of the restricted endurance of the patient with CP. A more in-depth questionnaire at the end of the experiment would have provided more precise feedback on the different game scenarios proposed. A structured interview will be conducted with each child during the next stages of the project to collect the user experience in a more precise way. Moreover, this study was a cross sectional one, the long-term effect of feedback intervention was not tested. Based on our findings, a randomized control trial (4-week protocol) with an active video game in AR including specific feedback characteristics is in progress. Finally, there are many factors to be considered in rehabilitation clinics to influence on the quality of walking, e.g., the fall risk, balance, etc, for people with cerebral palsy other than walking speed.

VI. Conclusion

Real-time visual feedback delivered through an AR headset is a feasible and acceptable intervention to provide immediate positive changes in walking speed for children with cerebral palsy. The feedback characteristics have an impact on the results, a *scenario* combining a gradient color, with fixed spatial anchor, disappearing according to the time demonstrated a significant increase in walking speed. Overall, the real-time feedback can provide many advantages as a gait training intervention: it could be implemented in an active and challenging video game; it received a positive evaluation from the participants as it is engaging and easy to understand; and most importantly, it provides unique concurrent information on walking performance that would otherwise be very difficult or even impossible for clinicians to deliver. In the future, clinical trials with multiple training sessions are needed to test the applicability of real-time feedback in the clinical setting.

Additional Files

Additional file 1 — Detailed Description of the displayed scenarios

Acknowledgment

The authors would like to thank all participants and people involved in this work and also would like to thank reviewers for their interesting comments. The software development has benefited from the expertise of PEARL Laboratory team, Bloorview Research Institute, Holland Bloorview Kids Rehabilitation Hospital, Toronto, Canada, in particular Pr. Elaine Biddiss, M. Ajmal Khan, and M. Alexander Hodge.

Disclosure

The authors declared no potential conflicts of interest concerning this article's research, authorship, and/or publication.

References

[1] S. M. Alhirsan, C. E. Capó-Lugo, and D. A. Brown, "Effects of different types of augmented feedback on intrinsic motivation and walking speed performance in post-stroke: A study protocol," *Contemp. Clin. Trials Commun.*, vol. 24, Dec. 2021, Art. no. 100863, doi: 10.1016/j.conctc.2021.100863.

[2] R. Almajid, C. Tucker, E. Keshner, E. Vasudevan, and W. G. Wright, "Effects of wearing a head-mounted display during a standard clinical test of dynamic balance," *Gait Posture*, vol. 85, pp. 78–83, Mar. 2021.

[3] E. A. Alcover, A. Jaume-i-Capó, and B. Moyà-Alcover, "PROGame: A process framework for serious game development for motor rehabilitation therapy," *PLoS ONE*, vol. 13, no. 5, May 2018, Art. no. e0197383, doi: 10.1371/journal.pone.0197383.

[4] Y. Baram and R. Lenger, "Gait improvement in patients with cerebral palsy by visual and auditory feedback," *Neuromodulation, Technol. Neural Interface*, vol. 15, no. 1, pp. 48–52, 2012, doi: 10.1111/j.1525-1403.2011.00412.x.

[5] K. Bell, S. Õunpuu, P. DeLuca, and M. Romness, "Natural progression of gait in children with cerebral palsy," *J. Pediatric Orthopaedics*, vol. 22, no. 5, pp. 677–682, Sep. 2002, doi: 10.1097/01241398-200209000-00020.

[6] E. Biffi, E. Beretta, and A. Cesareo, "An immersive virtual reality platform to enhance walking ability of children with acquired brain injuries," *Methods Inf. Med.*, vol. 56, no. 2, pp. 26–119, 2017, doi: 10.3414/ME16-02-0020.

[7] A. T. Booth, A. I. Buizer, J. Harlaar, F. Steenbrink, and M. M. van der Krogt, "Immediate effects of immersive biofeedback on gait in children with cerebral palsy," *Arch. Phys. Med. Rehabil.*, vol. 100, no. 4, pp. 598–605, Apr. 2019, doi: 10.1016/j.apmr.2018.10.013.

[8] A. T. C. Booth, A. I. Buizer, P. Meyns, I. L. B. O. Lansink, F. Steenbrink, and M. M. van der Krogt, "The efficacy of functional gait training in children and young adults with cerebral palsy: A systematic review and meta-analysis," *Develop. Med. Child Neurol.*, vol. 60, no. 9, pp. 866–883, Sep. 2018, doi: 10.1111/dmcn.13708.

[9] T. J. Brigham, "An introduction to gamification: Adding game elements for engagement," *Med. Reference Services Quart.*, vol. 34, no. 4, pp. 471–480, Oct. 2015, doi: 10.1080/02763869.2015.1082385.

[10] C. Bryanton, J. Bosse, M. Brien, J. Mclean, A. McCormick, and H. Sveistrup, "Feasibility, motivation, and selective motor control: Virtual reality compared to conventional home exercise in children with cerebral palsy," *Cyberpsychol. Behav.*, vol. 9, no. 2, pp. 123–128, 2006, doi: 10.1089/cpb.2006.9.123.

[11] R. Cano-de-la Cuerda *et al.*, "Theories and control models and motor learning: Clinical applications in neurorehabilitation," *Neurología*, vol. 30, no. 1, pp. 32–41, Jan. 2015, doi: 10.1016/j.nrleng.2011.12.012.

[12] C. Cho, W. Hwang, S. Hwang, and Y. Chung, "Treadmill training with virtual reality improves gait, balance, and muscle strength in children with cerebral palsy," *Tohoku J. Exp. Med.*, vol. 238, no. 3, pp. 213–218, 2016, doi: 10.1620/TJEM.238.213.

[13] S. Condino, M. Carbone, R. Piazza, M. Ferrari, and V. Ferrari, "Perceptual limits of optical see-through visors for augmented reality guidance of manual tasks," *IEEE Trans. Biomed. Eng.*, vol. 67, no. 2, pp. 411–419, Feb. 2020, doi: 10.1109/TBME.2019.2914517.

[14] B. Coolen, P. J. Beek, D. J. Geerse, and M. Roerdink, "Avoiding 3D obstacles in mixed reality: Does it differ from negotiating real obstacles?" *Sensors*, vol. 20, no. 4, p. 1095, Feb. 2020, doi: 10.3390/S20041095.

[15] M. Demers, K. Fung, S. Subramanian, M. Lemay, and M. T. Robert, "Do virtual interventions in individuals with cerebral palsy make use of motor learning principles? A systematic review," *JMIR Serious Games*, Aug. 2020, doi: 10.2196/23822.

[16] M. Demers, K. Fung, S. Subramanian, M. Lemay, and M. Robert, "Integration of motor learning principles into virtual reality interventions for individuals with cerebral palsy: Systematic review," *JMIR Serious Games*, vol. 9, no. 2, pp. 1–18, 2021, doi: 10.2196/23822.

[17] M. Frikha, N. Chaâri, Y. Elghoul, H. H. Mohamed-Ali, and A. V. Zinkovsky, "Effects of combined versus singular verbal or haptic feedback on acquisition, retention, difficulty, and competence perceptions in motor learning," *Perceptual Motor Skills*, vol. 126, no. 4, pp. 713–732, Aug. 2019, doi: 10.1177/0031512519842759.

[18] B. Furht, *Handbook of Augmented Reality*. New York, NY, USA: Springer, Aug. 2011.

[19] C. Gagliardi *et al.*, "Immersive virtual reality to improve walking abilities in cerebral palsy: A pilot study," *Ann. Biomed. Eng.*, vol. 46, no. 9, pp. 1376–1384, Sep. 2018, doi: 10.1007/S10439-018-2039-1.

[20] H. Graham *et al.*, "Cerebral palsy," *Nature Rev. Disease Primers*, vol. 2, no. 1, p. 15082, Dec. 2016, doi: 10.1038/nrdp.2015.82.

[21] A.-L. Guinet, G. Bouyer, S. Otmane, E. Biddiss, and E. Desailly, "Development of a serious game for gait intervention in augmented reality: A prospective study on the impact of virtual feedback on walking speed," *Gait Posture*, 2021.

[22] A.-L. Guinet, G. Bouyer, S. Otmane, and E. Desailly, "Reliability of the head tracking measured by Microsoft Hololens during different walking conditions," *Comput. Methods Biomech. Biomed. Eng.*, vol. 22, pp. 159–161, Oct. 2019, doi: 10.1080/10255842.2020.1714228.

[23] A.-L. Guinet, G. Bouyer, S. Otmane, and E. Desailly, "Validity of Hololens augmented reality head mounted display for measuring gait parameters in healthy adults and children with cerebral palsy," *Sensors*, vol. 21, no. 8, p. 2697, Apr. 2021, doi: 10.3390/S21082697.

[24] M. K. Holden, "Virtual environments for motor rehabilitation: Review," *Cyberpsychol. Behav.*, vol. 8, no. 3, pp. 187–211, Jun. 2005, doi: 10.1089/cpb.2005.8.187.

[25] J. Jelsma, M. Pronk, and D. Jelsma-Smit, "The effect of the Nintendo Wii Fit on balance control and gross motor function of children with spastic hemiplegic cerebral palsy," *Develop. Neurorehabilitation*, vol. 16, no. 1, pp. 27–37, 2013, doi: 10.3109/17518423.2012.711781.

[26] J. F. Knight and C. Baber, "Effect of head-mounted displays on posture," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 49, no. 5, pp. 797–807, Oct. 2007, doi: 10.1518/001872007X230172.

[27] M. Levin, "Feedback and virtual environments for motor learning and rehabilitation," *Schadae*, vol. 1, pp. 19–36, Jan. 2010.

[28] L. Y. Liu, S. Sangani, K. K. Patterson, J. Fung, and A. Lamontagne, "Real-time avatar-based feedback to enhance the symmetry of spatiotemporal parameters after stroke: Instantaneous effects of different avatar views," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 4, pp. 878–887, Apr. 2020, doi: 10.1109/TNSRE.2020.2979830.

[29] S. Lopes *et al.*, "Games used with serious purposes: A systematic review of interventions in patients with cerebral palsy," *Frontiers Psychol.*, vol. 9, p. 1712, Sep. 2018, doi: 10.3389/fpsyg.2018.01712.

[30] A. MacIntosh, E. Lam, V. Vigneron, N. Vignais, and E. Biddiss, "Biofeedback interventions for individuals with cerebral palsy: A systematic review," *Disability Rehabil.*, vol. 41, pp. 2369–2391, May 2018, doi: 10.1080/09638288.2018.1468933.

[31] J. Moizer *et al.*, "An approach to evaluating the user experience of serious games," *Comput. Educ.*, vol. 136, pp. 141–151, Jul. 2019, doi: 10.1016/j.compedu.2019.04.006.

[32] I. Novak *et al.*, "State of the evidence traffic lights 2019: Systematic review of interventions for preventing and treating children with cerebral palsy," *Current Neurol. Neurosci. Rep.*, vol. 20, no. 2, pp. 1–21, Feb. 2020, doi: 10.1007/S11910-020-1022-Z.

[33] D. Oeffinger, A. Bagley, and S. Rogers, "Outcome tools used for ambulatory children with cerebral palsy: Responsiveness and minimum clinically important differences," *Developmental Med. Child Neurol.*, vol. 50, no. 12, pp. 918–925, 2008, doi: 10.1111/J.1469-8749.2008.03150.X.

[34] N. Oliveira, N. Ehrenberg, J. Cheng, S. Blochlinger, and P. Barrance, "Visual kinematic feedback enhances the execution of a novel knee flexion gait pattern in children and adolescents," *Gait Posture*, vol. 74, pp. 94–101, Oct. 2019, doi: 10.1016/j.gaitpost.2019.06.016.

[35] A. Opheim, J. McGinley, E. Olsson, J. Stanghelle, and R. Jahnsen, "Walking deterioration and gait analysis in adults with spastic bilateral cerebral palsy," *Gait Posture*, vol. 37, no. 2, pp. 165–171, Feb. 2013, doi: 10.1016/j.gaitpost.2012.06.032.

[36] A. Orand, J. Ushiba, Y. Tomita, and S. Honda, "The comparison of motor learning performance with and without feedback," *Somatosensory Motor Res.*, vol. 29, no. 3, pp. 103–110, 2012, doi: 10.3109/08990220.2012.687419.

[37] D. T. Reid, "Benefits of a virtual play rehabilitation environment for children with cerebral palsy on perceptions of self-efficacy: A pilot study," *Pediatric Rehabil.*, vol. 5, no. 3, pp. 141–148, 2002, doi: 10.1080/1363849021000039344.

[38] R. Ronsse *et al.*, "Motor learning with augmented feedback: Modality-dependent behavioral and neural consequences," *Cerebral Cortex*, vol. 21, no. 6, pp. 1283–1294, Jun. 2011, doi: 10.1093/cercor/bhq209.

[39] P. Rosenbaum *et al.*, "A report: The definition and classification of cerebral palsy April 2006," *Develop. Med. Child Neurol. Suppl.*, vol. 109, 109, pp. 8–14, 2007.

[40] L. Sardi, A. Idri, and J. L. Fernández-Alemán, "A systematic review of gamification in e-Health," *J. Biomed. Informat.*, vol. 71, pp. 31–48, Jul. 2017, doi: 10.1016/j.jbi.2017.05.011.

[41] E. Sellier *et al.*, "Decreasing prevalence in cerebral palsy: A multi-site European population-based study, 1980 to 2003," *Develop. Med. Child Neurol.*, vol. 58, no. 1, pp. 85–92, Jan. 2016, doi: 10.1111/dmcn.12865.

[42] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review," *Psychon. Bull. Rev.*, vol. 20, no. 1, pp. 21–53, Feb. 2013, doi: 10.3758/S13423-012-0333-8.

[43] J. C. Slaboda, R. T. Lauer, and E. A. Keshner, "Continuous visual field motion impacts the postural responses of older and younger women during and after support surface tilt," *Exp. Brain Res.*, vol. 211, no. 1, pp. 87–96, May 2011, doi: 10.1007/S00221-011-2655-6.

[44] K. J. Sullivan, S. S. Kantak, and P. A. Burtner, "Motor learning in children: Feedback effects on skill acquisition," *Phys. Therapy*, vol. 88, no. 6, pp. 720–732, Jun. 2008, doi: 10.2522/ptj.20070196.

[45] P. M. van Vliet and G. Wulf, "Extrinsic feedback for motor learning after stroke: What is the evidence?" *Disab. Rehabil.*, vol. 28, nos. 13–14, pp. 831–840, Jul. 2006, doi: 10.1080/09638280500534937.

[46] L. A. Vos, M. R. Prins, and I. Kingma, "Training potential of visual feedback to improve dynamic postural stability," *Gait Posture*, vol. 92, pp. 243–248, Feb. 2022, doi: 10.1016/j.gaitpost.2021.11.040.

[47] D. Zhao, J. Playfoot, and G. Muntean, "An innovative multi-layer gamification framework for improved STEM learning experience," *IEEE Access*, vol. 10, pp. 3879–3889, 2022, doi: 10.1109/ACCESS.2021.3139729.

[48] M. Zwinkels *et al.*, "Effects of high-intensity interval training on fitness and health in youth with physical disabilities," *Pediatric Phys. Therapy*, vol. 31, no. 1, pp. 84–93, Jan. 2019, doi: 10.1097/PEP.0000000000000560.