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Abstract Exergames are serious games that involve physical exertion and are thought of as a form of exercise by using novel input models. Exergames are promising in improving the vestibular impairments of children with autism but often lack of adaptation mechanisms that adjust the difficulty level of the exergame. In this paper, we present the design and development of Circus in Motion, a multimodal exergame supporting children with autism with the practice of non-locomotor movements. We describe how the data from a 3D depth camera enables the tracking of non-locomotor movements allowing children to naturally interact with the exergame . A controlled experiment with 12 children with autism shows Circus in Motion excels traditional vestibular therapies in increasing physical activation and the number of movements repetitions. We show how data from real-time usage of Circus in Motion could be used to feed a fuzzy logic model that can adjust the difficulty level of the exergame according to each child's motor performance. We close discussing open challenges and opportunities of multimodal exergames to support motor therapeutic interventions for children with autism in the long-term.

Keywords Autism · exergame · vestibular system · children

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1 Introduction

Autism is a neurological disorder associated with cognitive impairments in communication, social interaction, and behavior [2]. Around 80% of children with autism exhibit significant sensory and motor disorders [26,47] and have different sensory integration capabilities [3][1], where the vestibular system is one of the most affected [2,4]. As a consequence, children with autism exhibit motor stereotypes (e.g., rocking, arms flapping) [2,25], balance problems, and atypical postures [27]. For example, they find it difficult to walk on uneven floors.

The vestibular system enables humans to maintain balance and orientation dealing with gravity challenges that may result in falls when standing up or when making complex movements[25]. To stimulate the vestibular system, vestibular therapies, using techniques from motor therapeutic interventions, create situations where patients could develop abilities for the self-regulation of movements and interpretation of sensory stimuli, thus, improving their balance and posture [12].

Vestibular therapy sessions usually include exercise routines consisting of the repetition of non-locomotor movements with changes in the patient's base of support. For example, during a session, therapists could ask patients to keep their arms steady while jumping on one foot [5]. To show children with severe autism how to do the movements during a vestibular therapy, the therapists use different visual supports as a strategy to model the behavior. (e.g., puppets, sequential visualizations of the movement) [35]. However, success-

[1] The unconscious process of the brain to organize information detected by one's senses and allow them to respond to the situation in a purposeful manner [3]

ful vestibular therapy is challenging given that (1) children with autism may find confusing and not engaging the visual supports; (2) they may find boring the task-repetition activity; and (3) there is a lack of mechanisms to evaluate and model the non-locomotor movements. As a consequence, most children with autism disengage from vestibular therapy before they accomplish the therapy goals, limiting their possibilities to improve their vestibular impairments.

Moreover, therapists determine the difficulty of the exercise routine of vestibular therapy based on each patients' motor capabilities. Most of the time, therapists need to adjust the difficulty level to challenge their patients and ask them to perform more complex movements while keeping them engaged during the therapy [51]. This dynamic game fine-tuning is a complex and time-consuming task for therapists. When this 'adjustment' is incorrectly made, it could highly affect patients' engagement and hinder their possibilities to properly complete the exercise routine because they lose their attention or get frustrated.

To cope with issues related to engagement and repetition of movements, some specialists have incorporated exergames into their motor therapeutic interventions [1, 9,22]. Exergames are serious games that involve physical exertion and are thought of as a form of exercise [43]. The use of exergames in motor therapies improves the rehabilitation process [51], offers multiple clinical benefits for children with neurodevelopmental disorders [23], helps patients to maintain the necessary physical activation during the therapy [41], and allows specialists [2] to collect relevant and detailed data for modeling the non-locomotor movements and assessing progress [18].

However, several research questions still need to be answered to successfully integrate exergames into the vestibular therapy of children with autism. The research questions that lead this project are:

1. What are the non-locomotor movements an exergame should incorporate to support the vestibular therapies of children with autism appropriately?
2. In which situations exergames excel traditional visual support material used during vestibular therapies supporting children with autism?
3. What behaviors could be used to design an adaptation mechanism for the dynamic game fine-tuning.

To answer these research questions, in this paper, we describe the design, development, and evaluation of Circus in Motion, a multimodal exergame to support the practice of non-locomotor exercises during a vestibular therapy.

[2] All the stakeholders with experience in vestibular therapies and motor skills development of children with autism including psychologist, physiotherapists, and clinicians

The main contributions of this wok include:

1. The design and development of a multimodal exergame prototype using a 3D depth camera to track the non-locomotor movements of children with autism;
2. empirical evidence showing how a multimodal exergame could potentially support the vestibular therapies of children with autism as a realization of the use of such interfaces;
3. a set of trigonometric functions to infer non-locomotor movements of children with autism;
4. a use case showing how the modeling of interaction from real-time usage of Circus in Motion could be used to design an adaptive mechanism according to each child's motor performance.

2 Related Work

In this section, we first describe research related to the design and evaluation of exergames supporting children with autism. We then describe examples of exergame to support the vestibular system, particularly focusing on posture and balance. Finally, we describe examples of exergames using adaptation mechanisms to balance the difficulty according to each player's skills.

2.1 Exergames supporting children with autism

Research has shown an increased interest in using exergame interventions to support children with autism [15], focusing on physical exercise in a classroom setting, in a motor therapeutic context, or in helping children recognize and express emotions through movements [7,10,11,37,40]. For example, FroggyBobby is an exergame where children with autism used arm movements to control and redirect the tongue of an avatar; in this case, a frog, to collect flying flies[10]. A deployment study, with seven children with autism, found that FroggyBobby improved the control of upper-limb movements after seven weeks of using the exergame.

Another example is the exergame designed by Bhattacharya et al. [7]. In this exergame, children with autism use hand movements to catch virtual objects to score points. A deployment study showed children with autism conducted novel movements during the game (i.e., movements that are uncommon when practicing exergames such as sitting down, crawling, and bending down) that could impact children's engagement, social behavior, and motor skills.

Overall, these results show that exergames are engaging for children with autism, and had promising support of the motor movement. However, it is not clear how to design an exergame that supports the vestibular system of children with autism.

2.2 Exergames supporting the vestibular system

Previous research has explored how to support the vestibular system focusing on improving the postural control [1,19] and both the dynamic [1] and static balance [8] using interactive prototypes[34], games in-lab [9,48] or videogames[9,22].

To support posture, exergames have explored how to improve the postural stability of patients by demanding them to practice activities related to strength and flexibility [41] (e.g., the iDance^{TM}, the Wii Fit^{TM} Plus, and the XR-Board^{TM}). For example, XR-Board^{TM} Dueller System offers a snowboard simulator that requires players to maintain their balance when navigating their way through a series of obstacles on a virtual ski slope. Players use a snowboard-shaped platform to control the digital animations of the exergame. The iDance^{TM}, the Wii Fit^{TM} Plus, and the XR-Board^{TM} exergames were used for 21 fourth grade neurotypical children for six weeks during their physical education classes. Results from the evaluation showed that exergames are a practical resource for physical education classes and are instrumental in improving the postural stability of children [41].

Another example is Physical Training Technology Probes (TTP)[34], a set of wearables devices that provide visual and audible feedback about bad postures. A deploy study with seven kids with Sensory-based Motor Disorder for six weeks shows that TTP helps children to maintain a static posture and become more aware of balance and posture control. However, these exergames, although some commercially available, have not yet been evaluated with children with autism.

Similarly, researchers have proposed exergames to help older adults and children with autism to better control their balance (e.g., Balance Game [8], Pixel Balance [19], V2R [1], and Travers et al. exergame[48]). For example, V2R [1] is an exergame that uses the Nintendo Wii Balance Board (WBB) to mimic activities that help people with vestibular problems to test their balance by practicing how to sit and stand up. The exergame helps patients to understand how to distribute their weight from one limb to another (e.g., the patient moves his feet from left to right by shifting his weight in the standing position). An evaluation with individuals with vestibular problems (aged between 18 and 80 years old) found that V2R could accelerate the recovery process of the patient in an independent manner [1]. This research project shows that exergames could successfully integrate the motor movements used during traditional vestibular therapies. However, the movements selected are focused on improving gait, and the sensor used is not appropriate for children with autism who may be at potential risk of falling [20].

More relevant to our work is Pixel Balance [19], and Travers et al.[48] exergame. Pixel Balance [19] is a motion-based touchless exergame demanding from children with autism to mimic pre-defined body shapes displayed in a virtual world. When the child 'covers' the shape with his posture, the exergame rewards him with a three seconds cartoon. The therapist manually configures each child's preferences and motor capabilities before each child plays with Pixel Balance. A deployment study of the use of Pixel Balance with five children with autism (aged 6 – 8 years old), during six sessions, found that Pixel Balance promotes the development of imitation skills, and helps children with autism to develop capabilities of body awareness and postural control.

Travers et al.[48] developed a game in the laboratory to train balance in young people with autism. The game consists of six ninja poses, three poses where both feet are used, and three poses where only one foot is used. Researchers selected those poses from Tai Chi and Yoga. While the children hold the pose, the exergame rewards them with a background scene that makes darker every second. To personalize the difficulty of the in-lab game, a research assistant defines a goal time per child to hold the posture (between 5 to 120s). A deployment study with twenty-nine children with autism, during eighteen sessions, found that this game allows the improvement of the poses and balance.

This body of work shows that exergames are appropriate to support patients with vestibular problems during vestibular therapies, mainly concerning balance and postural control. However, there is no evidence of what are the motor movements appropriate to support children with autism during vestibular therapies and if exergames could model those movements. There are open research questions regarding how to adjust children's capabilities automatically and the difficulty of the exercise routines to improve the efficacy of motor therapeutic interventions supported through exergaming.

2.3 Adaptation in exergames

Other research projects on artificial intelligence for exergaming have been focused in proposing adaptation mechanisms to balance the game difficulty and player's skills [31,38]. For example, Fruit Catcher, and Hay Collect [38] are two of the eleven exergames designed to support the rehabilitation of patients' posture and balance after a stroke. Both games support the lateral weight shift by small trunk movements. In the Fruit Catcher game, patients need to catch fruits that are falling from a tree. In Hay Collect, players' movements control a tractor to catch the hay bales and avoid rock formations. The frequency of the fruit falling and the hay bales are adjusted according to the patient's performance. The adaptation mechanism is updated using the Intelligent Game Engine for Rehabilitation (IGER) [38] . The IGER consists of a fuzzy system that captures the knowledge of the therapist about the motion performance of the player. The information is shown to the player using color-codes superimposed on top of each patient's avatar. A preliminary evaluation with patients suggests that the system could maintain a proper challenge level while keeping patients motivated. This example shows that the choice of difficulty for an exercise is associated with its therapeutic goal [29].

In general, these projects suggest that exergames could support the needs of patients during therapies and are appropriate for children with autism [19]. However, research to support children with autism during vestibular therapies is still scarce, and there is no evidence of which behaviors should be selected to design an intelligent adaptation mechanism for the dynamic game fine-tuning.

3 Circus in Motion

The Circus in Motion prototype is a multimodal exergame that allows children with autism to practice non-locomotor movements mimicking traditional vestibular therapies. The goal of the exergame is to help an avatar visit several circus acts and obtain visual and auditory rewards. Circus in Motion was designed to be used in a school-clinic specialized in the care of children with autism and is recommended to be set up by a psychologist.

The following scenario illustrates one example of the usage of Circus in Motion:

Marley is an eight years old child with autism with problems when trying to maintain his balance and posture. Marley and her teacher Miss Bella use Circus in Motion to practice non-locomotor movements. Miss Bella is a trained psychologist-teacher at the school-clinic that sets-up the exergame, gives physical prompts to Marley when needed, and validates that Marley is doing the therapy properly. First, Miss Bella sets-up the exergame specifying that Marley needs to complete ten repetitions by visiting all the Circus acts. Miss Bella activates the virtual jackpot machine. Circus in Motion shows the movement Marley must practice and the circus act. Marley must complete ten repetitions of lifting his right leg to control a clown's movement. Circus in Motion shows a map with an animation of digital footprints entering into the clown's act. When the footprints arrive at the selected circus act, the map blinks. Now it is time for Marley to practice the act. Circus in Motion shows a mini-tutorial where a digital avatar lifts his right foot, modeling the motor movement. After the tutorial, Marley is ready to practice the exercise. Marley lifts his right leg, and the clown mirrors his movement. When needed, miss Bella physically helps Marley to complete a movement. After seven repetitions, Marley stops moving, and Circus in Motion prompts Marley by saying, "Lift your right leg." As Marley does not pay attention to the verbal prompts that Circus in Motions gives after 5, 10, and 15 seconds, Circus in Motion automatically moves the clown and plays a sound. Finally, Marley successfully finishes his ten repetitions, and Circus in Motion rewards him with claps and balloons. Marley laughs, and Miss Bella congratulates him and makes a note of the progress of the child.

3.1 Design methods

To design the exergame, we followed an iterative user-centric design methodology [50]. First, we conducted two semi-structured interviews with specialists in psychology and rehabilitation therapies to discuss topics about the activities conducted during vestibular therapies, the material used, and the techniques being used to reward and prompt children with autism. Then, we conducted 15 hours of non-participatory observation of children with autism during vestibular therapies.

In order to have participants actively involved in the design process, we supplemented our interviews and observations with six design sessions with specialists (Table 1). During the design sessions, one HCI expert led

Table 1 Details of the participatory design sessions

#	Objective	Participants
1	To uncover a set of non-locomotor movements	1 physical therapist 1 HCI[1] student
2	To propose a set of low-fidelity prototypes	1 HCI expert 1 HCI student
3	To specify the movements proposed by specialists	1 physical therapist 1 HCI student
4	To propose novel ways of interaction	1 HCI student 1 HCI expert
5	To select the final prototype	2 HCI expert 1 psychologist of Pasitos 1 HCI student
6	To specify the difficulty levels	1 physical therapist 1 HCI student

[1]Human-Computer Interaction (HCI)

the session and encouraged specialists to brainstorm and reflect on prototype proposals and design ideas. This process led to low-fidelity prototypes and the specification of the exergame final design.

For data analysis, we transcribed all the interview data and observation reports. Data analysis included the use of qualitative techniques, such as open and axial coding, to score our interviews and then group our codes in an affinity diagram [13]. All the data collected during our design sessions were analyzed using techniques from rapid contextual design, such as sketches, storyboards, and new ideas for potential activities to incorporate on the proposed prototypes [50].

3.2 Findings

In the following sections, we describe the main findings of the design. We first present the non-locomotor movements an exergame should model to support the vestibular therapies of children with autism. Then, we describe the suggested prompting and rewards modeling. Finally, we present the game dynamic that specialists suggested to incorporate in the exergame to encourage children to perform the non-locomotor movements.

3.2.1 Motor movements

We found out that vestibular therapy should support non-locomotor movements that challenge children with autism to change their base of support, known their body scheme, move their head, and jump upright (Table 2). Each of these movements should vary the difficulty levels. For example, lifting the right foot is as challenging as lifting the left foot; however, standing on tiptoes involves more challenges related to strength and balance.

Therapists must select the difficulty level for each child, and the number of repetitions per movement. The children must perform all the movements in one session. To avoid the "accommodation effect,"[3] the exergame should randomly select the movements.

3.2.2 Multimodal prompts and rewards

Our findings indicate that prompts and rewards are fundamental to support the therapies of children with severe autism. Prompts involve verbal indications, to redirect the attention of the child; movement modeling, to help the child to imitate behaviors; and/or physical help, where the therapist physically moves children's body. Rewards can be given away in short- and long-term to increase children's engagement [32].

Specialists suggest that the exergame should trigger verbal and modeling prompts every five seconds (i.e., at 5, 10, and 15 seconds) three times before the physical help. Exergame verbal prompts include instructions on how to complete the non-locomotor movement; and modeling is provided to mirror animations of the corresponding movement (Table 3). After receiving the prompts, if the child does not correctly complete the movement, the exergame should compute the trial as 'incorrect' and moves to the next repetition. Even when the trial is marked as incorrect, moving along the game will reduce children's frustration and will give them a sense of completeness [32].

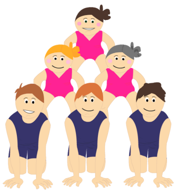
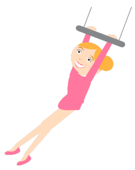
The exergame should provide short- and long-term rewards. Short-term rewards are provided every time patients correctly perform a movement (i.e., each trial), whereas long-term rewards are provided when patients finish the activity and complete the exercise routine (Table 3). Rewards can be sounds for each movement repetition and attractive visualizations like animated balloons at the end of the routine (Figure 1d).

3.2.3 Gameplay

The gameplay dynamic of Circus in Motion aims to help an avatar visit several circus acts and obtain visual and auditory rewards. Each non-locomotor movement was matched with a circus act and avatar (Table 2). In this manner, Circus in Motion encourages children with autism to perform all the non-locomotor movements while visiting all the circus acts.

[3] Children with autism could get used to performing the exercises in the same order, so we counterbalanced this problem by randomly selecting the exercises children with autism must practice

Table 2 Details of the motor movements and difficulty levels

Circus Act	Objective	Movement description and difficulty level [level]	Description of the circus act
Human Tower 	Changes a patient's base of support	[0] Lift the right foot and left hand. [0] Lift the left foot and right hand [1] Stand on tiptoes	Every time a child performs a correct movement, one character is added to the human tower. The human tower mimics the equilibrium that the child is trying to keep when changing the base of support.
Trapeze 	Non-locomotor movement (Head)	[0] Move the head left-right [0] Move the head right-left [1] Move the head up-down [1] Move the head down-up [2] Roll the head	Every time a child performs a correct movement, the trapeze artists will balance. The balanced movement mimics what children feel when moving their heads.
Fire ring 	Non-locomotor movement (Vertical Jump)	[0] Jump with the feet separately [1] Jump with the right foot [1] Jump with the left foot [2] Jump with both feet together [3] Jump alternating the foot	Every time a child jumps, the lion jumps. The lion mimics the jump of the child.
Clowns 	Body scheme	[0] Lift the right hand [0] Lift the left hand [0] Lift the right foot [0] Lift the left foot	The clown moves his extremities to mimic the movement a child is practicing acting like a mirror.

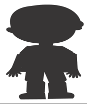
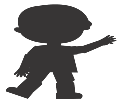
As suggested by specialists during our fifth participatory design session, we used analogies to represent the movements into each circus act. They commonly used similar analogies during therapy to ease the understanding of the children, as it supports positive behavior, psychological changes, and makes instructions more appealing to children when exercising [49].

The gameplay of Circus in Motion works as follows, to select the circus act, the therapist first pulls a virtual 'jackpot machine' (Figure 1a). Then, the exergame shows on the left side of the screen, the selected circus act, and on the right side, the movement that the patient should practice (Figure 1a), followed by an animation of the avatar going to the selected circus act showed in a map containing all the circus acts (Figure1b).

Next, the exergame displays a mini-tutorial using the virtual avatar to model the movement the children must practice (Figure 1c). At the end of the mini-tutorial, the exergame displays the avatar, the number of repetitions the patient must complete, and the trials the patient has performed (Figure 1c). Every time each child performs a movement, on the right side of the exergame, the avatar performs the circus act. For example, when the children jump, the exergame will show an animation of a lion jumping through a ring of fire.

The graphics of the avatars and the circus acts were designed following the guidelines for the design of visual supports [17] that have been previously used when designing technological interventions for children with autism [21, 24, 45]. Specialists also emphasize the importance of keeping the graphics as simple as possible to

Table 3 Modeling of prompts

Movement	Visual prompt		Auditory prompt
	From	To	
Lift the right foot and left hand.			"Lift your right foot and your left hand."
Lift the left foot and right hand.			"Lift your left foot and your right hand."
Move the head right-left.			"Move your head from right to left."
Lift the right hand			"Lift your right hand."
Lift the left foot			"Lift your left foot."
Lift the right foot			"Lift your right foot."

let children better focus on the practicing of the movements.

3.3 Developing Circus in Motion

Circus in Motion uses a 3D depth camera (i.e, the Microsoft Kinect sensor) to detect a child's movement. The 3D depth camera is connected via USB to the PC running the gameplay of the exergame. Circus in Motion uses a multimedia projector to display the visualizations and a pair of speakers to reproduce the sounds. The gameplay dynamic of Circus in Motion has been developed in C using the Microsoft Kinect SDK [4] and the XNA framework to handle multimedia events (Figure 2).

3.3.1 Modeling the non-locomotor movements interactions

To model the non-locomotor movements, we use the Microsoft Kinect-for-Xbox model 1473. The Kinect sensor has two cameras (i.e., RGB and infrared), an infrared (IR) emitter, 3 microphones and a 3-axis accelerometer.

To detect users, Kinect uses the IR emitter and IR sensor. The IR sensor has a frame rate of 30 fps and it is capable of tracking up to two users in a range of 2.6 to 13.1 feet. Once one user is detected, the sensor returns a set of twenty joints. We used the Skeleton library of the Microsoft Kinect SDK v1.8 [5] to gather the position of the twenty joints of the child's body and transform them into 3D coordinates. Using the coordinate's data, we defined trigonometric functions to compute a number that will indicate the movement being executed by the patient. If such a number is within a threshold, then the exergame will display the appropriate animation (Table 4).

To define each threshold, we conducted a pilot experiment with four neurotypical children without vestibular problems who performed all the exercises. Children performed ten repetitions of every movement, and for each participant, we computed the average of all the completed repetitions. This average was used to define the thresholds being used in Circus in Motion empirically. For example, to infer if the user is lifting his right hand, the exergame verifies if the angle between his/her shoulder and his arm is greater than or equal to 45 degrees.

[4] https://www.microsoft.com/en-us/download/details.aspx?id=40278

[5] http://www.microsoft.com/en-us/download/details.aspx?id=40278

Fig. 1 A graphic representation of the gameplay of Circus in Motion

Table 4 Trigonometric functions to infer the motor movements patients must practice when playing with Circus in Motion

Movement	Trigonometric functions	Threshold
Jump	$\frac{rightFoot.y+leftFoot.y}{2}$	≥ 5
Lift a hand	$\tan^{-1}\frac{hand.y-shoulder.y}{hand.x-shoulder.x}$ wrist.z $\approx hand.z \approx shoulder.z \approx elbow.z$	$\geq 45°$
Lift a foot	$\cos^{-1}\frac{foot.x*knee.x+foot.y*knee.y+foot.z+knee.z}{\sqrt{knee.x^2+knee.y^2+knee.z^2}*\sqrt{foot.x^2+foot.y^2+foot.z^2}}$	$\geq 18°$
Head movement	$\tan^{-1}\frac{head.y-neck.y}{head.x-neck.x}$	$77° < x < 103°$

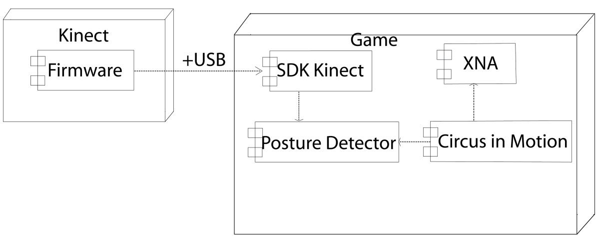


Fig. 2 Deployment diagram of Circus in Motion.

3.3.2 Delivery of multimodal prompts and rewards

Circus in Motion triggers verbal and gestural prompts when the user unsuccessfully completes the movement (Table 4). After that, and to avoid frustration, the exergame continues with the next exercise repetition -even if the child performs incorrectly the movement (Algorithm 1).

Circus in Motion gives short-term rewards where users receive a star when completing one repetition, either by themselves or after three audible prompts without response (Algorithm 1). Whereas when users finish all the repetitions, Circus in Motion displays an animated short film as a reward for completing a long-term goal (Algorithm 1).

Algorithm 1: Prompts and rewards

```
Result: visual and audible aids or rewards
Movements' states;
while state is static and prompt ¡ 4 do
    repeat instruction;
    increase prompt;
end
if state is movement or prompt = 4 then
    move avatar;
    play trial complete sound;
    if activity is finished then
        play activity complete sound ;
    end
    if activities are complete then
        show final screen;
        play clap sound;
    end
end
```

4 Evaluation of Circus In Motion

We conducted a controlled experiment to evaluate the use of Circus in Motion in a real-life setting at a school-clinic in order to:

1. Assess the performance of our algorithms to infer non-locomotor movements.
2. Understand in which situations Circus in Motion could assist traditional vestibular therapies.

4.1 Methods

We conducted a within-subjects controlled experiment with 12 children with autism, where participants assisted in a vestibular therapy session in two conditions:

1. using Circus in Motion and
2. using a foam puppet commonly used as a visual support during a traditional therapy.

In both conditions, we collected data about the movements performed by the participants to assess the performance of the proposed algorithm in general. Then, we compared both conditions to understand in which situations Circus in Motion could assist traditional vestibular therapies.

4.1.1 Participants

Twelve children with severe and mild autism, from 5 to 12 years old attending a public school-clinic located in the Northwest of Mexico (”Pasitos”), took part in the controlled experiment. All participants[6] were able to follow instructions, were not medicated, and did not have a bone fracture or a sprain. All the participants were diagnosed with sensory processing disorders and exhibited atypical posture and balance problems.

We followed the ethical considerations suggested by “Pasitos.” The Institutional Board of Pasitos approved the controlled experiment, and all parents consented on behalf of their children. We recruited participants through a meeting we had with the staff of Pasitos, where we explained an overview of the controlled experiment and risk and benefits for their participation. To protect the data collected, only the researchers involved in the controlled experiment had access to the data, and all the information was de-identified and anonymized.

4.1.2 Set-up and installation

We installed Circus in Motion in the exergame room of the Living Laboratory at Pasitos [46]. The exergame room, with dimensions of 3.65 m x 1.83 m, is surrounded by two surveillance cameras: one located in front of the user, recording user reactions when playing with the exergame, and the other one located behind the user, recording participants' interactions. To indicate the position where the child has to stand when playing with Circus in Motion, we placed a rectangle mark with red tape on the floor at a distance of 2.5 m in front of the Kinect sensor. The projector was 2 m over the floor and 3 m behind the display (Figure 3 left).

The traditional vestibular therapy was deployed in the same room to make sure both conditions were comparable and to let children feel comfortable in a room they already know. To mimic the prompting being provided by Circus in Motion, we created a cardboard puppet to show participants the movement they must perform (Figure 3 right). We used black foam to highlight the body part or limb participants need to practice. The foam body part was stuck together to the cardboard puppet using Velcro. The cardboard puppet mimics the modeling prompts that participants receive when playing with Circus in Motion, -such visual supports are commonly used as aids during traditional motor therapeutic interventions at Pasitos.

4.1.3 Procedure

We conducted a 4-days within-subjects controlled experiment where all the participants practiced different non-locomotor movements during a vestibular therapy for around 30 minutes in the two conditions (i.e., Circus in Motion, and traditional).

[6] For simplicity of reading, we call participants to the children with autism participating in the controlled experiment

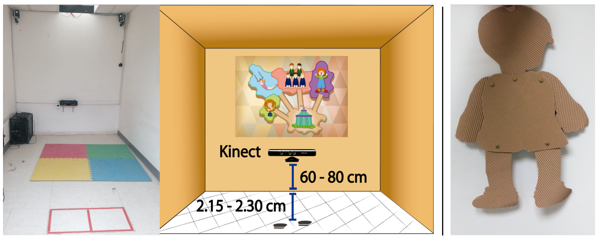


Fig. 3 The set-up Circus in Motion condition (left). The traditional therapy visual prompt (right)

To avoid effects related to learnability and fatigue, we used counterbalancing when assigning participants to each condition. We randomly assigned participants to two groups of equal size. First, one group conducted the traditional therapy, and then, they used Circus in Motion. The other group first played with Circus in Motion, and then, they performed the traditional therapy.

The same psychologist conducted the therapy of all the participants in the two conditions. To control the prompts being provided during the traditional therapy, the psychologist was trained to give participants one prompt when ignoring the activity and every five seconds for three times (i.e., at 5, 10 and 15 seconds).

As with any controlled experiment conducted in a real context, prototypes might not work as their best, and automated solutions may add an undesired level of uncertainty. Thus, we equipped Circus in Motion with an option that enables a researcher to act as a Wizard of Oz and manually update the output to ensure the child will receive the expected feedback on time. Dealing with uncertainty data was beyond the scope of this research at this point, and manually updates instances were not included in the data we used for analysis.

Every condition lasted, on average, 12 minutes (for a total of 24 minutes per participant in both conditions). We video-recorded all the sessions for a total of 6 hours and 40 minutes. Every day, upon completion of the experimental portion of the controlled experiment, we briefly interviewed the psychologist (4 semi-structured interviews), and at the end of the evaluation, we conducted a final interview. We relied mainly on psychologists' interpretation of the collected data to address our questions due to the high disability level of the children. Although they are not the final users, they are the primary caregivers of these children at the clinic and were used as "proxies" to gather their perceptions. This "proxy" technique is commonly used when working with non-verbal populations [44].

These interviews allowed us to follow up on interesting observed behaviors that occurred during the session and gather non-verbal participants' perceptions towards Circus in Motion. Interviews included questions to uncover the differences between using Circus in Motion and the traditional therapy, the practicing of motor skills, perceived impact on physical activation, and problems faced during the controlled experiment.

4.1.4 Data Analysis

Data analysis followed a mixed-method approach. To assess the performance of the proposed algorithms to infer non-locomotor movements (see aim 1 in section 4; Algorithm 1), we analyzed the recorded videos to compute the precision, accuracy, and recall. To compute the accuracy, precision, and recall, we synchronized our video recordings with the timestamps available in the system logs. One researcher viewed all the data to compute the confusion matrix manually. Then, we compute all the metrics.

To understand in which situations Circus in Motion could assist traditional vestibular therapies (see aim 2 in section 4), we supplement our previous analysis by scoring the video recording using techniques inspired by structured observation [36]. Four researchers viewed all the videos and systematically labeled participants' behaviors following a pre-defined coding scheme based on the Children's Activity Rating Scale (CARS) [39]. The CARS scale includes topics around physical activation and the practicing of non-locomotor movements (Table 4). We also coded if children exhibited an emotion, including positive and negative ones (Table 5). The Inter-observer agreement, among the four researchers that coded the videos, was acceptable (Fleiss kappa Avg. $\kappa = 0.91$). We estimated, for each participant and under each condition, the total and descriptive statistics of the time and frequency participants spend executing each behavior.

We recorded and transcribed all interviews with the psychologist. For initial data analysis, we used deductive analytical approaches, based on our initial questions. We additionally used inductive approaches to allow new themes to emerge from our data. To support our inductive analysis, we used open and axial coding and affinity diagramming [14]. Finally, we examined the themes regarding our inductive analysis to explain the results of our deductive analysis.

Table 5 A brief definition of the codification scheme used to code the target behaviors

Category	Behavior	Definition
Physical activity	Stationary	Motionless for 3 seconds or more (e.g., keep standing). Head, finger, or foot movement only.
	Movement of Limbs	Movements of the trunk, arms, and legs without moving the entire body from one place to another (e.g., keep standing and moving an arm).
	Translocation (slow speed)	Moving the body from one location to another at a slow speed (e.g., walk slowly).
	Translocation (medium speed)	Moving the body from one location to another at a medium speed (e.g., jump).
	Translocation (fast speed)	Moving the body from one location to another at a fast speed (e.g., walk fast).
Prompting: type of prompts children needed when playing the game	Verbal	The psychologist gives a verbal aid
	Physical	The psychologist gives physical aid
	Neither	The psychologist does not give any kind of aid.
	System	Aid was given by the system
Emotions: the emotions the child exhibit while playing the game	Positive	When the child is happy (smile, laugh).
	Negative	When the child is sad (cry), angry (frown).
	Neither	The child exhibits a neutral emotion.

4.2 Results

Our results show participants and practitioners positively and easily adopted Circus in Motion. Overall, we found out Circus in Motion better assist children participants to successfully complete the repetition of non-locomotor movements than the tools used during a traditional therapy. Even though Circus in Motion also assist practitioners when setting up a vestibular therapy and follow up children's progress; we did not evaluate the impact of the use of Circus in Motion for practitioners at this stage of the research process.

4.2.1 Use and Adoption

The psychologist reported participants found Circus in Motion "easy to use" by rapidly learning how to interact with the exergame and perceiving it as a useful tool in the sense that could appropriately support a vestibular therapy,

"*[With Circus in Motion, participants] were more engaged, they even laughed with the exergame. In contrast, in the traditional therapy [participants] were not aware [of their movements], they performed [the movements] with apathy*" Psychologist.

In general, participants found it difficult to express emotions, and most of the time, do not exhibit any emotion [1]. Our results show that for around 85% of the time in both conditions, our participants did not exhibit emotions. From those who exhibited emotions, the time of positive emotions was higher using Circus in Motion (13.54%) than with the traditional therapy (3.12%),

"*Almost always, when [participants] were in the traditional therapy condition, their emotions were neutral, they did not express anything. In contrast, when playing with [Circus in Motion], I noticed some children were excited about the music or maybe with the balloons*" Psychologist.

These observations might show participants can use Circus in Motion and seemed more engaged when playing with Circus in Motion than during the traditional therapy.

4.2.2 Movements' detection performance

Our analysis shows that our algorithm has the worst performance when detecting head movements, whereas it has the best performance when detecting when children are lifting their feet. Overall, our algorithm measured high regarding recall and precision for all the movements. This means the proposed algorithm is more sensitive to false positives avoiding frustrations in users when their movement is not recognized. However, paradoxically hampering how a therapist may measure progress by being overly optimistic.

The results in Table 6 show that the algorithm proposed to detect the non-locomotor movements is robust enough to use it in real-life situations and in real-time. Although researchers have proven that Kinect sensor can identify pose, simple stepping movements, and so on, in healthy adults (e.g., [28, 42]), to our knowledge, research showing its performance with individuals with coordination problems is scarce. Moreover, the dataset

Table 6 Results for movement detection

Movement	Accuracy [1]	Recall [2]	Precision [3]
Lift up right arm	0.75472	0.92857	0.77037
Lift up left arm	0.76923	0.87387	0.81513
Lift up right arm and left leg	0.77922	0.83333	0.87719
Lift up left arm and right leg	0.81169	0.86885	0.89076
Movements of head	0.711491	0.73643	0.75397
Lift up right leg	0.90476	0.91509	0.97
Lift up left leg	0.92683	0.9505	0.96
Jump	0.70701	0.7864	0.7714

[1]Accuracy=$\frac{TP+TN}{TP+FN+FP+TN}$
[2]Recall=$\frac{TP}{TP+FN}$
[3]Precision=$\frac{TP}{TN+FP}$
TP, true positive; FN, false negative
TN, true negative; FP, false positive

from 12 children with autism using the game for around 12 minutes might seem small from a modeling perspective point of view; but, when trying to test assistive, emerging technologies used as a therapeutic tool for children, the literature has made the compelling argument that experiments with people with disabilities are usually from 5 to 15 users [30] and the specialists suggested that the intervention must last at most 15 min. Therefore, we believe that our sample is very valuable with the natural challenges associated to using data captured in a real life context and in real time. Ideally, mechanisms to automatically adjust the thresholds according to each child's performance or to develop other features to improve accuracy should be developed

4.2.3 Prompts

In the Circus in Motion condition, our analysis indicates 66.67% of participants performed more repetitions without any prompt, but on average, participants received more time of prompts (+1.5% of the time). However, our results also show participants received less time of verbal prompts when using Circus in Motion ($\overline{X} = 4\%, \sigma = 5.14sec$) compared with the traditional therapy ($\overline{X} = 5.5\%, \sigma = 3.24sec$), and 66.67% of participants performed more repetitions without any prompt.

Circus in Motion gave 15.25 prompts on average to every participant (σ=9.01). These prompts were 58% effective, that meaning that participants were able to complete the repetition of the movement successfully after receiving the prompt. This result could mean that prompts were delivered at appropriate times by successfully capturing participants' attention.

Overall, these results show that only half of the prompts were effective, and participants still need many prompts when using Circus in Motion. Therefore, we suggest to develop a better reasoning algorithm to more precisely decide when it is the best time to trigger a prompt and for how long such prompt should last.

4.2.4 Repetitions of motor movements

Overall, 75% of participants performed 4.7% more repetitions in the Circus in Motion condition than in the traditional therapy condition. When using Circus in Motion, the psychologist also perceived an improvement in the accuracy of the participant's movements and an increase in the number of repetitions:

"*[With Circus in Motion participants] performed the movements in a more accurate way... [Participants] were highly aware of the capabilities of the [Kinect] to detect their movements. So, I felt that [participants] wanted to perform better [in the Circus in Motion condition] because the Kinect will detect an inaccurate movement. However, during the traditional therapy [condition], I felt their movements were done faster. Most of the time, they practiced the movement without enough precision, they were not putting a lot of effort into it, like 'Ok, I already stretch my hand, without having it fully stretched*" Psychologist.

All participants performed more physical activity using Circus in Motion than with the traditional therapy. Our analysis indicates that participants increased their level of physical activation by 98 points of energy expenditure, on average, using Circus in Motion ($\overline{X} = 171.75, \sigma = 28.59$) than during the traditional therapy condition ($\overline{X} = 73.333, \sigma = 29.71$, Figure 4). The psychologist explained that Circus in Motion promotes more and better physical activity than the traditional condition.

"*[Circus in Motion] promotes another type of exercise because when [participants] watched the puppet, they were like Ok! I just need to do this movement', and that is it. But with [Circus in Motion participants] were very excited and willing to work for the reward.*" Psychologist

These results show that participants completed more repetitions and increased more the physical activity during the Circus in Motion condition. This could be partially explained because the exergame gives participants a long-term goal motivating them to strive and finish correctly the movement to get the reward. Also, the Kinect capabilities to accurately detect how the movement was conducted give participants' reassurance

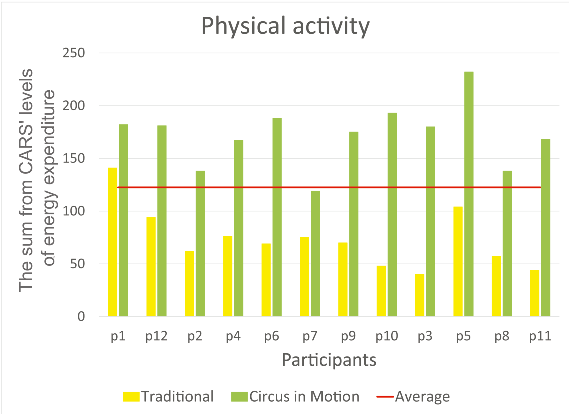


Fig. 4 The sum from CARS' levels of energy expenditure in both conditions.

on how the movement must be conducted but also prevent them from 'tricking' the therapist.

Overall, this controlled experiment reveals that a 3D depth camera is capable of modeling the non-locomotor movements to support vestibular therapy of children with autism, but only half of the prompts given by Circus in Motion where effecting, and the difficulty level, and the therapist should manually adjust the difficulty level. Therefore, to assist the therapist in determining the difficulty level, we develop an adaptive mechanism using the data gathering in the controlled experiment.

5 Towards an adaptation mechanism using children interaction with Circus in Motion

Therapists determine the difficulty of the exercise routine based on each patients' motor capabilities. Most of the time, therapists need to adjust the difficulty level to challenge their patients and ask them to perform more complex movements while keeping them engaged during the therapy [51]. This dynamic game fine-tuning is a complex and time-consuming task for therapists. When this 'adjustment' is incorrectly done, it could highly affect patients' engagement and hinder their possibilities to properly complete the exercise routine because they lose their attention or get frustrated. Adaptation is important to increase players' engagement and dynamically fine-tuning the game difficulty [52]. Adaptation is especially important for designing exergames to support individuals with disabilities during therapy sessions, as each individual is highly different from their peers, especially when working with individuals with autism.

Our controlled experiment revealed that the modeling of prompts and non-locomotor movements are essential to support the vestibular therapy of children with autism. Thus, we particularly used the number of prompts, the performance of the movement, and the completed number of repetitions could feed the exergame execution to adapt the difficulty of the next routine of movements by taking into account the latest patient's performance. We used the data captured during our controlled experiment to design and develop an adaptive mechanism using a configuration tool and a fuzzy system. The configuration tool allows the therapist to create and personalize the difficulty levels of the exergame. The fuzzy-based movement routine selector allows the customization and adaptation of the exergame considering the user profile, the movement performance, prompts, and the number of completed repetitions.

5.1 Configuration tool

We developed a dedicated interface where therapists could configure the number of repetitions and the motor movements children should complete at each session and for each level of the exergame. Therapists could also adjust the time frame for triggering prompts and the complexity of the movement to be practiced. For example, a simple configuration for a level identified as 'very easy' involves two repetitions per movement and a waiting time span of two seconds before receiving a prompt. Participants will play the easiest scenario, including practicing those movements to understand the body scheme (i.e., the clowns game). In contrast, the 'very hard' level will demand from participants to conduct ten repetitions per movement with a waiting time span of 10 seconds before receiving a prompt. Participants will need to play all the circus acts involving the practicing of more complex exercises than just those related to body scheme (Figure 5).

5.2 Fuzzy-based movement routine

To select the next difficulty of the routine according to each child's capabilities, we developed a Mamdani fuzzy logic system [33]. Our fuzzy logic system uses three linguistic variables as inputs: number of prompts, the number of completed repetitions, and the movement performance. For input, we scored each participant's performance during the use of the exergame. We used an R vector of size 3 with normalized numbers between [0, 1]. Numbers were empirically defined according to the following function:

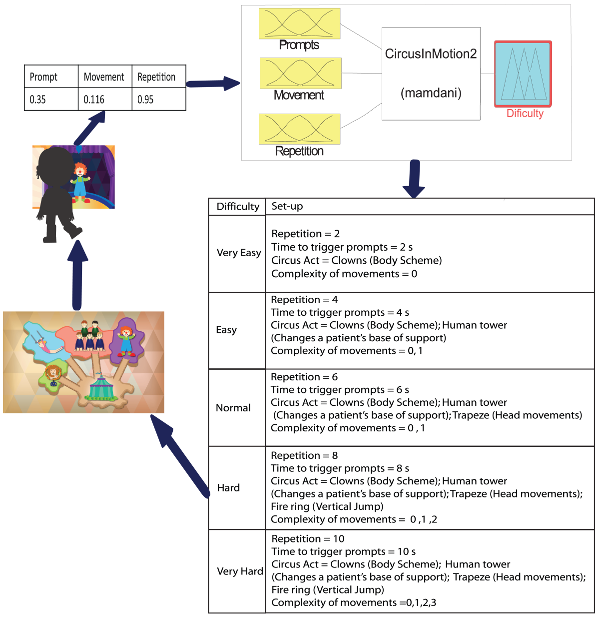


Fig. 5 A mock-up of how the fuzzy system updates the difficulty for the next session.

$X = x_1, x_2, x_3,$
where,
x_1 = Percentage of verbal prompts given by the exergame
x_2 = Percentage of each participant's performance (higher values are assigned when the child follows the movement in the right direction)
x_3 = Percentage of each participant's completed repetitions
The output of the fuzzy system is a categorical value in $y = \{very\ easy, easy, normal, hard, very\ hard\}$

It is important to note that the categorical values are pre-defined by the therapist (See an example in the table of Figure 5). The system automatically defines the next difficulty level according to the performance of the child during the current session (Figure 5). We defined different membership sets for each variable identified as relevant and using the results from our controlled experiment. For repetitions and prompts, we used three membership sets including *few*, *average*, and *many*. For movement accuracy, we used four membership sets: *wrong*, *poor*, *good*, and *excellent*. For difficulty, we defined five membership sets: *very easy*, *easy*, *normal*, *difficult*, and *very difficult* (Figure 6). Then, a psychologist and an expert in Human-Computer Interaction designed 22 rules for all the inputs and their categories. For example, Algorithm 2 shows an example of three of the rules to increase the difficulty level include those related to prompts, movements, and repetitions.

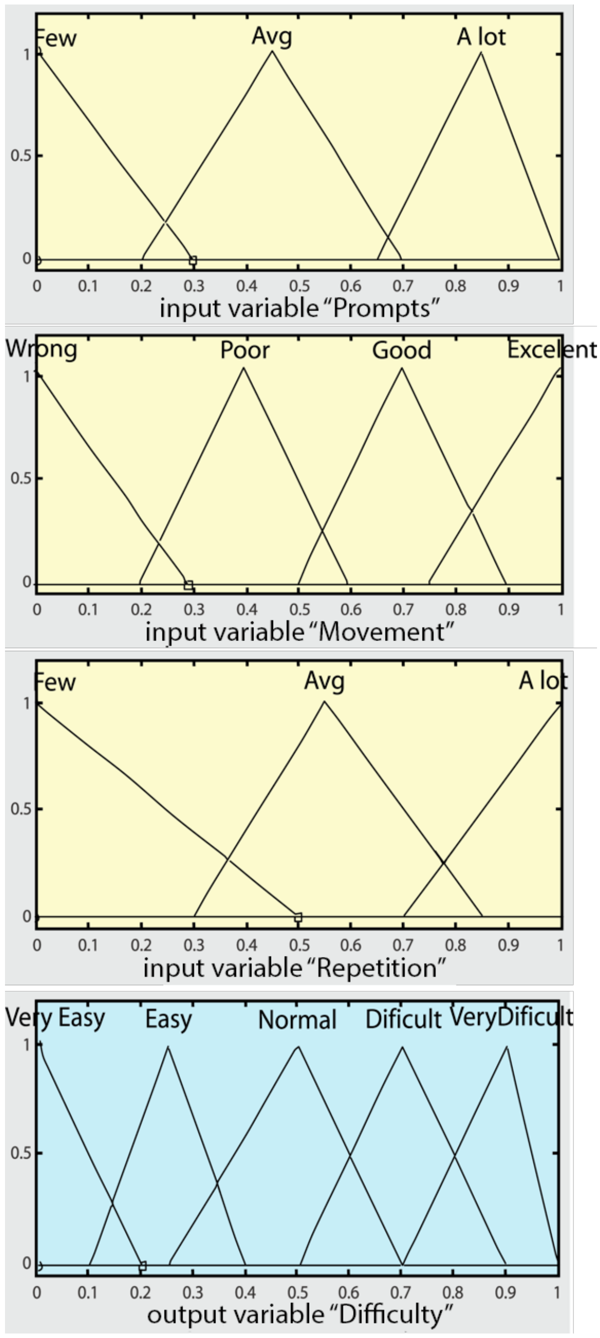


Fig. 6 Fuzzy sets created for inputs: prompts, movement accuracy, repetitions, and output: difficulty.

The system uses the Zadeh technique [6] to combine the fuzzy set and the center of the mass technique to defuzzifies the output.

Algorithm 2: Increase the difficulty level

```
Result: Difficulty level
Membership sets of prompts, movement and
  repetition;
if prompt is a lot and movement is poor and
  repetition is few then
  | difficulty is very easy
end
if prompt is few and movement is excellent and
  repetition is a lot then
  | difficulty is very difficult
end
if prompt is few and movement is good and
  repetition is average then
  | difficulty is normal
end
if prompt is few and movement is good and
  repetition is average then
  | difficulty is normal
end
if repetition is a lot and prompts is a lot then
  | difficulty is easy
end
if movement is poor or prompts is a lot then
  | difficulty is very easy
end
if movement is excellent and prompts is average and
  repetitions is a lot then
  | difficulty is very difficult
end
```

5.3 In-lab evaluation of the fuzzy system

To evaluate the developed fuzzy system regarding the selection of the level of difficulty of the next movement routine, we used as input the behavior of every child who participated in the evaluation of controlled experiment (more details in sections 4 and 5). We specifically used the percentages of the number of prompts, the performance of movement, and the number of repetitions that every child performed when playing with Circus in Motion.

Our results show that the fuzzy system is capable of selecting the next routine according to each child's motor capabilities and motor performance during the therapy (Table 7). For example, participant 1 needed many prompts and exhibited a poor performance when practicing the movements and completing the repetitions. So the fuzzy system assigns an '*easy*' routine for the next session. In contrast, participant 3, needed a few prompts and exhibited a *good* motor performance successfully completing several repetitions. So for their next session, the fuzzy system assigns a '*very difficult*' routine.

These results show that for every child, the exergame suggests a different difficulty level according to child performance. As future work, the fuzzy system should be evaluated to understand how it works in a real-time situation for the long term.

Table 7 An example of how the fuzzy system provide a different output per child according with their performance

Participant	Prompt	Movement	Repetition	Output
12	35%	11.66%	95%	Very Easy
1	100%	34.30%	60%	Easy
6	65%	40.05%	81.25%	Easy
2	55%	59%	72%	Normal
7	22.5%	40.84%	85%	Normal
9	45%	38.11%	87.5%	Normal
4	17.5%	86.52%	76.25%	Difficult
8	22.5%	69.23%	87.5%	Difficult
10	42.5%	75.16%	90%	Difficult
3	2.5%	96.54%	74%	Very Difficult
5	25%	88.81%	78%	Very Difficult
11	25%	89.74%	95%	Very Difficult

6 Discussion and Conclusions

In this paper, we present the design and development of Circus in Motion, a multimodal exergame that supports children with autism during the practicing of non-locomotor movements. Circus in Motion was designed following a user-centric design methodology. This methodology allowed us to properly select the non-locomotor movements that children should practice and control a virtual avatar performing different circus acts. We used the Skeleton library of the Microsoft Kinect SDK in tandem with a set of trigonometric functions with empirical thresholds to appropriately track the non-locomotor movements suggested by the specialist (see the description of the movements in Table 4).

To evaluate the impact of Circus in Motion in a real-life scenario, we conducted a controlled experiment with 12 children with autism at a school-clinic. Our results show that children with autism increased their physical activity and the number of completed repetitions when using Circus in Motion. The psychologist perceived that participants were more excited and engaged during the Circus in Motion condition. Overall, these results show exergames are promising in supporting vestibular therapies of children with autism, and, Circus in Motion could potentially support traditional vestibular therapies by increasing the number of repetitions and the amount of physical activation. The results from our performance evaluation of the tracking of non-locomotor movements show that our algorithm is robust enough to work in real-time situations even where conditions cannot be fully controlled.

We also proposed how the data from the usage of Circus in Motion could be used to feed an adaptation mechanism using fuzzy logic techniques. We proposed that the number of prompts, the performance of movement, and the completed repetitions could help to infer the difficulty level for the next movement routine. A preliminary evaluation in the lab using the results of the controlled experiment as inputs to the fuzzy system shows that the fuzzy system properly computes the difficulty level according to each child's performance.

Overall, we learned that working with data captured in real-time with children with autism can be used to develop algorithms that are robust enough to be used in real-time. The data can be used to create databases that take into account information from neurodiverse users. Physiological signals such as heart rate or emotions could be used in tandem with the behaviors we identified to improve the accuracy of the fuzzy system.

We observed certain limitations and opportunities for future work in our investigation. From the design point of view, one of the main challenges when designing Circus In Motion was to appropriately match a movement to a Circus Act, because not all movements have a "natural" correspondence to a Circus act. Therefore, we need to further investigate other potential scenarios that could provide a better match for the movements and investigate if current configuration may disturb the perception of motor skills in the long term.

From a technical point of view, we only test our trigonometric function with children with autism. Therefore,it is important to test the generalization of our approach in more use cases with other diverse populations beyond the case of autism. This controlled experiment is a first step showing the use of Kinect is robust to be used by children with autism performing non-locomotor movements; but differences with other populations including neurodiverse individuals must be characterized to propose unbiased algorithms than can be able to estimate unconventional body postures especially of individuals with coordination problems(e.g., [16]).

From a methodological point of view, the controlled experiment was conducted only with 12 children with autism, in one school-clinic in Mexico (i.e., Pasitos). Additionally, children with autism only play once with Circus in Motion. Therefore, it is impossible to generalize these results. The experiment should be replicated in the long term to (1) avoid bias due to the "novelty effect" of using the exergame in a short period of time; (2) understand if Circus in Motion affects the decision making of practitioners, reduce their stress levels, workload, and (3) validate their potential in supporting clinical assessment. Moreover, the fuzzy system was only tested in the lab with the data of the controlled experiment. The readers should be advised that a longer controlled experiment with more participants should be conducted to generalize and evaluate the significance of our results, with particular emphasis on measuring variables with more clinical relevance. As this is one of the first studies of this kind, the objective of this experiment was not to generalize our findings; but to get preliminary insights into how to conduct such studies in the area, and proposed an adaptation mechanism for further testing. There is a level of uncertainty associated with the estimation of information. Hence, as future work, we encourage research devoted to investigating uncertainty mechanisms to deal with the specificity and sensitiveness of such solutions. Both prototype proposals and use cases of their deployment in concrete scenarios, especially in challenging contexts like education of healthcare, are scarce and urgently needed.

Overall, as future work, we plan to conduct a long-term controlled experiment to investigate the efficacy of Circus in Motion as a therapeutic intervention, and how the exergame using the adaptive mechanism could potentially improve the control of the vestibular system of children with autism. It is important to conduct a randomized controlled trial with a control group to evaluate the effectiveness of using Circus in Motion as a therapeutic intervention. Such a controlled experiment will enable us to demonstrate if Circus in Motion improves the vestibular system in children with autism using traditional motor assessment clinical tests and investigate in which situations it excels traditional vestibular therapies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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