Integrating Mixed Reality and Body Weight Support Technology for Immersive Pediatric Rehabilitation

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***Abstract*—Interventions involving the use of assistive technology have the potential to enhance motor outcomes for children with mobility challenges. Keeping up with the intervention, however, is challenging due to decreased engagement and motivation toward practicing the training tasks. To address these challenges, this work focuses on the development of a pediatric motor training environment that combines dynamic body weight support and mixed reality technology. Both components allow for personalized, variable motor practice in an environment enriched with gamified activities. This paper describes the system configuration alongside five game scenarios that were developed to target various motor skills, such as standing, walking, squatting, and reaching. Preliminary results on the mixed reality environment performance as well as next steps in this work are discussed.**

***Index Terms*—augmented reality, virtual reality, mobility, serious games, child**

I. Introduction

Providing children with motor disabilities access to assistive technology can be an effective intervention strategy [1]. Traditional mobility interventions typically involve the use of treadmills (often in combination with partial body weight support [BWS] and/or a robotic device) and walkers; while valuable for gait, these tools may refrain children from engaging in variable motor practice and interaction activities, such as manipulation of objects in the environment [2], [3]. The use of dynamic BWS, on the other hand, is a promising tool for inducing immediate and long-term effects on ambulatory ability, while allowing for other activities, as shown in studies with young children [4], [5]. Nevertheless, such training has not been adequately explored in older children that may face mobility challenges, such as those with Cerebral Palsy (CP).

Engaging children with CP in mobility training interventions can be challenging; a great effort is required from them to complete demanding tasks, which may, in turn, decrease motivation and engagement in the activities [6], [7]. Nevertheless, the likelihood of keeping up with training within a session or across sessions increases when the latter involves structured leisure activities and physical objects for environmental enrichment, which can be achieved through gamification [7]–[9].

Serious games are gamified activities in which learning (in its various forms) is the primary goal alongside entertainment. These are developed for a broad spectrum of application areas, from education to health care, in an effort to increase user motivation and engagement in tasks that children might otherwise find tedious, difficult, and/or disengaging [10]. In rehabilitation, serious games have shown promise for increasing engagement when users participate in standing and walking tasks, leading to changes in locomotion and real-world motor skill acquisition [11]–[13]. Virtual serious games use digital accessories to increase engagement by removing the constraints of physical objects and the training environment [10]. Currently, many virtual serious games targeted for motor training are limited to the use of 2D screens such as monitors or projectors; this may affect the amount of sensory feedback needed to close the action-perception loop, and may lead to less effective skill transfer to real world tasks [14].

One approach to combat this problem is the use of virtual, augmented, or mixed-reality head mounted displays (HMDs), which are headsets that can project virtual objects in a 3D environment around the user. Virtual reality HMDs use a completely virtual environment to display these objects, separate from the real world. Mixed reality HMDs transfer the games from a computer screen or a purely virtual environment into the real world, by bringing the virtual components of serious games into the real world environment with the user. These mixed reality environments (XREs) seem to be more effective at generating true-to-life experiences and movements typically used in everyday life, with 3D mixed reality games having greater effectiveness at training motor skills when compared with 2D screen-based or virtual reality games [15].

The overall goal of this work was to develop a novel pediatric motor training environment that combines the flexibility of a dynamic BWS with an XRE (BWS-XRE). Specifically, this paper discusses the challenges associated with the development of such an environment and describes the different components included in the current prototype. The prototype is designed as a closed-loop system that responds to changes in the performance of the child while targeting specific motor training goals.

II. Approach

A. System Description

The current system consists of a BWS device, an XRE setup (headset and game), and sensors to monitor the user's movements; all connected to a central computer (Fig. 1).

The BWS device (PUMA®, Enliten, LLC, Newark, DE) is a portable, commercial device that consists of an overhead structure of beams connected to a wearable harness and a counterweight. The amount of unweighting in the vertical plane can be adjusted through the counterweight, while allowing the user to move freely in the other planes.

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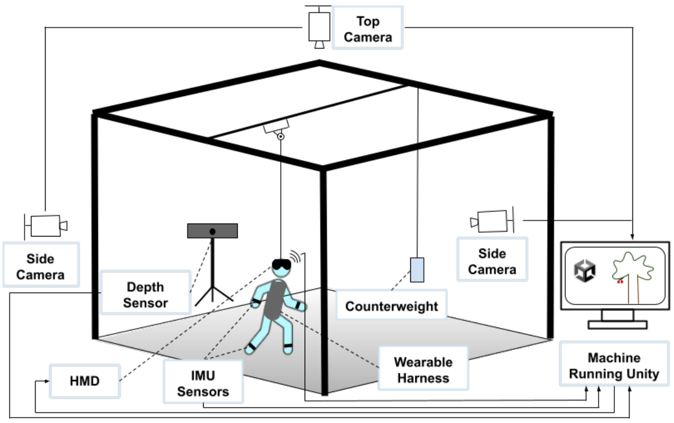

Fig. 1: Diagram of the system architecture. The main coordinator of the system (computer running Unity v2022.3.5f1) manages information flow through a secure network. Various sensors gather information on user movement to evaluate task performance. The researcher can then adjust game difficulty through the use of either holographic remoting or commands sent from the computer to the HMD over the network.

The HoloLens 2 (Microsoft, Redmond, WA), a wireless mixed-reality HMD, is chosen for our pediatric users due to its relatively lightweight design and fast response. The user can see, hear, and interact with objects using built-in functions available in the Mixed Reality Toolkit 3 (MRTK3) through the Unity game development engine (Unity Technologies, San Francisco, CA). Although this HMD utilizes hand and head tracking to facilitate interaction with objects in the XRE, it does not provide information on full-body movement, which is required to close the system feedback loop. To obtain the latter, a depth sensor (Kinect v2, Microsoft, Redmond, WA) is integrated with wearable inertial measurement units (IMUs) (Trigno, Delsys, Natick, MA). Three video cameras (Logitech, Lausanne, Switzerland) placed all around the environment also provide top and lateral views of the user's activity.

The processing and management of the BWS-XRE system takes place in a computer workstation running MRTK3 and holographic remoting (via Unity). Data from the main sensors are acquired and securely transferred within the BWS-XRE system via an encrypted local network that is not connected to the internet or any external device. The XRE can be transmitted in real time to the HMD over this local network, or computed and displayed using the onboard hardware of the HMD, while hand-tracking, eye-tracking, and depth sensor information from the HMD sensors are transmitted to the workstation in real time over the network for both cases. Information from the standalone depth and camera sensors is transmitted through wired connection to a USB hub connected to the workstation. Control of the HMD can be retained solely by the researcher remotely at the workstation, who can reset the scenario if users accidentally exit and also rapidly swap between games and training systems.

B. Interaction Games

Five games are included in the current BWS-XRE system. All games but one (which focuses on familiarization) come with specific motor training goals that children can achieve while engaging in various activities. The targeted engagement duration for each game is three minutes, with 3-minute breaks in between, resulting in a total XRE exposure of 15 minutes across all games. All games have built-in 3-minute timers which indicate when the time in each game has concluded. This measure is taken to minimize any potential risks associated with prolonged use of HMDs, such as motion sickness and/or physical discomfort. Information on training goals and other game characteristics is summarized in Table I and Fig. 2.

Spontaneous Play. This is the first game introduced to the user and does not have overarching motor training goals beyond the user's familiarization with the overall system. This is accomplished by providing the user with XRE interaction opportunities (e.g., grabbing, throwing, kicking, leaning, etc.) so that they obtain an understanding of how their physical movements can directly affect the virtual environment.

Fruit Fair. In this game, the user is tasked with crossing a bridge and picking fruit from trees in order to complete deliveries at their fruit stand (Fig. 2A). The flow of the game is the following: Starting with traversing the bridge, the user must then enter the garden where the fruit trees are located. The trees contain a variety of fruit; the user must pick fruit from the correct tree corresponding to a fruit order, sort them into the right baskets, and take the full baskets to the delivery truck by crossing the bridge again.

The game offers users with various levels of task difficulty and feedback on their performance at different stages of participation. Initially, the first obstacle, the bridge, varies in size (the smaller, the harder), allowing the user to engage in various levels of balance training. On the fruit picking stage, the trees grow and drop fruit at varying rates (the faster, the harder), giving the user multiple time windows to reach for and grasp the fruit before they fall to the ground and disappear. In order to maintain engagement and a positive attitude towards training with the games, if/when the user fails or takes too much time to traverse the obstacles on their way to complete the order (e.g., "falls off" the bridge, many rotten fruit are collected, etc.) no negative penalties are accrued. In lieu of penalties, a pop-up sign will guide them towards how to effectively play the game.

TABLE I: Characteristics of Each Game and Training Goals

Game	Feedback	Primary Motor Training Goals	Task Difficulty	Difficulty Modifier
Fruit Fair	Auditory, Visual	Reaching, Grasping, Standing, Walking	High	Rotten fruit, fruit disappear
Chasing Bubbles	Auditory, Visual	Reaching, Walking, Kicking, Jumping	Low	Bubble speed, size, frequency, timer
Seashell Squat	Auditory, Visual	Reaching, Grasping, Sit-to-Stand, Squatting	Medium	Trash accumulation rate, timer
Floor is Lava	Auditory, Visual	Standing, Walking, Jumping	Medium	Obstacle size and distance, timer

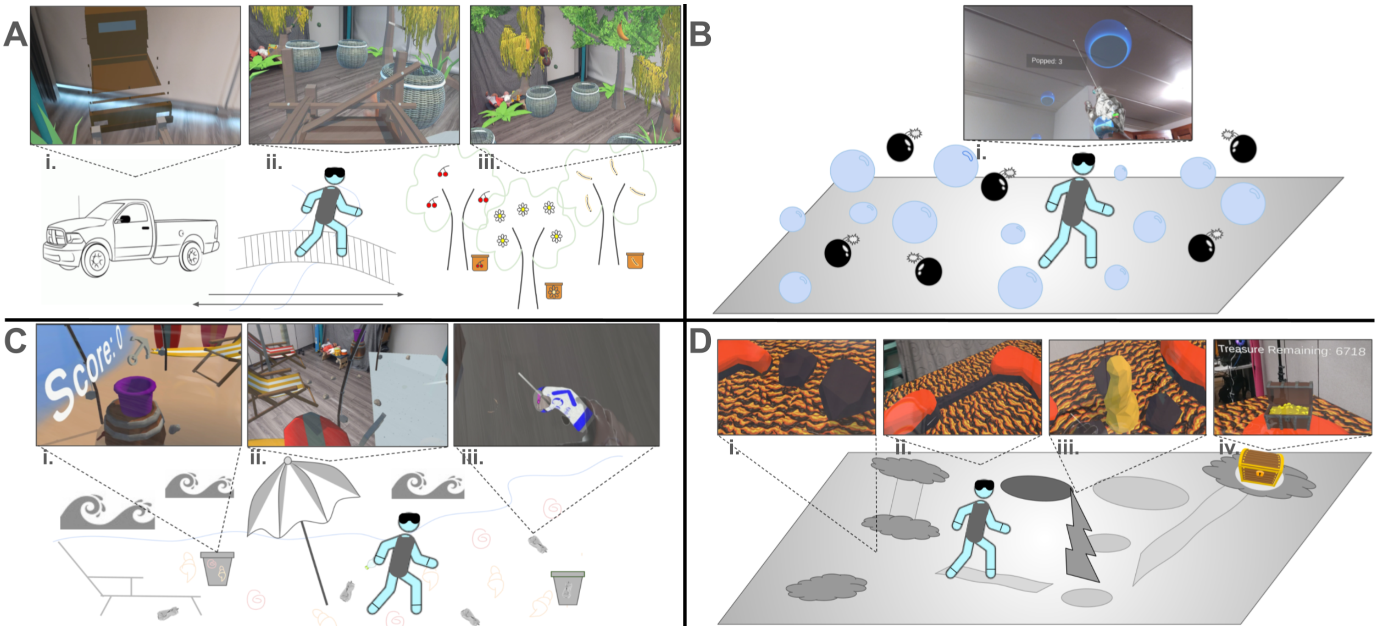

Fig. 2: Overview of our serious games Fruit Fair (A), Chasing Bubbles (B), Seashell Squat (C), and Floor is Lava (D). Snapshots (i-iv) are taken directly from the XRE system. See the Approach section for detailed descriptions of each game.

The user's performance informs potential game adjustments to facilitate the user's training at their current level of ability before progressing to more difficult scenarios; examples include changes in bridge size, number of fruit baskets required to be collected and sorted, and time given to the user to complete these tasks before a failure is initiated.

Chasing Bubbles. In this game, the user is tasked with popping virtual bubbles floating in the room (Fig. 2B). The game starts with the user standing in the center, and once the bubbles appear, the user has to move around to chase them down and pop them with either their hands or feet. The goal is to pop as many bubbles as possible in the allotted time.

The game is inspired by common exercises found in rehabilitation sessions, but with a twist; compared to the traditional play style of this game, the XRE allows fine-tuning of the task difficulty as well as training personalization based on the child's performance and need. For example, the size of bubbles and the frequency they appear or move in the environment can be adjusted (e.g., the smaller the bubble or the faster it moves, the harder), based on the number of bubbles popped and time to complete the task in a previous trial. To make it even more difficult, obstacles (viewed as floating bomb objects) can appear, which upon interacting with these will not count towards their score. On personalization, there may be a need for the child to perform limb movement from a specific side of the body (e.g., in the case of hemiplegia). This can be achieved by having the virtual bubbles "react" to touch from the user's left hand or foot only. Finally, the user is given visual and auditory feedback while playing the game through the scoreboard, a popping animation for the bubbles, and an auditory "Pop!" sound whenever the bubbles are touched.

Seashell Squat. In the third game, the user is tasked with keeping the beach clean and free of the pointy seashells by squatting down and disposing of them (Fig. 2C). The game begins with the user standing in the middle of a beach covered with shells. They must squat and grab the shells off the ground, requiring them to train in a similar to sit-to-stand transitions, before depositing the shells into a bucket.

Similar to the previous games, the difficulty and feedback provided to the user can be adjusted. Trash will wash up on the beach which, if left unchecked, will cover the beach. If the user collects enough shells or trash, they gain a boost to their allotted time to clean the beach. As the difficulty increases, the opportunity to collect shells increases, but so does the rate at which trash washes up on the beach, providing a harder challenge but more opportunities to increase their score in the allotted time. Auditory feedback is given in the form of sounds of seagulls and waves when they successfully collect seashells or trash. Visual feedback regarding the time left to complete the task, the number of shells collected, and the amount of trash present on the beach is provided on the scoreboard.

Floor is Lava. The fourth game is a twist on the classic children's game of the same name; the user is tasked with traversing a balance course to avoid lava (Fig. 2D). The game starts with the user placed at one corner of the designated area, and once the course appears, the user must move around using platforms and bridges to keep safe. The goal is to reach the treasure placed in the map without "falling off" of the platforms by stepping off them.

Various virtual objects are utilized for game manipulation. One obstacle type, the bridge, is similar to that seen in Fruit Fair and varies in size allowing the user to engage in balance training in the same manner. A second obstacle type, the jumping stones, require the user to step or jump across lava pits in order to reach the next platform. These stones vary in size (the smaller, the harder) and distance from each other (the farther, the harder) depending on the difficulty. The final obstacle are lava geysers, which require the user to correctly time (less time to cross is harder) when they cross the bridge or step to another stone. The user is given visual and auditory feedback while playing the game through a timer, animations for the obstacles, and ambient noise of an active volcano.

III. System Performance Preliminary Results

Preliminary data on the system's performance indicate that all interaction games are running in a relatively stable manner with no dips in frame rate and without overloading the device's memory. Performance metrics at the 3-minute time point after the game is initiated are shown in Table II. Peak memory usage is shown as a percentage of the total available memory.

TABLE II: Interaction Game Performance Metrics

Game	**Frame Rate (frames / sec)**	**Peak Memory Usage (%)**	**Frame Time (ms)**
Baseline (No Game)	120	28.12%	8.3ms
Fruit Fair	120	38.73%	8.3ms
Chasing Bubbles	120	27.81%	8.3ms
Seashell Squat	120	37.45%	8.3ms
Floor is Lava	120	43.21%	8.3ms

IV. Open Challenges & Further Improvements

Our BWS-XRE system aims to enhance engagement, motivation, and personalization of motor training for children facing mobility limitations. Five serious games have been developed targeting variable motor practice; nevertheless, further modifications are planned to address challenges associated with designing interactive environments for pediatric populations.

User retention is crucial for enhancing motor training outcomes. Mitigation of potential adverse effects associated with mixed-reality use (e.g., motion sickness) or unwieldy technically complex systems is required. By incorporating the appropriate degrees of movement in a 3D environment, robust sensory feedback mechanisms afforded by the HMD, and controlled exposure to the system, we aim to reduce these effects and facilitate a pleasant motor training experience.

On the HMD side, further improvements can be performed to address technical challenges in system stability and comfort which may affect its long-term use for motor training. There are also challenges related to the software aspects of mixed-reality processing, as these elements are typically rendered from the perspective of an adult with a greater height and inter-pupillary distance than children. Lastly, in relatively sparse environments, primarily consisting of blank walls or ceilings, the device may not always acquire accurate data regarding the spatial arrangement of barriers in the environment, which may cause disruptions in immersive motor training.

Such instability can be minimized through system adaptations that enable users to perform movements requiring fine adjustments with accurate tracking [16], as is needed for motor training. The weight, overall footprint, and software capabilities of mixed-reality HMDs are advancing rapidly with every generation. Further advancements in software compatibility between devices allows researchers and developers to easily port games to other mixed-reality HMDs, so long as the software running on the HMDs are compatible with MRTK3. Taken together, these advancements mean that future game systems could be built to accommodate multiple mixed-reality HMDs, allowing for widespread utilization of the XREs. With the continuous improvements in portability and capabilities of mixed-reality HMDs, this design has the potential to prolong and increase engagement of children in motor training while fostering positive long-lasting benefits on its users.

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