Customisable Lower Limb Rehabilitation Carpet for Children with Cerebral Palsy

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Abstract

Cerebral Palsy (CP) affects motor coordination, resulting in slow walking and irregular step and stride lengths. Effective rehabilitation exercises are essential for strengthening leg muscles and enhancing mobility in children with CP. However, traditional hospital rehabilitation programs often lack engagement, making it challenging for children to maintain consistent participation. Additionally, many advanced lower extremity rehabilitation systems remain largely inaccessible. This study introduces an interactive gaming carpet combined with intelligent gait pattern analysis to enhance rehabilitation efforts. The gaming carpet employs visual and auditory cues to train leg coordination and correct stepping patterns, making the exercises more engaging for children. Meanwhile, the intelligent gait analysis system provides therapists with objective data to assess conditions and develop personalized exercise plans. Initial tests indicate that this system effectively engages children and improves adherence to rehabilitation exercises, while also providing accurate progress monitoring. This innovative approach demonstrates significant potential for integrating game-based interventions and data analysis into CP rehabilitation, offering practical solutions for both clinical and home-based settings.

CCS Concepts

• **Human-centered computing → Empirical studies in interaction design**.

Keywords

Cerebral palsy rehabilitation, Lower limb training, Interactive gaming carpet, Motion Analysis

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1 Introduction

Cerebral Palsy (CP), commonly diagnosed in toddlers between 2 to 24 months, is a widespread physical and societal challenge [12]. In China, the incidence rate is approximately 2.48 per thousand, with around 40,000 new cases each year [11], highlighting its growing societal impact. Individuals with CP struggle with motor coordination, balance, mobility, and fine motor skills. Additionally, some may exhibit cognitive and perceptual deficits similar to those seen in autism, which can hinder daily activities [7]. Therefore, active participation in rehabilitative exercises is crucial for their overall development, making the effectiveness and persistence of rehabilitation the primary goals of such training. Lower limb rehabilitation devices such as gait trainers and treadmills are designed to enhance the stability and muscle strength of the knee, ankle, and foot. However, the training process with these devices can often seem monotonous. Occupational therapy (OT) workstations, as depicted in Figure 1, are developed to improve toe pointing ability, foot coordination, lower limb coordination, and cognitive abilities, evolving into sophisticated rehabilitation tools. Nonetheless, these devices are expensive and require supervision by healthcare professionals. According to Lauglo et al.'s theory [10], involving children with CP in high-intensity real-world activities that incorporate their own motor skills can provide both physiological and psychological benefits.

Such theories have already been applied in practical rehabilitation training. For example, in a virtual game system for upper limb rehabilitation exercises in children with CP [6]. Testing revealed that, compared to using a visual arm movement instrument, visualizing hand movements through abstract objects allowed children

Figure 1: Occupational therapy (OT) workstation.

Figure 2: Lokomat.

to perform faster, with fewer corrections to produce smoother motions, and consumed less mechanical energy. This indicates that using games to assist in the rehabilitation of children with "mild CP" is feasible. Due to the different flexibility of upper and lower limbs, in terms of lower limbs, the "mild CP" mentioned above refers to children with CP who are classified as GMFCS I-II under the GMFCS, a system for classifying gross motor function (GMF) in children with CP. They have fewer functional limitations, less functional limitation of the ankle and a better degree of cooperation [4]. Therefore, this study explores how games incorporating positive audio-visual feedback can be used to guide and motivate children to actively and efficiently participate in rehabilitation activities. In response to this research objective, several interaction mechanisms are proposed which can be provided in a professional healthcare setting through a novel and easily deployable device, specifically designed for exercises of the hip, knee, and ankle joints. To help doctors and parents to be able to monitor the recovery of children with CP, an evaluation system has been considered for recording, monitoring, comparing, and analyzing, providing real-time rehabilitation status of the child to doctors and parents.

2 Related Works

2.1 Existing lower limb CP rehabilitation systems

Recently, the potential of lower limb exoskeletons (such as Mile Bot series and Indego) and VR games (like Catch the Star) as rehabilitation aids has gained attention [2]. Mainstream robotic toys offer engaging training scenarios, but may not fully cater to children's needs due to varying muscle weakness in their bodies. Avicrobot's offerings, including a lower limb rehabilitation system and an intelligent training robot, provide a level of customization. The device, equipped with integrated sensors, serves as a game controller to emulate the rehabilitation process while collecting real-time data. However, the high cost of Avicrobot restricts its usage to medical institutions. Furthermore, its design, tailored for adults, poses operational difficulties for children. In contrast, Lokomat, as depicted in Figure 2, offers customization for children along with the above features, but it also comes with a high cost and low accessibility outside of the clinical setting making it unavailable to most patients.

In Chung's article [4], a stepping game with two reachability enhancement features including leg extension and seated navigation, was implemented for lower limb rehabilitation training to evaluate and explore the gaming experience. Comprehensive test results indicated that the game could motivate leg exercises. However, overly complex games might distract users from focusing on leg exercises, thereby not contributing to efficient rehabilitation training.

2.2 Exergames for rehabilitation in children with CP

Compared to upper limb rehabilitation, game development of lower limb rehabilitation is not as common. At an early stage, in order to allow children with CP (GMFCS level III) to participate in vigorous physical activity while socializing with friends, Hernandez et al. developed the Liberi exergame which was implemented using the Unity game engine. Five children with CP participated in it using a stationary recumbent bicycle and a standard Logitech wireless game controller over an eight-week home trial. The result has shown that it is possible to create action oriented exergames that can be played and enjoyed by children with CP at GMFCS level III [8]. At that time, the therapist got little feedback from the user's lower limbs through this system. In 2018, Camilo et al.used PlayTherapy's exergame architecture which consists of three core components: GUI Component, World Component and Logic Component to build game system. This design ensures that these games, designed for physical rehabilitation under the guidance of a physical therapist, integrate seamlessly with Kinect 2 technology to effectively track patient movement. They developed an exergame called Tiro Libre, as is shown in Figure 3, which rehabilitates the hip by simulating a soccer goal kicking exercise, with regard to movement mapping correctness, Tiro Libre was evaluated positively. But given the Kinect 2's hefty price tag, it's not the sensing device we persue [3].

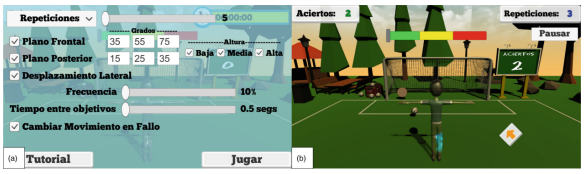

Figure 3: Tiro Libre exergame screens.

Recently, some researchers used dance mats as tracking devices for four exergames for children with disabilities called "Matchmat," "Left or Right?", "Crazy Car " and "Fishing". As illustrated in Figure 4, the dance mat was a flexible, interactive device that could be placed either horizontally on the floor and manipulated with the feet, hands, or body, or vertically on the wall and interacted with using the hands. The results of the study showed that the product had a potential therapeutic effect, and the children were keen to use the Dance Mat to play the games, but in order to avoid frustration, the target group was children at GMFCS level III or lower [13]. In addition to this, the small size and nature of the dance carpet result in limited space for activities and lack of expandability.

In the rehabilitation of children with CP, the lower limbs, due to their greater distance from the brain and involvement of more nerves and joints, make the evaluation of rehabilitation effects more ambiguous. Currently, there are no popularized mature devices that integrate games with lower limb rehabilitation equipment, which is the primary reason we want to explore this area. Overall, three aforementioned game systems all use a computer display as visual feedback, which serves the purpose of attraction but has the ensuing

Figure 4: Physiotherapists testing the prototypes and exploring the mat in different ways, using: (left) lower limb; (right) upper limbs.

disadvantage that they also focus too much attention on the virtual world rather than the real-world scene. In contrast, DiamondTouch is a multi-user touch technology for tabletop, front-projected displays that operates without a standard computer display. It allows multiple users to interact on the same surface and accurately distinguishes individual inputs by completing a signal circuit through the user's chair. However, this system requires users to remain seated, which minimally affects finger recognition but significantly impacts foot recognition [5]. Moreover, Promoting, improving or restoring the ability to walk is the most common goal in the lower extremity rehabilitation for children with CP [14]. We expect to realize this through our game.

3 Game Design

To better engage children with CP in lower limb rehabilitation games, we have adopted design recommendations proven effective in CP game practices. We designed a universal carpet hardware and three interchangeable game themes. In the hardware design, to help children with CP grasp the general rules of the game, we simplified the interaction point arrangement. We designed a 6x6 array with a total of 36 interaction points, presenting a more straightforward and user-friendly game interface for children with CP. To reduce the burden of judging the game state, we equipped each interaction point with a set of LED light rings to provide real-time feedback to the children.

3.1 A rural-themed Whack-A-Mole

This Whack-A-Mole game encourages children with CP to step on as many targets as possible within a fixed time, enhancing their reaction ability and increasing their exercise under appropriate pressure. The game features a warm-toned farmhouse environment, complemented by soothing music and voice prompts from the moles to create an immersive gaming experience for children with CP, thus enhancing their engagement. At the start of the game, children need to find and step on the red LED lights. At the end of the game, their scores are announced (see Figure 5). Considering the limited gross motor skills and reaction abilities of children with CP, the game de-emphasizes precise timing of actions. Once a mole appears (with the red light on), it remains visible, and children can challenge their previous scores at their own pace. The game records, including scores, reaction times, and distances between interaction points, are uploaded for review by physical therapists.

3.2 A drawing-based pattern connector

This pattern-connecting game aims to enhance children with CP's precision in stepping while improving their image recognition skills. The interchangeable gameplay cover features a drawing board and a series of simple icons. A painter character and associated sound effects create a sense of drawing with their feet on the floor. When the game begins, lights forming the image turn on, and children can step on each light sequentially to change all red indicator lights to green at their own pace (see Figure 6). To account for children with CP's limited visual-spatial processing skills, the game should clearly indicate available options, with all LED lights in the pattern lit simultaneously to shorten decision-making time and reduce cognitive load. Additionally, errors are minimally penalized, with no feedback for incorrect steps, encouraging positive gameplay progression.

3.3 A sport-oriented soccer simulator

This soccer simulator game aims to increase social interaction among children with CP and enhance their motivation for rehabilitation through peer interaction. The interchangeable gameplay cover design mimics the layout of a real soccer field, with yellow graphics on both sides representing goals. The carpet is divided into two sections for two players. At the start of the game, each player steps on red LED lights in their respective areas, turning them green. The player with the most green lights within the fixed time wins (see Figure 7). Given the competitive nature of the game and the limited visual-motor integration skills of children with CP, each round presents a single option (one red LED light) to reduce decision-making complexity. To prevent physical collisions, the game ensures that LEDs lighting up are spaced far apart, ensuring player safety.

Overall, the hardware and three accompanying games are designed with careful consideration of children with CP's limited gross motor skills, attention span, motor planning integration, and social interaction abilities. Combining these aspects with engaging gameplay aims to maximize the children's rehabilitation motivation. Additionally, the hardware's built-in cameras capture knee joint elevation, protraction, and lateral exertion. These motion data not only provide real-time auditory and visual feedback during the game but also upload to physical therapists to help monitor progress and develop rehabilitation plans. The Whack-a-Mole game focuses on training children's lower limbs to develop instantaneous force, the pattern connector game focuses on training children's memory skills and correcting the angles of their walking postures, and the soccer simulator game focuses on exercising children's interaction skills and providing more intense lower limb training.

4 Conceptual Design

4.1 Carpet Design Principles

In the initial version, the carpet design incorporated a layer of porous foam, which provided simplicity in structure, ease of curling, and convenient storage. Nonetheless, subsequent evaluations revealed a significant issue: the design made it challenging to discern whether the carpet was being pressed by feet or other parts of the body, as shown in Figure 8. To address this issue, the project

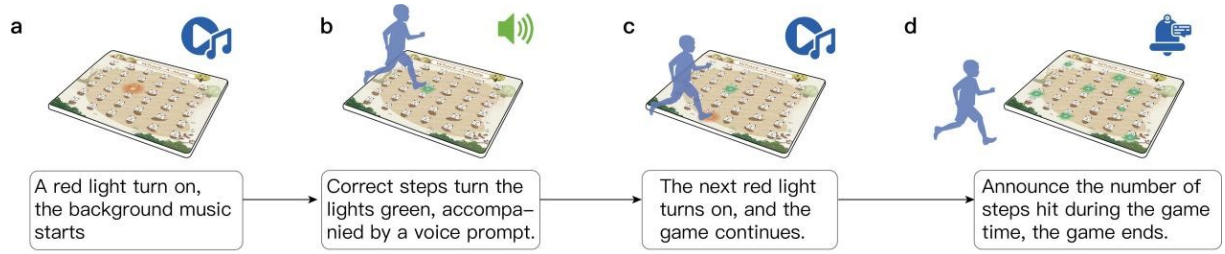

Figure 5: Sequence of interactions for the Whack-A-Mole game.

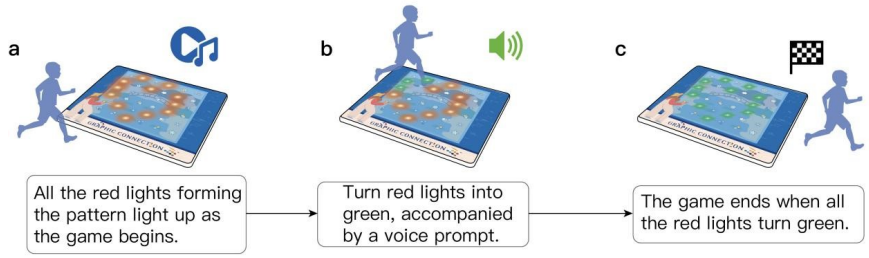

Figure 6: Sequence of interactions for the pattern connector game.

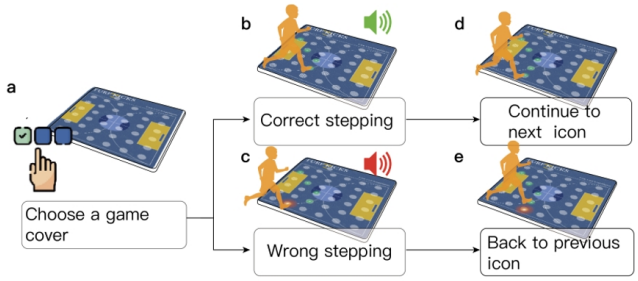

Figure 7: Sequence of interactions for the dual-player soccer simulator.

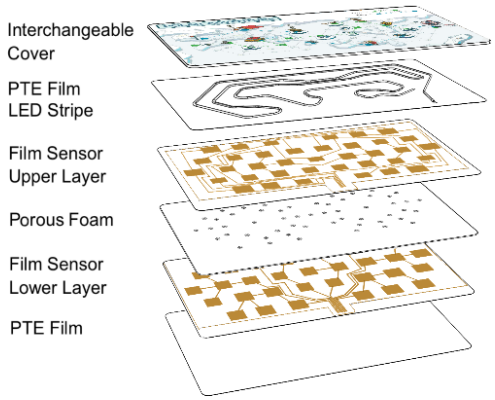

Figure 8: Technical and functional construction of the prototype.

proposes the development of an innovative detection method inspired by the mechanics of a keyboard. This approach entails using feet as input keys, with copper conductive tape affixed to the soles. When the conductive tape contacts a detection point, it establishes a conductive pathway, enabling the microcontroller to recognize the activation of that specific point. As no other parts of the body possess conductive material similar to the feet, activation will not occur if other body parts come into contact with the detection points.

To address this challenge, the revised design employs wire conduction to ascertain whether a point has been stepped on. Rather than relying on pressure, this method uses a conductor connection to change the conduction state. This is accomplished by running wires from the lower layer of the carpet through to the upper layer and then back again, leaving a segment of the wire exposed on the upper layer, as shown in Figure 9. The contacts are arranged both horizontally and vertically. When a copper sheet is affixed to the foot and the two contacts are simultaneously stepped on, the wires are connected, thereby completing the circuit. This method effectively resolves the issue identified in the initial version, and it is anticipated that children with CP will utilize their feet for training purposes.

4.2 Gesture version-based evaluation system

To enhance the effectiveness of the interactive gaming carpet and provide valuable feedback to therapists, a gesture vision-based evaluation system was integrated into the prototype. This system employs MediaPipe, a robust tool for human pose estimation, to analyze the movements of children with CP during gameplay. Incorporating pose recognition into the game ensures that children

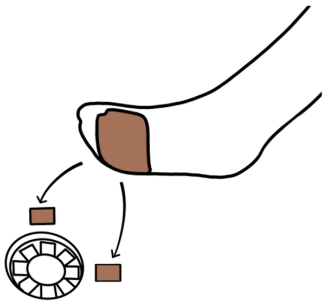

Figure 9: Schematic diagram of contact points.

remain focused on their rehabilitation exercises, whereas methods such as exoskeletons may interfere with their training. Concurrently, the posture landmarks detected by MediaPipe provide therapists with crucial data to evaluate the effectiveness of the rehabilitation exercises and to tailor treatment plans accordingly [9]. The system calculates the angles of various joints, such as the knee and hip, enabling therapists to assess the range of motion and identify areas needing improvement. By analyzing the sequence and timing of foot placements, the system offers insights into gait pattern abnormalities, assisting therapists in developing targeted interventions. Additionally, the system tracks changes in joint angles and gait patterns over time, allowing therapists to monitor progress and adjust treatment plans as necessary [1]. The gesture vision-based evaluation system significantly enhances the value of the interactive gaming carpet for the lower limb rehabilitation of children with CP. By providing real-time feedback on movement patterns and joint angles, the system enables therapists to closely monitor progress and develop personalized treatment plans. This integration of technology and gameplay creates a dynamic and effective rehabilitation tool that promotes engagement and improves outcomes for children with CP.

5 Preliminary Testing

The carpet-based game design was tested in a hospital, with five children participating in the device evaluation (see Figure 10). According to related articles, children with CP typically require engaging game setups to capture their attention. Therefore, the primary objectives of the test were to ascertain the following: 1) whether the children comprehend the game rules; 2) whether the patients receive adequate guidance through visual, auditory, and tactile feedback; 3) whether the setup is user-friendly and the game intensity is appropriate; 4) the efficacy of this rehabilitation method in successfully achieving exercise objectives.

Firstly, we provided some basic training on the usage of the carpet device, demonstrated the game methods, and then allowed the children to try them out. Under the guidance of the physician, the five children quickly grasped the game rules. During gameplay, they did not exhibit any signs of distraction, indicating that the games, which incorporate sound and light changes, are more captivating than traditional rehabilitation methods. Furthermore, the therapists reported that the children could engage in training for extended periods, suggesting that the game intensity was appropriately set. In terms of hardware, the multi-layer design of the

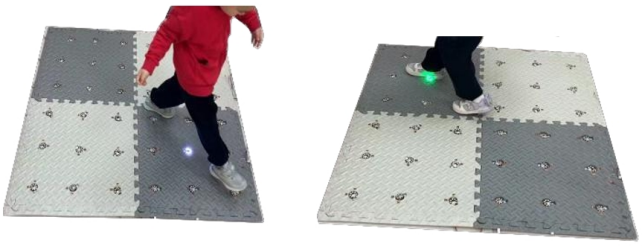

Figure 10: User Testing.

game carpet, which is collapsible and detachable, alleviates storage pressure and allows children to engage in the same rehabilitation games at home. The therapists held a positive view of our game and confirmed its effectiveness and accessibility for maintaining diverse rehabilitation exercises. However, they noted that the duration and accuracy of gameplay are not reliable references for assessing the children's lower limb capabilities. To address this, we used gesture vision-based evaluation system to get real-time generated three-dimensional posture images for accurate analysis, as illustrated in Figure 11. For long-term treatment, we plan to improve the carpet's power supply and cloud storage functionality in the future, enabling therapists to monitor the children's home rehabilitation and perform precise analyses of their rehabilitation progress.

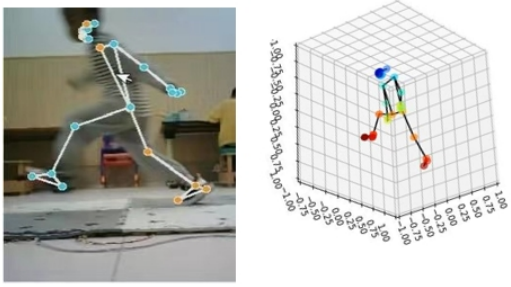

Figure 11: Real-time 3D images for posture analysis.

6 Conclusion

This study presents the design and implementation of an interactive lower limb rehabilitation product, specifically tailored for knee joint flexion and extension exercises, incorporating advanced data analysis and rehabilitation guidance. Utilizing a novel foot-operated detection method, a camera module, and various interactive components, the system provides intuitive user interaction and precise gameplay feedback. Motion data are continuously transmitted for real-time processing and analysis using MediaPipe and deep learning techniques, offering comprehensive assessments of rehabilitation progress. This enables clinicians to make data-driven adjustments to treatment protocols. The three integrated games are specifically designed to engage school-age pediatric patients, enhancing their motivation and enjoyment in the rehabilitation process. Preliminary tests show an increased willingness to participate in therapy, with more accurate and data-driven progress

monitoring, significantly improving the effectiveness of rehabilitation. Additionally, the product's ease of assembly, portability, and user-friendly operation make it suitable for both clinical and home-based lower limb rehabilitation. The study underscores the potential of combining game-based interventions with data analysis in cerebral palsy rehabilitation, offering a promising approach to enhance therapeutic outcomes and accessibility. Future improvements will focus on enhancing the power supply and cloud storage capabilities, providing better hardware support and facilitating easier access to rehabilitation data for therapists. Additionally, while the product shows promising results, the durability of the carpet over time remains a concern, as floor-based equipment is subjected to more wear and tear compared to table-based activities. Addressing this in future designs by selecting more durable materials or developing a maintenance protocol will be crucial to ensuring the system's long-term viability. We also aim to develop a quantitative, comprehensive method for gait evaluation, potentially revolutionizing rehabilitation assessment techniques.

Acknowledgments

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