Multi-Sensory Non-Dominant Hand Rehabilitation in Pediatric Cerebral Palsy Using a Wearable Device with Remote Monitoring

Mutiah Apampa
220520511
Supervised by: Dr. Ekaterina Ivanova
MSc. Artificial Intelligence

Abstract—**Rehabilitating the non-dominant hand of Cerebral Palsy (CP) patients is a lengthy process that often extends beyond clinical release. This project aims to create an engaging rehabilitation system, enabling pediatric CP patients to independently exercise at home. The system encompasses a multi-sensory wearable device, a game, and a smartphone application.**
This paper presents findings from three preliminary studies, assessing the system's effectiveness and usability in terms of comfort, ease of use, feedback efficiency, hand dexterity improvement, and overall satisfaction. Three healthy participants, aged 7 to 8, along with their parents, engaged in evaluation sessions, utilizing the device. To facilitate comparisons with CP patients, participants were encouraged to use their non-preferred hand.
The first trial aimed to establish game familiarity. In the second trial, feedback was intentionally omitted to assess its impact on engagement. The third trial encompassed all feedback mechanisms.
The outcomes reveal active participant engagement, rapid motor learning, and a willingness to continue device usage which highlights the potential effectiveness of this approach in pediatric CP rehabilitation.

I. Introduction

Our hands serve a remarkable function in our day-to-day activities, enabling us to execute intricate tasks such as sewing, knitting, or simply tying shoelaces. For individuals without any health conditions, these activities may seem effortless and natural. However, the coordination and control of hand functions are intricately linked to the functioning of our central nervous system, particularly the brain (Arnould et al. 2014).
Unfortunately, for children with cerebral palsy (CP), these activities are far from easy. CP is the most prevalent physical disability among children, affecting approximately 1 to nearly 4 out of every 1,000 live births (*Data and Statistics on Cerebral Palsy* 2021). This condition disrupts the proper functioning of the central nervous system, leading to impairments in hand functioning and other motor skills (Rosenbaum et al. 2007, Klingels et al. 2012). Understanding the difficulties encountered by children with CP in performing everyday tasks highlights the significance of developing effective interventions and therapies to improve their hand functions.
CP is a group of permanent neuromotor disorders that affects movement, coordination, muscle tone, and posture (NHS choices n.d.). Studies have shown that persistent hand preference within the first year of life may be an early predictor of cerebral palsy (Sellier et al. 2016, Today 2020).
Unilateral cerebral palsy (uCP) is characterized by the predominance of upper limb impairments in one hand/arm, which can significantly impact the ability to use both hands together (McIntyre et al. 2011). As a result, children with uCP face difficulties in performing various daily activities that require coordinated hand movements. This includes tasks like dressing, eating, and playing. Without timely and effective therapy, children with uCP tend to avoid using their more affected hand, leading to increased physical impairment, reduced functionality, decreased independence, and limitations in engaging in leisure activities (Eyre et al. 2001, Imms et al. 2016, Arner et al. 2008, Arnould et al. 2014).
Rehabilitation plays a crucial role in enhancing motor control and functional outcomes for pediatric patients with CP. Traditional rehabilitation strategies, including individual therapy sessions conducted in a clinical setting, possess inherent limitations concerning treatment frequency, intensity, cost, and mobility demands (Ozgur et al. 2018). This lack of intensive practice can impede motor skill development and hinder the achievement of functional goals. Home-based therapy has emerged as a promising strategy to address these challenges (Ozgur et al. 2018). Providing therapy in familiar environments offers increased treatment frequency, scheduling flexibility, and the potential for skill generalization into daily activities (Novak et al. 2009). Given the susceptibility of children to lose interest and enthusiasm during therapy sessions, which could potentially hinder overall progress, it becomes imperative to develop innovative and engaging approaches for delivering rehabilitation interventions. This approach is essential for maximizing therapy effectiveness and promoting meaningful participation.
One effective approach is the use of interactive rehabilitative serious games. These games provide engaging and motivating experiences that encourage intensive practice and motor learning (Bortone et al. 2017, Da Silva et al. 2021, Ozgur et al. 2018). They make use of auditory and visual feedback systems to enhance sensory perception and provide real-time performance data for progress tracking (Bortone et al. 2017). The integration of serious games into rehabilitation has shown

Identify applicable funding agency here. If none, delete this.

to be useful in enhancing neuroplasticity among children with CP (Choi et al. 2023). Neuroplasticity, the brain's adaptability to reorganize and strengthen neural connections, is crucial for skill acquisition and habit formation (Ozgur et al. 2018). By capitalizing on the brain's capacity for neuroplasticity through repetitive practice, serious games have emerged as valuable tools for rehabilitation (Da Silva et al. 2021). By incorporating motivational elements such as points accumulation, games provide immediate feedback through visual and auditory cues, effectively engaging cognitive processes and enhancing motor learning (Li et al. 2009).

One of the options suitable for providing home-based training is wearable technology (Lang et al. 2020, Maceira-Elvira et al. 2019). Wearable technologies have emerged as a promising avenue in rehabilitation, offering fresh opportunities to enhance patient outcomes and streamline therapy delivery (Lang et al. 2020, Maceira-Elvira et al. 2019, Bortone et al. 2017). These devices possess the capability to capture and monitor a wide range of movement data, providing valuable insights into patients' motor performance and progression (Lang et al. 2020). They also offer real-time feedback, enabling the tracking of an individual's movements and allowing necessary adjustments during therapy sessions (Brown et al. 2022).

Furthermore, wearable technology facilitates remote monitoring and assessment, thus supporting at-home rehabilitation and reducing the necessity for frequent in-person visits to healthcare facilities (Lang et al. 2020). Previous research suggests that active utilization of such technologies has the potential to enhance the utilization of impaired limbs (Brown et al. 2022).

Building upon these advancements, this paper introduces an interactive rehabilitative video game controlled by wearable technology with multi-sensory feedback, tailored for children with cerebral palsy and impaired non-dominant hand function. The project aims to create a motivating, convenient home-based therapy solution, incorporating haptic, visual, and auditory feedback, along with at-home monitoring for remote assessment by parents and healthcare professionals.

The study's objectives involve evaluating the feasibility and effectiveness of the proposed technology. Quantitative and qualitative data collection will facilitate assessing the game's impact on motor abilities, motivation, and involvement.

II. Related Work

Several systems for telerehabilitation already exist, with varying degrees of technological sophistication. Some systems utilize wearable devices in combination with applications, albeit without multisensory feedback (Brown et al. 2022). Other approaches, such as the Kinect-Based Constraint-Induced Therapy (CIT) Study, incorporate auditory and visual feedback to enhance engagement (Hsiao et al. 2017). A different avenue involves serious games implemented on wearable devices, integrating haptic, auditory, and visual feedback to provide an enriched user experience, although lacking remote assessment (Bortone et al. 2020). These systems share a common goal of integrating entertainment elements into rehabilitation to enhance patient motivation.

Moving forward, we delve into a concise review of relevant studies that contribute to the context of this project and highlight areas in which this study offers improvements. Brown et al. (2022) investigated the perspectives of 25 participants on an approach utilizing wearable devices and a smartphone application to encourage the use of the affected upper limb for children with hemiplegia, albeit without sensory feedback. Da Silva et al. (2021) extended their study to 44 participants, including children with CP and typically developing individuals. The results demonstrated that children with CP derived enjoyment from serious games, performed comparably to their peers, and exhibited enhanced performance and physical activity levels, affirming the effectiveness of serious games for at-home therapy. Hsiao et al. (2017) introduced a KINECT-based rehabilitation game tailored for children with CP, achieving intensive motor training goals and heightened motivation.

A standout development in the field is the Neuro Rehabilitation System by Bortone et al. (2017), targeting children with movement disorders. This system amalgamates serious games, virtual reality, and haptic technologies to enhance patient engagement. The integration of multisensory feedback during motor exercises, along with customizable virtual scenarios, contributes to personalized and effective rehabilitation. Another innovation, the BUDI system, designed by Stanford medical student Blynn Shideler and team, is in the testing phase. This wearable device aims to enhance accessibility and flexibility in pediatric rehabilitation, particularly catering to children with cerebral palsy by offering remote physical therapy services (Berger 2022).

Insightful research conducted by Demeke et al. (2023) revealed limited parental involvement in-home therapy programs. However, technological advancements have introduced the potential for remote training and monitoring through the internet. Pagaki-Skaliora et al. (2022) showcased the efficacy of remote treatment in enhancing the functional abilities of children with CP, thereby improving accessibility to healthcare services while alleviating caregiver burden.

Current rehabilitation strategies for pediatric CP reveal notable gaps and limitations. Some systems, like costly VR and robotic solutions, lack accessibility for a significant portion of the pediatric population. Additionally, existing approaches struggle to maintain engaging and consistent therapy experiences outside clinical settings, impeding sustained progress. Moreover, the integration of multisensory feedback, critical for effective rehabilitation, is often lacking. The incorporation of remote monitoring capabilities, crucial for sustaining therapy momentum, is also inadequately addressed in some methodologies. This study seeks to bridge these gaps by introducing an interactive rehabilitative video game controlled by wearable technology. Enriched with multi-sensory feedback, this game aims to enhance motor control and functional outcomes for children with CP, while also providing remote monitoring capabilities for both parents and healthcare professionals.

III. Methods

Fig. 1 shows a schematic diagram of the project.

A. Game Design

For the purpose of this specific research, the development focus revolved around creating a video game as shown in Fig. 2. This choice was motivated by the inherent advantage of video games, which can be easily customized and fine-tuned over a prolonged duration. This flexibility increases the chance of sustained engagement, even in instances where the child's interest diminishes, thus preserving the game's effectiveness when used alongside the device.

A racing game was developed using a developer-focused, open-source game engine platform known as Unity3D by building on its karting game template (*Unity* n.d.). This platform offers a variety of intricate components enabling the creation of three-dimensional entities and agents for console games.

In this racing game, players controlled a car's movements through a wearable device. The game took place within a single scene, featuring a camera that ensured continuous visibility of all game elements. Graphics were deliberately kept simple to minimize potential distractions.

Within this scene, several key elements were included: a controllable kart, a predefined path to follow, rocks as obstacles, and enticing pieces of food that both accrued points and incentivized movement.

B. Game Design Rationale

The game design prioritizes rehabilitation through interactive gaming, focusing on the non-dominant hand. The aim is to seamlessly integrate therapeutic exercises with enjoyable gameplay for more effective recovery. During each round of gameplay, the primary objective was to navigate the car from the starting point to the finish line while collecting the food items to accumulate points. These strategically placed items encouraged lateral movements, thereby facilitating a wider range of motion for the user. The mechanics of the game involve simple motions: moving forward, backward, left, and right to either avoid obstacles or accumulate points. These natural movements contribute to the reestablishment of coordination and motor skills, aligning with previous studies conducted in the context of CP rehabilitation (Li et al. 2009).

To enhance the immersive experience, the game provided instant visual and auditory feedback. When the user hits the food items, the wearable device generated a resonating vibration (provided as haptic feedback via the wearable device) accompanied by a corresponding sound. This sensory experience was further enhanced by on-screen confetti effects. Ultimately, the game's objective is to create an immersive experience that promotes the practice of specific hand movements for rehabilitation purposes. By making therapy enjoyable and accessible, users are empowered to integrate it into their daily lives, thereby promoting sustained progress.

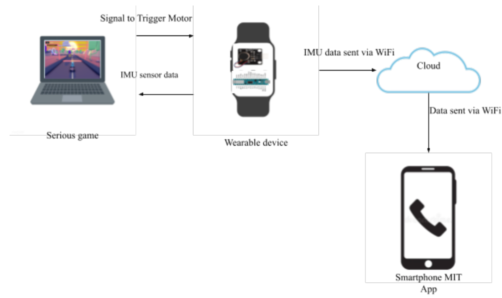

Fig. 1. Schematic diagram of the project

Fig. 2. A scene in the game

C. Hardware Design

The wearable device (Fig. 4) consisted of a microcontroller (Arduino Nano IoT) with an integrated inertial measurement unit (IMU) sensor (LSM6DS3), as well as built-in WiFi and Bluetooth capabilities (Arduino n.d.). Additionally, the prototype included a Vibration Motor Module, as depicted in Fig. 3. The user's arm acceleration along the X, Y, and Z axes was captured using the accelerometer. An algorithm was developed and programmed onto the microcontroller in C++ to detect user movements and control the game accordingly.

For protection and durability, the device was housed in a 3D-printed case made from flexible and safe Thermoplastic Polyurethane (TPU). To supply the necessary 5V power to the motor, the microcontroller was configured to operate using a USB connection in accordance with its manufacturer's specifications (Arduino n.d.).

D. Smartphone Application

Another aspect of the project involved the creation of an app catering to therapists, guardians, or parents of the patients,

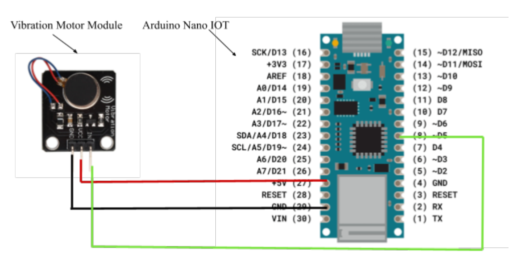

Fig. 3. Circuit design of the wearable device

Fig. 4. Wearable Device

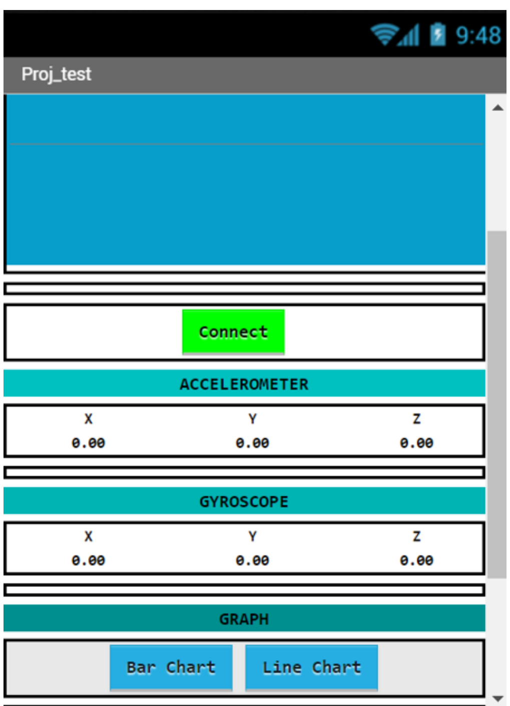

Fig. 5. A screenshot of the App for Remote Monitoring

seeking to monitor therapy frequency. Developed utilizing the MIT App Inventor (*MIT App Inventor* n.d.), the app established a wifi connection with the device to facilitate motion data transfer for visualization.
Upon launching the app, a prompt to connect with the wearable device is presented (Fig. 5). Once the connection is established, data transmission to the cloud commences. Post each therapy session, the data is securely stored in the cloud. When prompted, the app retrieves the stored data from the cloud and generates a visual representation of hand usage frequency across various time frames. This app seamlessly integrates data management and visualization to provide valuable insights into therapy progress.

IV. DESIGN EVALUATION

A. *Participants*

Three children (mean age: 7 ± 0.82, with 3 being female) were recruited from the local community. These children possessed diverse levels of prior exposure to video games. Each participant and their parent willingly volunteered for the study. All participants were right-handed and had no prior health conditions i.e. there were no indications of mental, cognitive, or neurological disorders among the participants.
Prior to engaging in the study, all participants and their parents were provided with a comprehensive information sheet. This document contained detailed information about the study's purpose, task instructions, and data handling procedures. Both the children and their parents provided written informed consent, demonstrating their willingness to participate in the study and adhere to its requirements.

B. *Experimental protocol*

The experiment comprised three distinct trials, each serving specific purposes. The first trial aimed to establish familiarity with the game and assess the children's motivation levels. This initial phase was designed to help participants become proficient in the gestures necessary for effective game interaction. In the second trial, feedback was intentionally omitted to explore its impact on the children's engagement.The third trial involved activating all feedback mechanisms.These trials were conducted under the supervision of both the parents and the author. The game was run on a laptop running on Windows 11, to which the wearable device was connected via USB. The laptop was placed approximately 3m from the participants. Participants were encouraged to use their non-preferred hand for the purpose of facilitating the comparison with the non-dominant hand of children with CP. These measures were implemented to gain a more precise understanding of the participant's interactions.
The Smileyometer rating scale (Sim & Cassidy 2013), displayed in Fig. 6 commonly employed to assess children's interactions with technology was used in this study. The questionnaire comprised 8 questions while the Me-cue questionnaire (Thüring & Mahlke 2007), consisting of 12 questions was administered to parents.

Fig. 6. Smileyometer rating scale

The questionnaire encompassed specific categories: three questions related to Visual Aesthetics, six focusing on Ease of Use, six addressing Feedback Effectiveness, and five concerning Overall Satisfaction. Due to the limited participant pool, conducting a randomized trial was deemed unfeasible. Consequently, the trials were divided into those incorporating sensory feedback and those without it. The subsequent sections detail the results.

V. RESULTS

Among the child participants, 100% reported the highest rating of ”Fantastic” for Visual Aesthetics, with 16.67% indicating the device was easy to use ”All of the time”. Additionally, 66.67% expressed it was ”Most times” easy to use. Regarding the feedback, 88.89% of participants found it ”Fantastic,” while the remaining respondents liked it ”Really much.” All participants indicated their willingness to play the game again, with 83.3% rating their overall satisfaction as ”Fantastic” (see Fig. 7).
Among the parent participants, 100% ”strongly agreed” that both the device and game design were visually pleasing.

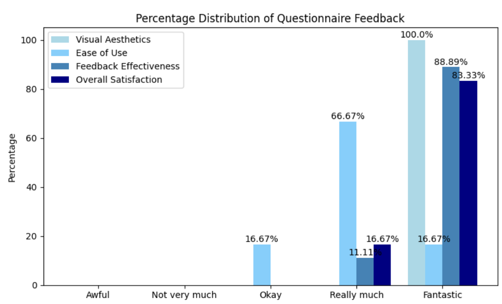

Fig. 7. Percentage distribution of children participants questionnaire feedback

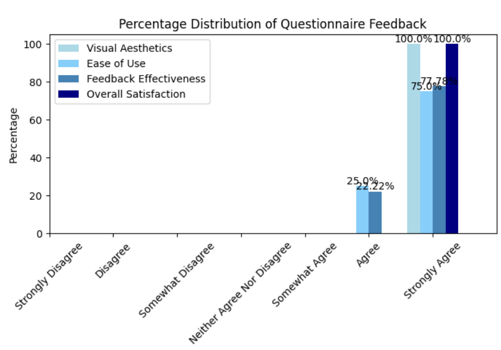

Fig. 8. Percentage distribution of parent participants questionnaire feedback

Additionally, 77.78% ”strongly agreed” that their children responded positively to the feedback, with the remaining participants indicating ”Agreement.” Furthermore, 75% ”strongly agreed” that the device was easy to use, while 15% ”agreed.” Overall, 100% of the parent participants expressed ”strong agreement” with their satisfaction(see Fig. 8).
In terms of improvement suggestions, the majority of comments recommended incorporating additional speed boosts (see Table I).

A. Comparative Analysis

A comparative analysis was conducted based on participants’ prior gaming experience, categorizing them into either Novice or Intermediary levels. Notably, participants with an Intermediary level of experience outperformed Novice participants, achieving a higher number of collected items and demonstrating greater proficiency in completing the races in a shorter duration (see Fig. 9 & 10).
Subsequently, another comparative analysis was carried out, this time comparing the outcomes of the 2nd and 3rd trials (with and without feedback respectively). The results indicated that the inclusion of feedback yielded an increase in the number of collected items. Additionally, as the trial sequence progressed, the duration of time required for completion consistently decreased (see Fig. 11 & 12).
A central focus of this study was to evaluate the device’s impact on enhancing hand dexterity. This improvement in hand

TABLE I
COMMENTS MADE BY PARTICIPANTS

Participant	Comments
Kids	*“Maybe Cupcakes, Add more speed bumps”* *“Could you add Ice cream that gives a boost”* *“Can I get faster speed after eating the cookie?”*
Parents	*“She wanted to continue playing the game”* *“She was very comfortable playing the game”*

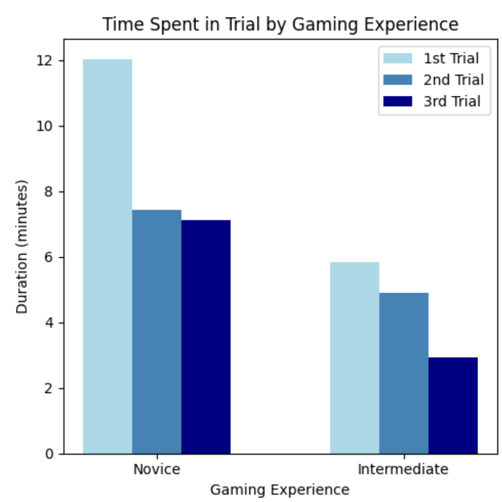

Fig. 9. Time spent in each trial by gaming experience

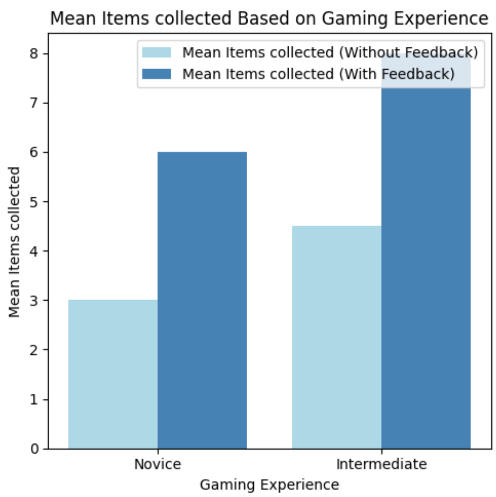

Fig. 10. Average items collected by gaming experience

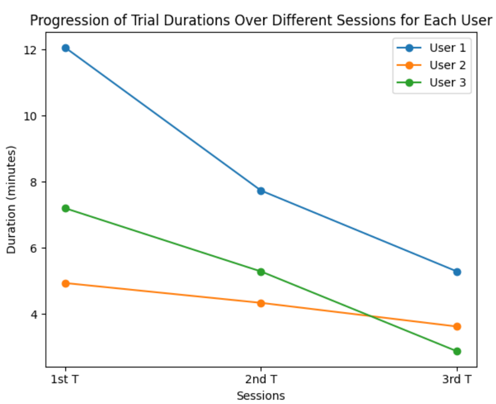

Fig. 11. Duration of each trial per User

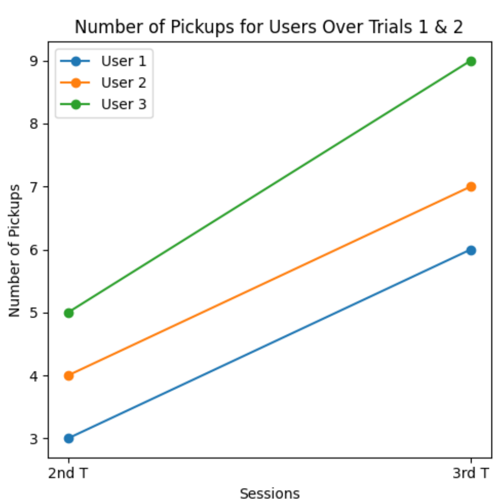

Fig. 12. Number of items collected per User for Trials 1 & 2

dexterity was quantitatively measured and is evident in both the reduction of duration time and the increase in the collection of food items as participants became more familiar with the game (refer to Fig. 11 & 12).

VI. Discussion

In this study, the application of serious gamification and multi-sensory feedback using a wearable device with remote monitoring to enhance user engagement and motor skills in a rehabilitative context were explored.

The results of the user study conducted on healthy children were highly promising. Providing real-time haptic, visual and auditory feedback during gameplay demonstrated its potential to positively influence participants' hand dexterity. The noticeable improvement in hand movements and coordination throughout the progression of the trials highlights the role of sensory feedback in stimulating motor learning processes, especially for individuals with neuromotor impairments.

Analyzing participants' responses and performance across varying levels of gaming experience highlighted the importance of prior familiarity with gaming environments. Participants at the Intermediary level showcased improved proficiency and higher engagement compared to Novice participants. This suggests that those with prior gaming exposure could leverage their existing skills for better interaction with rehabilitation games, leading to more effective skill acquisition and therapy outcomes. Notably, participants with little experience also exhibited accelerated motor learning and quick adaptability. As participants internalized the feedback cues, they displayed heightened motor control and task efficiency, reaffirming the practical value of real-time sensory feedback.

In conclusion, this paper opens up several promising avenues for future research and development in the realm of pediatric cerebral palsy rehabilitation. The feedback, the ease of usability, improvement in hand dexterity and the overall satisfaction are valid indicators that the wearable device with multi-sensory feedback for serious gaming is promising. However, while the study's findings are promising, it is important to acknowledge certain limitations, including the relatively small sample size, the exclusive inclusion of healthy children as participants, the absence of human feedback on the app, and the use of a short-term assessment.

VII. Future Work

While this study has yielded valuable insights, there are still avenues for future research and development. The sample size was moderate, and future research could gain from larger and more diverse participant cohorts. Additionally, the follow-up duration was relatively short, making it necessary to explore the durability of the observed improvements over an extended period. Further research could also investigate the optimal frequency and duration of therapy sessions for maximal benefit.

It's important to note that the current findings are based on data collected from healthy individuals, which serves as a foundational benchmark for subsequent measurements. The ultimate aim of this study is to extend this methodology to therapy involving cerebral palsy patients. Employing a user-centered design approach involving end-users, encompassing children with cerebral palsy, caregivers, and healthcare professionals, in the design and evaluation of the interventions can ensure that the technology aligns with their requirements, preferences, and experiences.

Exploring the implementation of machine learning models to offer personalized therapy based on device usage is another prospective avenue. This extension could lead to a more comprehensive exploration of the device's effectiveness in pediatric neurorehabilitation for children with cerebral palsy, thus providing a more comprehensive understanding of its potential advantages.

REFERENCES

Arduino (n.d.), 'The arduino nano 33 iot documentation'. Accessed: August 23, 2023.
URL: *https://docs.arduino.cc/hardware/nano-33-iot*

Arner, M., Eliasson, A. C., Nicklasson, S., Sommerstein, K. & Hägglund, G. (2008), 'Hand function in cerebral palsy: Report of 367 children in a population-based longitudinal health care program', *The Journal of Hand Surgery* **33**(8), 1337–1347.
URL: *https://doi.org/10.1016/j.jhsa.2008.02.032*

Arnould, C., Bleyenheuft, Y. & Thonnard, J. L. (2014), 'Hand functioning in children with cerebral palsy', *Frontiers in Neurology* **5**, 48.
URL: *https://doi.org/10.3389/fneur.2014.00048*

Berger, J. (2022), 'Medical student designs wearable device for kids with cerebral palsy', *Stanford Report* .
URL: *https://news.stanford.edu/report/2022/07/22/digital-solution-kids-cerebral-palsy/*

Bortone, I., Barsotti, M., Leonardis, D., Crecchi, A., Tozzini, A., Bonfiglio, L. & Frisoli, A. (2020), 'Immersive virtual environments and wearable haptic devices in rehabilitation of children with neuromotor impairments: a single-blind randomized controlled crossover pilot study', *Journal of NeuroEngineering and Rehabilitation* **17**(1), 144.

Bortone, I., Leonardis, D., Solazzi, M., Procopio, C., Crecchi, A., Briscese, L. & et al. (2017), Serious game and wearable haptic devices for neuromotor rehabilitation of children with cerebral palsy, *in* 'Converging Clinical and Engineering Research on Neurorehabilitation II', Springer, pp. 443–447.

Brown, R., Pearse, J. E., Nappey, T., Jackson, D., Edmonds, G., Guan, Y. & Basu, A. P. (2022), 'Wrist-worn devices to encourage affected upper limb movement in unilateral cerebral palsy: Participatory design workshops', *Frontiers in rehabilitation sciences* **3**, 1021760.
URL: *https://doi.org/10.3389/fresc.2022.1021760*

Choi, J. Y., Yi, S.-h., Shim, D., Yoo, B., Park, E. S. & Rha, D.-w. (2023), 'Home-based virtual reality-enhanced upper limb training system in children with brain injury: a randomized controlled trial', *Frontiers in Pediatrics* **11**.

Da Silva, T. D., Da Silva, P. L., Valenzuela, E. J., Dias, E. D., Simcsik, A. O., de Carvalho, M. G., Fontes, A. M. G. G., Alberissi, C. A. O., de Araújo, L. V., Brandão, M. V. D. C., Dawes, H. & Monteiro, C. B. M. (2021), 'Serious game platform as a possibility for home-based telerehabilitation for individuals with cerebral palsy during covid-19 quarantine - a cross-sectional pilot study', *Frontiers in psychology* **12**, 622678.

Data and Statistics on Cerebral Palsy (2021). Accessed: July 13, 2023.
URL: *https://www.cdc.gov/ncbddd/cp/data.html*

Demeke, Z. D., Assefa, Y. A., Abich, Y. & Chala, M. B. (2023), 'Home-based therapy and its determinants for children with cerebral palsy, exploration of parents' and physiotherapists' perspective, a qualitative study, ethiopia', *PLOS ONE* **18**(2), e0282328.
URL: *https://doi.org/10.1371/journal.pone.0282328*

Eyre, J. A., Taylor, J. P., Villagra, F., Smith, M. & Miller, S. (2001), 'Evidence of activity-dependent withdrawal of corticospinal projections during human development', *Neurology* **57**(9), 1543–1554.
URL: *https://doi.org/10.1212/wnl.57.9.1543*

Hsiao, L., Huang, W., Hsu, T., Lin, S., Chen, H. & Wang, T. (2017), 'Development of a kinect-based bilateral rehabilitation game for children with cerebral palsy', *Journal of the Neurological Sciences* **381**, 191–192.
URL: *https://doi.org/10.1016/j.jns.2017.08.548*

Imms, C., Mathews, S., Richmond, K. N., Law, M. & Ullenhag, A. (2016), 'Optimising leisure participation: A pilot intervention study for adolescents with physical impairments', *Disability and Rehabilitation* **38**(10), 963–971.
URL: *https://doi.org/10.3109/09638288.2015.1068876*

Klingels, K., Demeyere, I., Jaspers, E., De Cock, P., Molenaers, G., Boyd, R. & Feys, H. (2012), 'Upper limb impairments and their impact on activity measures in children with unilateral cerebral palsy', *European Journal of Paediatric Neurology* **16**(5), 475–484.

Lang, C. E., Barth, J., Holleran, C. L., Konrad, J. D. & Bland, M. D. (2020), 'Implementation of wearable sensing technology for movement: Pushing forward into the routine physical rehabilitation care field', *Sensors* **20**(20), 5744.
URL: *https://doi.org/10.3390/s20205744*

Li, W., Lam-Damji, S., Chau, T. & Fehlings, D. (2009), 'The development of a home-based virtual reality therapy system to promote upper extremity movement for children with hemiplegic cp', *Technology and Disability* **21**, 107–113.

Maceira-Elvira, P., Popa, T., Schmid, A. C. & Hummel, F. C. (2019), 'Wearable technology in stroke rehabilitation: towards improved diagnosis and treatment of upper-limb motor impairment', *Journal of neuroengineering and rehabilitation* **16**(1), 142.

McIntyre, S., Morgan, C., Walker, K. & Novak, I. (2011), 'Cerebral palsy–don't delay', *Developmental Disabilities Research Reviews* **17**(2), 114–129.
URL: *https://doi.org/10.1002/ddrr.1106*

MIT App Inventor (n.d.). Accessed: Aug. 2023.
URL: *https://appinventor.mit.edu/*

NHS choices (n.d.), 'Cerebral palsy'.

URL: *https://www.nhs.uk/conditions/cerebral-palsy/*

Novak, I., Cusick, A. & Lannin, N. (2009), ‘Occupational therapy home programs for cerebral palsy: double-blind, randomized, controlled trial’, *Pediatrics* .

Ozgur, A. G., Jonas Wessel, M., Johal, W., Sharma, K., Özgür, A., Vuadens, P., Mondada, F., Hummel, F. C. & Dillenbourg, P. (2018), Iterative design of an upper limb rehabilitation game with tangible robots, *in* ‘2018 13th ACM/IEEE International Conference on Human-Robot Interaction (HRI)’, pp. 241–250.

Pagaki-Skaliora, M., Morrow, E. & Theologis, T. (2022), ‘Telehealth and remote interventions for children with cerebral palsy: Scoping review’, *JMIR rehabilitation and assistive technologies* **9**(4), e36842.

Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., Dan, B. & Jacobsson, B. (2007), ‘A report: the definition and classification of cerebral palsy april 2006’, *Developmental Medicine and Child Neurology. Supplement* **109**, 8–14.

Sellier, E., Platt, M. J., Andersen, G. L., Krägeloh-Mann, I., De La Cruz, J., Cans, C. & of Cerebral Palsy in Europe (SCPE) collaboration, S. (2016), ‘Decreasing prevalence in cerebral palsy: a multi-site european population-based study, 1980 to 2003’, *Pediatric Research* **79**(5), 649–655.

Sim, G. & Cassidy, B. (2013), Investigating the fidelity effect when evaluating game prototypes with children, *in* ‘27th International BCS Human Computer Interaction Conference’, London, United Kingdom, pp. 1–6.

Thüring, M. & Mahlke, S. (2007), ‘Usability, aesthetics, and emotions in human-technology interaction’, *International Journal of Psychology* **42**(4), 253–264.

Today, C. P. N. (2020), ‘Early signs of cerebral palsy poorly studied, delaying rehab, other help’, *Cerebral Palsy News Today* . [Online].
URL: *https://cerebralpalsynewstoday.com/2020/03/18/early-signs-of-cerebral-palsy-poorly-studied-delaying-rehab-other-help/*

Unity (n.d.). Accessed: Aug. 2023.
URL: *https://www.unity.com/*