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Proprio: A Computer-Vision-Based App for Upper Extremity Proprioception Training

THESIS

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in Mechanical and Aerospace Engineering

by

Callen Stephen Zimmer

Thesis Committee:
Professor David Reinkensmeyer, Chair
Professor John Michael McCarthy
Professor Camilo Velez Cuervo

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ABSTRACT OF THE THESIS

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Stroke-induced neurological impairments affect millions globally, with movement-related disability one of the most common long-term consequences. Recent evidence suggests that proprioception – the ability to perceive the position and movement of body parts in space – plays a key role in movement rehabilitation after stroke. Proprioception is required for accurate control of the upper extremities during daily activities and also plays an important role as a teaching signal when learning new movement patterns. Stroke commonly impairs upper extremity proprioception, but there are few technologies available to help retrain proprioception. This thesis addresses this challenge by developing and testing a serious game – called "Proprio" – designed for at-home proprioceptive training using personal computer or smartphone technology, which offers a cost-effective, scalable solution.

Proprio integrates real-time hand position tracking using the MediaPipe computer vision framework with an engaging, game-based exercise aimed at improving proprioception. The game is based on a popular, intuitive, and motivating music-based

game (GuitarHero) in which users try to hit notes that stream across the screen. In Proprio, users hit notes by using the finger on one hand to point to a target finger or knuckle on the other hand at the correct moment indicated by streaming music notes. Computer vision detects the spatiotemporal accuracy of the pointing movements to drive game play.

This thesis provides a detailed design description of Proprio and reports the results of an experimental study in which twelve individuals in the chronic phase of stroke trained with Proprio in the laboratory during two sessions spaced 1-2 days apart, followed by a follow-up assessment session one week later. Participants trained with a computer-based version of Proprio for 20–30 minutes per session. We evaluated improvements in proprioceptive-based pointing skill using gameplay performance and motion capture metrics. We also evaluated usability using a widely used measure, the System Usability Scale (SUS).

Participants significantly increased their success at hitting notes over the three sessions by 12% +/- 5% SD and 7% +/- 7% SD when the target hand was the paretic hand or the unimpaired hand, respectively. Normalized pointing accuracy also improved significantly over time. Self-assessed technological proficiency predicted game performance ($p < 0.05$). The overall SUS score was 82.5 +/- 10 SD, indicative of a very satisfactory level of usability based on reference scores from a large database of other usability studies.

These results demonstrate the feasibility and preliminary efficacy of using Proprio to train upper extremity proprioception. We have now created a version of Proprio that can be played on a smartphone. This research contributes to the growing field of digital health solutions for neurologic rehabilitation.

INTRODUCTION

In recent decades, the number of stroke cases has increased significantly. It was estimated that one in six people would have a stroke in their lifetime as of 1999, a number that escalated to one in four by 2016, with 63% of these strokes occurring in individuals under the age of 70 [1]. Many stroke survivors incur sensory motor impairments, with approximately half experiencing impaired proprioception [2].

Proprioception refers to the ability to sense the position and movement of one's body parts in space through the integration of sensory data from proprioceptors [3], [11]. This sensory skill is crucial, as impairments in proprioception can impede daily activities and are linked to longer rehabilitation times [4], [5]. Proprioception is known to play an important role in both motor control and motor learning [32], [33]. Despite the impact of proprioceptive impairments, there are few techniques or technologies that are regularly used in clinical settings to try to enhance proprioception, making development of proprioception-training strategies a focal point of interest in rehabilitation sciences.

Many studies have demonstrated that training focused on proprioception can improve proprioception including for healthy individuals, after joint sprains and surgeries, and in various neurologic conditions [25], [34]. A few studies have shown that proprioceptive training after stroke can lead to functional gains, as highlighted by a review summarizing the positive impact of both therapist- and robot-based proprioceptive rehabilitation therapies on upper extremity function in stroke patients [35]. One study investigated the effect of upper extremity proprioceptive training in patients with chronic hemiplegia after stroke compared to a control group that received only conventional treatment [6]. They found significant improvements in motor function and daily activities (measured by Fugl-Meyer Upper Extremity Motor Assessment, Action Research Arm Test, and Motor Activity Log-28) in both groups, with greater improvements in the group receiving additional proprioceptive training. A different study evaluated the influence of proprioceptive training on lower limb function in individuals with stroke using an ankle-foot robot [7]. They found that proprioceptive training significantly improved walking speed, balance, and motor function compared to regular physical activity alone.

Robot-based proprioceptive training has drawbacks, such as the need for costly devices and safety concerns. Thus, robotic proprioceptive training remains rare in clinical settings, and there is a need for cost-effective, easy-to-use proprioceptive training that can be made available at home. Democratizing proprioceptive training technology could also help make it accessible in lower-income regions, where stroke rates and age-standardized incidences are notably higher [1]. The goal of this thesis was to develop and test an application that helps solve this problem.

DESIGN BACKGROUND FOR A PROPRIOCEPTIVE TRAINING APP

Smartphones for proprioceptive rehabilitation

Smartphones are now ubiquitous, including in low income countries [13], and provide a potential platform for a proprioceptive training app. A recent review described how a number of studies have already leveraged smartphone technology to assist in proprioceptive testing, mainly in the context of back pain, ankle sprains, and knee surgery [12]. Smartphones leverage built in sensors to reliably measure joint position and range of motion (ROM), essential components in proprioceptive testing. However, this review also noted that "there is lack of studies on Smartphone applications which can be used in an autonomous way to provide physical therapy exercises at home."

Serious Games for Rehabilitation

A key consideration for at-home rehabilitation programs is that motivation to engage in training often declines over time [8]. Serious games, defined as digital games designed for purposes beyond pure entertainment, such as education, training, health improvement, and rehabilitation, can motivate users in their rehabilitative progress if designed properly [9], [10]. In recent decades, there has been a surge in the development of serious games aimed at enhancing exercise for rehabilitation purposes. Often, these games depend on specialized training devices, such as Balance Boards or other input devices incorporating Inertial Measurement Units (IMUs), which can be expensive and not widely accessible [10]. For instance, the Sensamove Miniboard, which is a wobble board providing visual feedback, has been shown to significantly improve balance in individuals with stroke but is costly and less feasible for widespread use [14]. This highlights the challenge of making such specialized equipment widely available. Consumer-level smart devices—such as smartphones—come prepacked with a multitude of sensors, and thus have the potential to implement serious games for rehabilitation, making an accessible alternative for these therapies.

Computer Vision for Rehabilitation

The advent of the Xbox Kinect camera in 2010, which featured an RGB camera, a depth camera, and a microphone, caused a rapid increase in interest in design rehabilitation games driven by computer vision [15]. Research involving this device demonstrated its effectiveness in rehabilitation. For example, a study found that Kinect-based, virtual reality, movement training significantly enhanced upper limb motor function when combined with conventional physiotherapy, as evidenced by improvements in the Fugl-Meyer Assessment Scale for Upper Extremity (FMA-UE) and the Box and Block Test (BBT) [29]. Another randomized control trial reported notable improvements in various components of the FMA-UE following movement training guided by the Kinect [30].

Microsoft stopped manufacturing the Kinect in 2015. However, personal computers and smartphones are equipped with RGB cameras, making them potential tools for rehabilitation applications. Recent advances in computer vision using RGB cameras, facilitated by advancements in neural networks, have given low-cost cameras human motion tracking abilities similar to the Kinect. These advancements include the development of algorithms that can accurately capture and analyze human motion. For instance, a study found no significant differences in knee joint reproduction error when measured using Vicon, a well-established 3D optoelectronic motion capture system, versus DeepLabCut, a 2D deep learning-based motion capture from sagittal video files [19]. The development of innovative algorithms such as OpenCap [20] and MediaPipe [21], specifically MediaPipe Hands [22], which efficiently predicts a human hand skeleton from a single RGB camera, further supports the integration of this technology into mobile applications for real-time upper extremity tracking. A review studied the use of RGB cameras in clinical measurement for rehabilitation, highlighting their accuracy and potential for widespread clinical use [36].

Visual Feedback in Proprioception Training

Visual feedback delivered with computer or smartphone screens can also play a crucial role in enhancing proprioceptive training. To effectively deliver this feedback, advanced computer graphics software like Unity can be leveraged [16]. Unity's advanced visual capabilities not only allow for engaging and immersive game environments but also enhance the effectiveness of training by facilitating clearer, more impactful visual feedback. Studies employing Unity have demonstrated that serious games developed on this platform can lead to better rehabilitation outcomes compared to traditional, non-gamified approaches. For instance, a study comparing gamified and non-gamified VR environments for wheelchair skills training found that while performance metrics were similar, the gamified environment significantly reduced cybersickness and increased user engagement [26]. Additionally, a scoping review of serious games in various health interventions, including those developed on platforms like Unity, indicated that gamified systems often lead to higher engagement and better training adherence, ultimately resulting in improved rehabilitation outcomes [27]. There is some preliminary evidence in the context of proprioceptive training that judicious incorporation of visual feedback can benefit proprioceptive learning [7], [28].

METHODS

Design Overview

In order to test the effectiveness of a serious game for proprioception training after stroke, we developed a software application (Proprio), first deploying it on Windows PCs, then later on smartphones. Proprio is designed to be neither graphically nor processing intensive, ensuring it remains playable on any smart device produced within the last five years. We chose to focus on training proprioception of the upper extremity, which can be significantly impaired after a stroke and is important for activities of daily living.

Figure 1: Screen capture of Proprio (main gameplay scene). Notes are moving from left to right of screen. The user is shown a live feed of themselves with hand tracking overlayed.

Proprio is structured as a rhythm-based activity featuring a variety of songs with different beats per minute (BPM). Notes flow across the screen from right to left, and players are challenged to hit these notes precisely on the beat as they move over a visual target at the left side of the screen (See Figure 1). Players interact with the game by using the index finger of the opposite hand (the "pointing hand") to touch their fingers on their "target hand" —specifically the index, middle, ring, or pinky of one hand— to hit different notes.

The player is instructed to hold their target hand in front of their body, which keeps it out of the player's visual field since they are watching the game on the screen and not looking down at their hand. Thus, they must accomplish the action of pointing to their target hand by relying on upper extremity proprioception – that is, by using proprioception to direct the pointing hand to the target hand. In this sense, the game mimics aspects of a common clinical test of proprioception, which is to try to touch the index fingers of the two hands together with the eyes closed.

We employed MediaPipe Hands [22] for real-time tracking of hand and finger positions due to its high accuracy in position tracking and compatibility with smart devices. Successful note play is determined by how accurately the player proprioceptively touches the fingertips at the correct moment when a note appears.

As mentioned earlier, while playing Proprio, the player is instructed to position the target hand in front of their torso (see Figure 2). We chose this position because it places the hand out of view but also because it is achievable by almost all people with stroke, even with severely hemiparetic arms. Of note, proprioceptive acuity increases when the hands are closer to the body [24], which may help enhance the playability of Proprio.

Figure 2: Basic hand positions during Proprio gameplay with MediaPipe hand recognition points overlayed.

Not all individuals with stroke retain the ability to fully extend their fingers. For those unable to touch fingertip to fingertip, the game accommodates by allowing players to touch either the Proximal Interphalangeal (PIP) or Metacarpophalangeal (MCP) joints instead (see Figure 3). This adjustment ensures that all users, regardless of their hand mobility limitations, can participate effectively in the game.

Figure 3: Adaptability to different landmarks on the hand. Left: Fingertips (TIP), Center: PIP joints, Right: MCP joints

During gameplay, the player is also given feedback based on how successful they were in playing each note on beat, with indicators such as "Missed", "Late", "Perfect", or "Early" (See Figure 1). The primary goal is to achieve as many correct notes as possible, and the game uses a star rating system to score performance, with a 90% perfect performance earning the maximum score of three stars. This star rating system, similar to that used in widely recognized mobile games like Angry Birds [23], is intended to help maintain player motivation. It encourages improvement without discouraging players who may not hit every note by allowing them to see potential for scoring higher in future attempts. Additionally, a combo score is presented during gameplay to incentivize players to string together sequences of correctly hit notes, enhancing the engagement and competitive element of the game. The combo score increases with each consecutive correctly timed note, resetting if the player misses a note.

User Feedback and Iterative Development

As we developed Proprio, we subjected it to extensive user testing and obtained detailed feedback that we used to improve it. Our primary goal was to enhance the game's usability and motivational aspects, ensuring it serves as an effective rehabilitation tool. Both non-stroke and stroke players participated in the testing phases, which were conducted using the computer version of Proprio. The feedback collected facilitated improvements across various dimensions, including audio, visual elements, game settings, and overall gameplay interaction.

An initial feedback collection was conducted with 12 participants with no past occurrence of stroke, yet three of them were not considered due to errors in data acquisition. The age of participants were 24.4 ± 2.0 years with 3 females and 6 males. Most participants were right-handed with all users rating their own technological proficiency high. We designed a Usability Survey regarding the usability of the application. The sections of said survey can be seen in Table 1 below.

Table 1: Usability Survey Categories

Section Number	Section Title
1	First Impressions
2	Navigation and Layout
3	Screen Clarity
4	Consistency
5	Interaction and Responsiveness
6	Use of Icons and Symbols
7	Color scheme
8	Song Tempo and Selection
9	Information Hierarchy
10	Error Messages and Feedback
11	Suggestions for Improvement
12	Overall Satisfaction
13	Additional Comments

In response to the UI/UX survey, several audio-related changes were made to enhance the user experience. Participants noted the absence of background music in the menu, which is a common feature in similar games. This feedback led to the addition of copyright-free background music, creating a more immersive and enjoyable pre-game environment. Additionally, participants suggested the inclusion of sound effects for menu interactions, which were subsequently implemented to provide audio feedback for user actions, enhancing the overall interactivity and responsiveness of the game.

User feedback highlighted the need for improved visual clarity and contrast within the game's interface. Participants found some colors difficult to differentiate, prompting a redesign of the color scheme to enhance visibility and stylization. Figure 4 below shows the old design versus the new one. This new design not only improved text and graphic visibility but also made the interface more aesthetically pleasing. To enhance accessibility, a new menu was also added to allow for complete control over UI colors. This allows people with differentiating color blindness to fully set the game to their preference, which saves each time Proprio is loaded. The play menu was redesigned based on popular game interfaces [23], allowing users to select songs easily and intuitively. Additionally, graphical animations were added to explain adjustable settings, such as hitbox size, making the interface more user-friendly. Animations were also added to the tutorial of Proprio, with the goal of making the game easy to understand and play.

Figure 4: Adjustments made to song selection and overall main menu based on user feedback. Showing the different songs that the user can select to play. Left: old version, Right: new version based on user feedback.

Feedback also pointed out several areas where the game settings could be more informative and customizable. For instance, the term 'options' was changed to 'settings' to clarify its purpose. Detection feedback was improved by visualizing red circles that increase or decrease with the slider adjustment. Users can now customize interface buttons and note colors according to their preferences, enhancing usability for individuals with color differentiation difficulties. Furthermore, the settings menu now includes the ability to adjust game difficulty, allowing players to choose between slow, medium, or fast modes (See Figure 5). This customization ensures that the game is adaptable to different skill levels and user preferences.

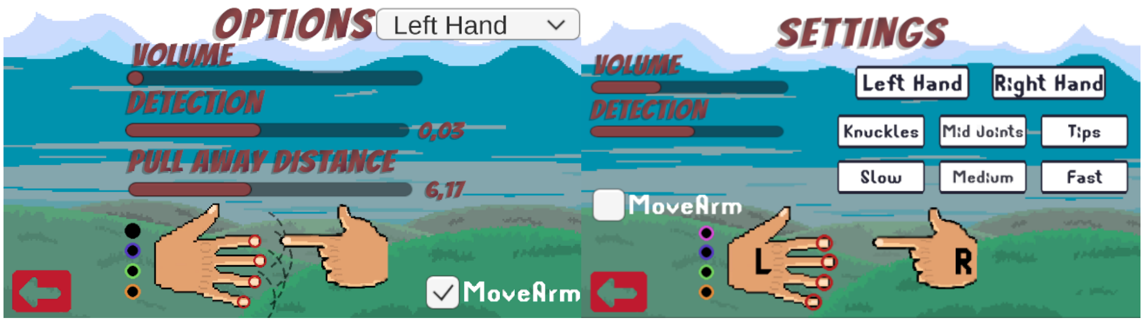


Figure 5: Adjustments made to game "settings" menu. Left: old version, Right: New version based on user feedback. Added additional settings.

The gameplay mechanics were refined based on user feedback to enhance the overall playing experience. Initially, the game started too quickly for some players, so a 5-second delay was introduced before displaying notes, giving players time to prepare. Note assignment was adjusted to ensure that notes do not repeat on the same finger consecutively, providing a more varied and engaging experience. Real-time feedback was enhanced by adding particle effects that indicate timing accuracy (blue for early, green for perfect, and red for late) and displaying performance metrics for each note. Additionally, a star-based system was implemented at the end of the game to motivate players by showing their overall performance and encouraging continuous improvement.

These iterative changes, based on user feedback, significantly improved the functionality and user experience of Proprio.

Experimental Design

We designed an experimental study to evaluate the effectiveness of Proprio in enhancing proprioceptive abilities. We also used the study to assess user engagement and usability, which are critical to the sustained use and success of any rehabilitative tool. For this experiment, we conducted testing of the game using an RGB web camera on a Windows-based computer. The built-in webcam (MSI Prestige 15) had 720P resolution at 30 frames per second, comparable to the front-facing cameras on most modern smartphones, which typically offer similar or higher resolutions.

Inclusion criteria included a confirmed diagnosis of stroke, being above the age of 18, and having the ability to minimally move the non-paretic hand as required by to play Proprio. We aimed to include individuals with a broad range of motor impairment levels to ensure that the application was playable by as many individuals with stroke as possible. Twelve participants were recruited, with a mean age of 56 years (SD = 12), and the duration since their stroke ranged from 295 to 4280 days. The experiment was conducted in the laboratory with a computer and webcam set up with the program installed. A single experimenter escorted participants into the testing room where the screen and camera were positioned at a fixed distance(2 feet away from participant) aimed at their chest (See Figure 6), ensuring a consistent setup across all sessions. Participants were allowed to rest their target arm on a support to prevent fatigue. A standardized explanation of the session's protocol was provided, detailing the assessment process, game objectives, and feedback mechanisms. Informed consent was obtained from each participant in accordance with ethical guidelines and IRB requirements.

Figure 6: Example set-up for testing participants. Proprio is being played on computer a set distance from participant.

Before the first session, a trained physical therapist evaluated each participant's motor impairment level using, the BBT and FMA-UE. We also measured upper extremity proprioceptive ability using a customized evaluation that leveraged the MediaPipe computer vision before the start of each session. Participants performed the evaluation using an autonomous Python program, which hid their target hand from sight while they positioned it against their torso. They then were instructed to attempt to touch the index finger of their pointing hand to various target points on the target hand. The assessment was conducted on both hands, with each hand undergoing 30 attempts per session. We used MediaPipe to measure the distance error (cm) between the intended target and the actual placement of the pointing hand to quantify each participants' proprioceptive accuracy. The distance error was recorded at the moment the participant first stopped moving their pointing hand and before they could self-correct upon missing the target hand.

We introduced participants to the Proprio game through a tutorial to ensure familiarity with the gameplay mechanics. The tutorial explained how to play Proprio through text prompts and animations. Participants first played 3 songs using their paretic hand as the target hand for roughly a ~10-minute game round.

After a short rest period of 3-5 minutes, a second ~10-minute game round was conducted using the opposite hand as the target hand, during which three different songs were played. The notes per minute of each song varied and was recorded to later analyze if song speeds correlated to performance. Each participant repeated the same protocol 24-48 hours after the initial session with the same songs for each hand, and then again approximately one week later.

Following the initial gameplay session, participants completed the System Usability Scale (SUS) questionnaire to assess the usability of the game. The SUS is a simple, ten-item Likert scale that provides a global view of subjective assessments of usability, measuring aspects of effectiveness, efficiency, and satisfaction [18] and has been used previously to evaluate systems designed for proprioceptive assessment [17]. Responses range from one (strongly disagree) to five (strongly agree); the specific questions are presented in Table 2 below.

Additionally, we asked participants to rate their technological proficiency on a scale from zero (no proficiency) to five (high proficiency).

Table 2: System Usability Scale (SUS) Questions

Question	Items
1	I think that I would like to use this system frequently.
2	I found the system unnecessarily complex.
3	I thought the system was easy to use.
4	I think that I would need the support of a technical person to be able to use this system.
5	I found the various functions in this system were well integrated.
6	I thought there was too much inconsistency in this system.
7	I would imagine that most people would learn to use this system very quickly.
8	I found the system very cumbersome to use.
9	I felt very confident using the system.
10	I needed to learn a lot of things before I could get going with this system.

Data Analysis

For the MediaPipe proprioception assessment, we averaged errors across landmarks to get a baseline distance error (cm) for each hand. In order to better understand error improvement, we also analyzed distance error when normalized to each participant's maximum distance error between all sessions.

We also averaged the percentage of notes successfully hit for each game round to obtain a performance metric for both the paretic and non-paretic hands in each of the sessions. We also used this metric when comparing participants' self-assessed technological proficiency.

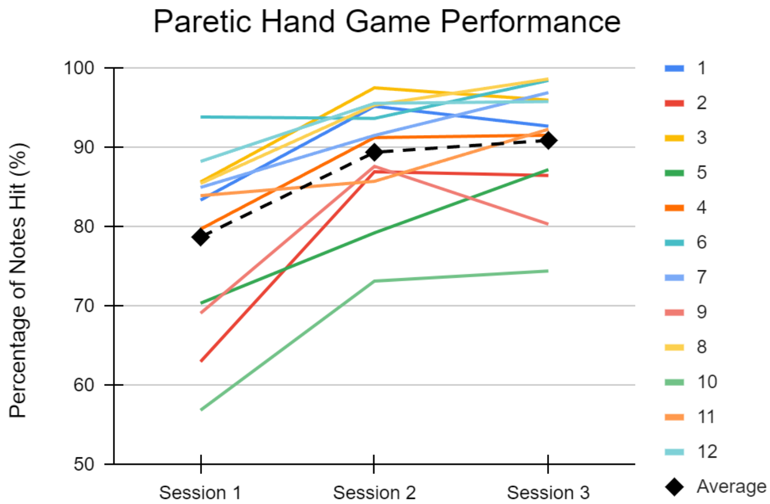
We handled missing data when comparing paretic target hand versus non-paretic target hand by listwise deletion. ANOVA and Post-hoc analysis were conducted in python.

RESULTS

A total of 12 individuals who had experienced a stroke played Proprio for approximately 20 minutes during three sessions spaced over two weeks. We assessed these participant's proprioceptive accuracy using a custom-designed proprioception assessment that relied on MediaPipe-based computer vision. Table 3 provides an overview of the participants as well as their game settings. Three participants were unable to use their paretic hand as the pointing hand for playing Proprio on the non-paretic hand due to impaired active range of motion. We excluded one participant's paretic hand dataset from the MediaPipe proprioception assessment as there were inconsistencies in the target hand placement between the three sessions.

Table 3: Participant Information (ISCH is Ischemic, HEM is Hemorrhagic)

Participant Number	Sex	Age	Days Post Stroke	Paretic Side	Dominant Hand	Type of Stroke	BBT Score	FM Score	Target Point
1	M	42	4280	Right	Right	ISCH	32	47	TIP
2	M	65	2201	Right	Both	ISCH	27	53	PIP
3	M	68	3018	Right	Right	ISCH	46	56	TIP
4	M	68	2466	Right	Right	HEM	26	59	TIP
5	F	29	854	Left	Right	ISCH	0	30	MCP
6	M	60	1676	Left	Left	ISCH	50	57	TIP
7	F	60	1557	Right	Right	HEM	43	51	TIP
8	M	41	1372	Right	Right	HEM	14	48	PIP
9	M	69	4132	Left	Right	HEM	3	24	MCP
10	F	60	1993	Right	Right	ISCH	40	57	TIP
11	M	64	4254	Left	Right	HEM	46	60	TIP
12	M	46	295	Right	Right	HEM	3	31	PIP



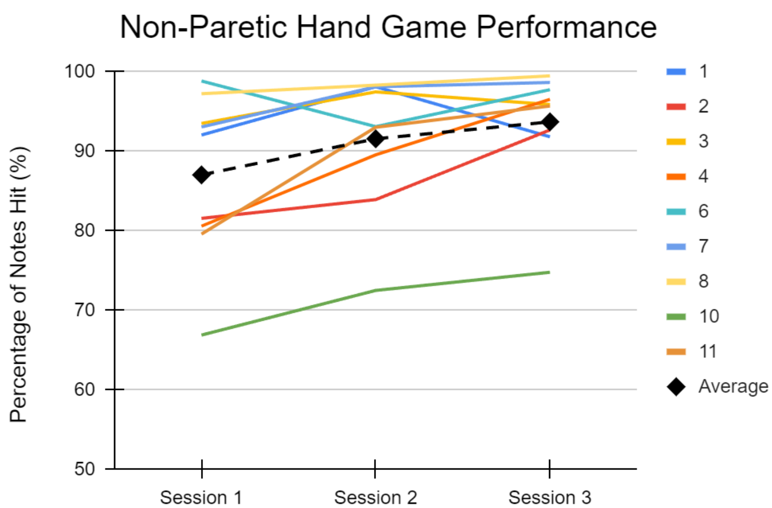


Figure 7: Game performance for each session. The top graph is based on pointing with paretic hand as target hand, while bottom graph is non-paretic hand as target hand. The dashed lines represent the mean performance across participants. The legend shows each participant by number.

Game Success Over Time

Participants increased the percentage of notes hit across sessions both when the paretic hand was the target and when the non-paretic hand was the target (Figure 7). The mean scores for the paretic hands increased from 79% (SD = 11%) on Session 1 to 91% (SD = 8%) on Session 3, while the non-paretic hands increased from 87% (SD = 10%) to 94% (SD = 8%) over the same period. ANOVA analysis indicated significant differences in performance across sessions ($F(2, 57) = 7.2$, $p = 0.002$). Post-hoc analysis further revealed that performance significantly increased on the paretic hand from Session 1 to Session 2 (mean difference from Session 1 = 10.6, $p = 0.016$) and was maintained at Session 3 (mean difference from Session 1 = 12.2, $p = 0.005$). The Session 1 to Session 3 improvement was significantly larger when the paretic hand was the target ($p = 0.041$).

Proprioceptive Accuracy Over Time

We used our custom-designed MediaPipe proprioception assessment to determine if the participant's proprioceptive accuracy improved over time (See Figure 8). ANOVA analysis did not reveal any significance between sessions when looking at the distance error (cm) improvement. We calculated the normalized distance error, which is each participant's error expressed as a percentage of their maximum error across the three sessions (See Figure 8). An ANOVA statistical analysis revealed a significant improvement in proprioception for both the paretic and non-paretic hands' normalized distance errors over the testing period (paretic hand: $F(2, 33) = 7.69$, $p = 0.002$; non-paretic hand: $F(2, 24) = 4.19$, $p = 0.027$). Post-hoc analysis showed significant differences in normalized error between Session 1 and Session 3 for both hands (paretic hand: Session 1 vs. Session 3: $p = 0.002$; non-paretic hand: Session 1 vs. Session 3: $p = 0.022$). However, only in the paretic hand was there a significant difference in normalized error between Session 1 and Session 2 (Session 1 vs. Session 2: $p = 0.02$).

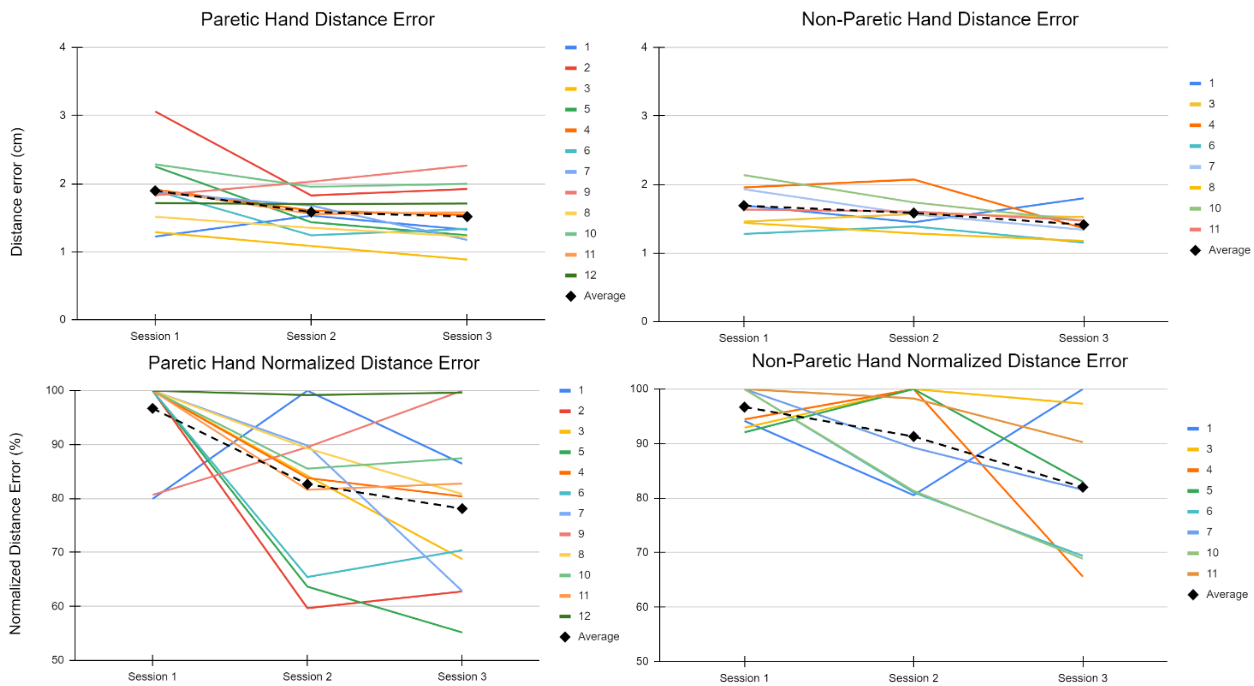


Figure 8: Proprioceptive improvement in paretic and non-paretic evaluations over first 2 sessions and one week follow-up. The first row shows the average distance error (cm) of perceived position from the true position of both the paretic and non-paretic hand over each of the sessions the assessment took place. The second row shows the normalized distance error (%) for each participant across all sessions. The dashed lines indicate the average for each session of testing between all stroke participants. The legend shows each participant by number.

System Usability

The SUS questionnaire means and standard deviations from participants can be seen in Table 4. The overall SUS score for the Proprio was calculated to be 82.5 (SD = 10.7). According to research on the SUS, a score above 68 is considered above average, while scores in the 80s are typically associated with excellent usability, placing products in the top 10% of usability evaluations [18], [31].

Table 4: Mean and standard deviation values for participant SUS responses

Question Category	Mean	Std. Deviation
1. System Frequency	4.3	1.0
2. Unnecessarily Complex	1.5	0.7
3. Ease of Use	4.3	0.7
4. Technical Support	2.3	1.6
5. Function Integration	4.6	0.5
6. System Inconsistency	1.5	0.7
7. Learnability	4.6	0.7
8. Cumbersome	1.6	0.9
9. User Confidence	4.2	0.9
10. Learning Time	2.2	1.6

Performance Relationship Self-Assessed Technological Proficiency

At the suggestion of our grant managers who had extensive experience in developing apps for persons with a disability, we asked participants to rate their technological proficiency on a 5-point Likert scale. We found that self-assessed technological proficiency was moderately correlated with game success when the paretic hand was the target on all testing sessions (See Figure 9). There was a clear linear trend observable in the data on each testing day, even as performance improved across testing days ($P < 0.05$). This suggests that higher confidence in handling technology correlates with improved in-game performance.

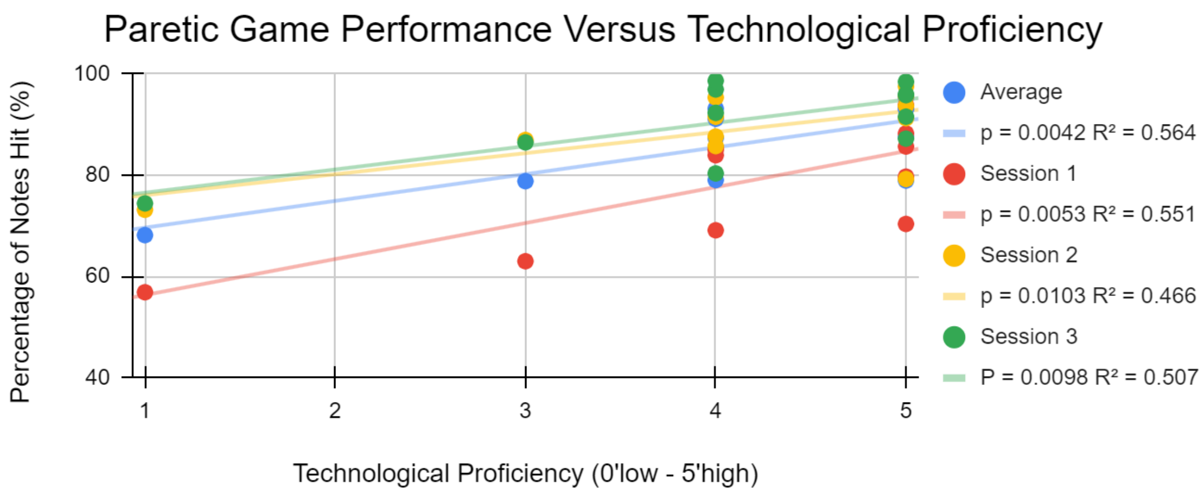


Figure 9: Game performance when the paretic hand is the target (expressed as % of notes hits) versus user-assessed technological proficiency (0'low - 5'high) for each day and an average across all days. Each dot is a participant.

DISCUSSION

This study aimed to explore the effectiveness of a serious game designed for at-home proprioceptive training for individuals post-stroke. The results demonstrated significant progression in game performance. There was also improvement in normalized hand proprioception accuracy following 7 days after initial testing began. This finding aligns with the hypothesis that targeted game-based proprioceptive training can enhance proprioception.

Proprioceptive Training and Learning

Participants increased the percentage of notes hit across sessions for both paretic and non-paretic hands. This improvement was larger when the paretic hand was the target, especially when comparing the differences between Session 1 and Session 3. This could be because accuracy is initially impaired by the paresis and incoordination of the paretic hand, which might mask improvements in proprioception. Proprio gameplay was not only learnable but also retainable. Participants internalized and applied the game's feedback to improve their game performance consistently over time.

The largest gains occurred between Session 1 and Session 2 for the paretic hand, with these improvements being maintained and evenly slight increased at Session 3, one week later. This suggests that the initial phase of Proprio may involve a steep learning curve where participants rapidly adapt to using proprioception as part of controlling the game, followed by a phase of skill consolidation where improvements in performance are maintained with continued practice.

Increases in game play success could theoretically arise due to other factors besides improvement in proprioceptive accuracy, such as improved understanding of the game or improved internal mapping of fingers to notes. To assess whether participants' proprioceptive accuracy improved over time, we employed a custom-designed MediaPipe proprioception assessment. ANOVA results for the non-normalized distance error scores across the three sessions indicated no significant differences. However, after normalizing the distance error scores to each participant's maximum error, significant differences were observed. Normalization was performed to account for individual differences in baseline performance, allowing for a more accurate comparison of relative improvements across sessions. Normalized proprioceptive accuracy improved significantly for both the paretic and non-paretic hands over the testing period. This improvement is in line with the hypothesis that proprioceptive training can enhance sensory-motor integration and accuracy. Consistent with findings from a systematic review [25], the pattern of proprioceptive accuracy improvement was consistent with a two-phase learning process, with rapid improvements following the initial session and slower gains thereafter, along with sustained retention at one week post-intervention.

The retention of proprioceptive performance observed in this study corroborates the growing body of evidence suggesting that serious games can be an effective tool for rehabilitation [15], [9], [10].

Usability

Regarding specific aspects of system usability, participants reported a high likelihood of frequent system use, with a mean score of 4.3 (SD = 1.0) out of 5. The system was perceived as straightforward, as reflected by a low complexity score of 1.5 (SD = 0.7) and a high ease of use score of 4.3 (SD = 0.7). However, responses indicated a moderate perceived need for technical support, with a mean score of 2.3 (SD = 1.6), suggesting that there could be some improvements in game tutorial and start-up walkthrough.

Participants rated the integration of various functions within Proprio highly, with a mean score of 4.6 (SD = 0.5). This indicates that the functions were considered well integrated and conducive to a seamless user experience. Conversely, the system was rated low on perceived cumbersomeness, with a mean score of 1.6 (SD = 0.9), reinforcing its user-friendly design.

Confidence in using the system was high among participants, as denoted by a mean score of 4.2 (SD = 0.9). The learning curve was manageable, with participants rating their required learning time at a mean score of 2.2 (SD = 1.6), suggesting that while some users adapted quickly, others needed more time to familiarize themselves with Proprio.

Participants reported that the system was easy to use and well-integrated, suggesting that the design choices made during development successfully addressed user needs. However, some feedback indicated a moderate perceived need for technical support, pointing to potential areas for further improvement in game tutorials and start-up walkthroughs. These findings demonstrate that Proprio not only meets but exceeds standard usability criteria, making it a promising option for home-based proprioceptive training.

Influence of Self-Assessed Technological Proficiency

Our findings suggest a somewhat surprising and noteworthy relationship between self-assessed digital literacy and the efficacy of this particular technology-based interventions. Participants who reported higher levels of technological proficiency tended to perform better in the game. This observation highlights the importance of considering technological familiarity when designing and improving Proprio.

The positive correlation between technological proficiency and game performance also underscores a potential barrier to the widespread adoption of technology-based rehabilitation solutions: the digital divide. Participants with lower technological proficiency might struggle more with understanding the game or manipulating the game interface. To mitigate this issue, future iterations of Proprio could include simplified interfaces or introductory tutorials designed to make the game more accessible to users with varying levels of technological literacy.

Furthermore, adapting the game to the user's performance could enhance motivation and possibly improve training results. By personalizing the difficulty and providing supportive feedback, Proprio could help bridge the gap for those less familiar with technology, ensuring that all users can train proprioception.

These considerations are crucial for the future development and implementation of Proprio, ensuring that it is inclusive and effective for a diverse range of users. By addressing the digital divide and making the game more accessible, we can maximize its potential as a tool for proprioceptive training and rehabilitation.

Limitations and Future Directions

This study's limitations include its relatively small sample size and short duration, which may affect the generalizability and long-term applicability of the findings. Additionally, the reliance on self-reported measures for technological proficiency and motivation could introduce bias. The inability for some participants to play Proprio and do the proprioception assessment using their paretic hand as the pointing hand is also a limitation in this study.

To address these limitations and expand upon the findings, future studies could explore longer intervention periods with larger and more diverse populations. Additionally, integrating adaptive difficulty levels based on user performance and feedback could make Proprio more personalized and responsive to individual needs, potentially enhancing its effectiveness.

Another limitation in this study was the testing of Proprio on a computer-based platform before its successful deployment on smartphones. We have already ported Proprio to both Android and iPhone devices. This was done seamlessly thanks to Unity's framework [16]. Future studies should test that the phone-based user interface and interaction with Proprio remain consistent with this study's SUS score and data.

It is also essential to compare the efficacy of serious game based training to traditional proprioceptive training methods in future studies. Such comparative analyses could help establish games as a viable alternative or supplement to proctored training, particularly in settings where access to physical therapy resources is limited.

CONCLUSION

This thesis developed and validated a serious game designed for proprioceptive training. Proprio leverages the accessibility of modern computer and smartphone technology to provide a cost-effective, engaging solution that can potentially improve outcomes in proprioception rehabilitation at home, a crucial need given the rising incidence of strokes globally and the resulting proprioceptive impairments.

The findings from this study confirm that gamified proprioceptive training can enhance and retain proprioceptive accuracy, particularly in the paretic hand of stroke survivors. These improvements are potentially vital as they could contribute to the restoration of daily functions and the overall quality of life for individuals affected by stroke, a possibility future clinical trials with Proprio could test. Importantly, Proprio showed that technology, when applied thoughtfully, can overcome some of the barriers posed by traditional rehabilitation methods, offering a scalable solution that can be adapted to various levels of impairment and technological proficiency.

However, the research also highlighted the digital divide as a potential challenge in the widespread adoption of such technology-based solutions. Addressing this issue through simplified user interfaces and adaptive difficulty settings can make Proprio more inclusive, ensuring that its benefits extend to a broader population, including those with limited technology exposure.

In conclusion, Proprio demonstrates that a well-designed serious game can be an effective and user-friendly tool for proprioceptive training in stroke users. As we move forward, the potential to incorporate more advanced technologies such as augmented reality and machine learning could further enhance the effectiveness and appeal of these interventions. Continued research and development in this area will not only improve the functionality of these games but also could improve the rehabilitation process for stroke survivors worldwide. This study sets the stage for a transformative approach to proprioception rehabilitation through democratization that leverages smartphone technology, providing innovative, accessible, and enjoyable home-based training solutions that meet the needs of a diverse patient population.

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