Design and Preliminary Evaluation of a Kinematically-Adaptive Immersive Virtual Reality Exergame for Post-Stroke Rehabilitation

Diseño y Evaluación Preliminar de un Videojuego de Realidad Virtual Inmersiva y Cinéticamente Adaptativo para la Rehabilitación Post-Accidente Cerebrovascular

Julián Felipe Villada-Castillo (iD)
Universidad Tecnológica de Pereira, Pereira, Colombia
jfvillada@utp.edu.co

John Edison Muñoz-Cardona (iD)
Wilfrid Laurier University, Waterloo, Canada
john.munoz.hci@uwaterloo.ca

Abstract

Introduction: Upper limb rehabilitation after a stroke faces challenges such as low motivation and adherence to traditional therapies. This study presents an Immersive Virtual Reality (IVR) exergame incorporating a kinematically adaptive difficulty system that dynamically modifies exercise complexity in real time based on movement data collected by VR equipment.
Objective: To evaluate the effectiveness of an adaptive system based on dimensionless jerk to optimize therapeutic effort in post-stroke participants.
Methodology: A usability study was conducted with 20 participants divided into a control group (non-adaptive version) and an experimental group (adaptive version). The Borg Fatigue Scale and the Virtual Reality Neuroscience Questionnaire (VRNQ) were used to measure engagement, perceived fatigue, and user experience.
Results: The adaptive system improved participants' engagement and therapeutic outcomes and therapeutic outcomes. The experimental group reported perceived physical effort levels closer to the ideal therapeutic range defined in the literature. Additionally, this group achieved higher evaluations in user experience and immersion.
Conclusions: The exergame proved to be an effective and personalized tool for post-stroke rehabilitation. While areas for improvement were identified, such as responsiveness in advanced stages, this system offers a dynamic and motivating approach to optimizing recovery processes.

Keywords:
Immersive Virtual Reality (IVR); Exergame; Kinematically Adaptive System; Post-Stroke Rehabilitation; Dimensionless Jerk; Borg Fatigue Scale; Therapeutic Personalization.

Resumen

Introducción: La rehabilitación de extremidades superiores tras un accidente cerebrovascular enfrenta desafíos como la baja motivación y adherencia a terapias tradicionales. Este trabajo propone un exergame Inmersivo de Realidad Virtual (IVR) con un sistema de dificultad cinemáticamente adaptativo que ajusta dinámicamente la complejidad de los ejercicios en tiempo real, utilizando datos de movimiento capturados por equipos de realidad virtual.
Objetivo: Evaluar la efectividad de un sistema adaptativo basado en el tirón adimensional para optimizar el esfuerzo terapéutico en pacientes post-stroke.
Metodología: Se realizó un estudio de usabilidad con 20 participantes divididos en un grupo control (versión no adaptativa) y un grupo experimental (versión adaptativa). La escala de fatiga de Borg y el Cuestionario de Neurociencia de Realidad Virtual (VRNQ) se utilizaron para medir el compromiso, la fatiga percibida y la experiencia del usuario.
Resultados: El sistema adaptativo mejoró el compromiso de los participantes y los resultados terapéuticos. El grupo experimental mostró niveles de esfuerzo físico percibidos más cercanos al rango terapéutico ideal, según lo definido por la literatura. Además, este grupo obtuvo mejores evaluaciones en experiencia de usuario e inmersión.
Conclusiones: El exergame inmersivo y cinemáticamente adaptativo demostró ser una herramienta personalizada y eficaz para la rehabilitación post-stroke. Aunque se identificaron áreas de mejora, como la capacidad de respuesta en etapas avanzadas, este sistema ofrece un enfoque dinámico y motivador para optimizar el proceso de recuperación.

Palabras Claves: Realidad Virtual Inmersiva (IVR); Exergame; Sistema Cinemáticamente Adaptativo; Rehabilitación post-stroke; Dimensionless Jerk; Escala de fatiga de Borg; Personalización Terapéutica.

Introduction

Stroke is a leading cause of disability worldwide, impacting over 15 million individuals annually, of these, one-third are left with some form of permanent disability that impacts their quality of life [1]. The recovery of upper limb motor function is one of the greatest challenges in post-stroke rehabilitation, as only a small percentage of survivors regain full mobility in this limb [2].

This motor disability not only impacts individual independence but also imposes a significant burden on healthcare systems and caregivers due to the need for continuous and long-term assistance [3]. Traditionally, post-stroke rehabilitation has relied on physiotherapy, which involves repetitive exercises aimed at restoring mobility and strength in the affected limb [4]. However, this approach is often perceived by participants as monotonous and unmotivating, which can reduce adherence to long-term treatments and negatively impact outcomes [5]. In response to this reality, emerging technologies such as IVR have emerged as promising alternatives to enrich the rehabilitation process [6].

IVR allows participants to interact with controlled, three-dimensional virtual environments designed to replicate real world situations, where they can perform therapeutic exercises interactively and engagingly [7]. Unlike traditional therapies, IVR offers a more playful and motivating approach, increasing participant engagement and improving adherence to treatment [8]. In this context, Motion Health VR emerges, an IVR exergame specifically designed for upper limb post-stroke rehabilitation [9].

This exergame not only stands out for offering an attractive immersive experience for participants but also incorporates a kinematically adaptive difficulty system, an innovative element that adjusts the complexity of therapeutic tasks in real-time according to the participants physical abilities [10]. The system uses movement data obtained during the therapy session to evaluate movement quality through kinematic features, such as dimensionless jerk, which measures the smoothness of movement [11].

With this information, the system dynamically adjusts parameters such as the number of required repetitions, the speed of objects, or the time available to complete a task [12]. This adaptive approach aims to keep participants within an optimal therapeutic effort range, where the level of challenge is sufficient to foster significant improvements in motor function without causing excessive fatigue or demotivation [13]. In post-stroke rehabilitation, this balance is crucial, as physical overload can increase the risk of injury or worsen the condition, while a therapy that is not demanding enough may limit progress [14]. Moreover, the ability of IVR to create environments that adapt to the cultural and psychological needs of participants is another key point [15].

The customization of the therapeutic environment allows for a more user-centered approach, improving participant motivation and increasing the chances of success in therapy [16]. This is particularly relevant in long-term rehabilitation settings, where sustained engagement is essential to achieving significant results. This article details the design and implementation of the kinematically adaptive difficulty system of Motion Health VR, as well as the feature used to adjust the difficulty in real time. Additionally, the implications of this approach for post-stroke rehabilitation are explored, highlighting its potential to improve therapeutic outcomes by offering a more dynamic, personalized experience tailored to each participants individual needs.

Related Work

In physical rehabilitation based on interactive technologies, exergames and IVR systems have shown great potential for improving therapeutic outcomes in participants with motor disabilities, especially in post-stroke rehabilitation [17].

A key aspect in the design of these systems is real time difficulty adaptation, which personalizes therapeutic tasks according to the participants abilities [18]. Below are some adaptation approaches used in previous studies and compared to the kinematically adaptive approach of Motion Health VR.

1) Performance-Based Adaptation: This approach adjusts the difficulty according to the participants performance. If a participant completes a task faster or with greater precision than expected, the system increases the difficulty [19].

This method is simple, as it is based on the participants success or failure relative to the games objectives [20]. However, it does not take movement quality into account, which limits its effectiveness in motor rehabilitation [21], [22].

2) Physiological Biomarker-Based Adaptation: This approach uses physiological signals, such as heart rate or blood oxygenation levels, to adjust the difficulty [23]. It is useful in exergames aimed at controlling cardiovascular load, but it does not directly address movement quality, which is essential in post-stroke rehabilitation [24]

3) Perceived Fatigue-Based Adaptation: In this approach, participants report their fatigue level through subjective scales such as the Borg scale [25]. Based on this self-assessment, the system adjusts the difficulty to avoid excessive fatigue [26]. However, relying on subjective perception may not accurately reflect the participant's actual physical condition. The contribution of this study includes the implementation a real-time kinematic adaptation system, adjusting the games difficulty based on kinematic features measured in real-time using the headset and controllers of the VR equipment as proposed by Munoz and colleagues [23]. This provides a continuous and accurate assessment of motor control, crucial for post-stroke rehabilitation. The system dynamically adjusts parameters from each game mechanic like object speed and the number of repetitions according to predicted fatigue levels measured via kinematic data. This way, the participant always works within a therapeutically appropriate range, optimizing progress without inducing excessive fatigue. The adaptive system was collaboratively designed involving people with stroke and then, a pilot study was conducted to evaluate the impact of the adaptation on both the perceived levels of fatigue and the game user experience.

Methodology

The exergame "Motion Health VR" has been specifically designed for the rehabilitation of post-stroke participants, immersing them in a virtual environment where they perform cyclical upper limb movements, such as elbow flexion and extension [27]. These movements are inspired by rich Colombian traditions. Initially, the game introduces activities that allow participants to familiarize themselves with it using their more dexterous hand, progressively motivating them to use the hand with reduced mobility to perform exercises that benefit their recovery. The game difficulty can be manually adjusted by the researcher through a visual assessment of the participant's motor abilities by changing some of the game parameters to increase/decrease the difficulty. The game was created to mimic movements commonly recommended by physiotherapists in traditional therapies (See Table I). Participants were required to sit and use a standalone IVR system (e.g., Meta Quest 2), enabling full immersion while optimizing both the therapeutic and entertainment potential of the technology.

TABLE I. REHABILITATION MOVEMENTS PROPOSED FOR THE EXERGAME

Movement	Application	Action in the Exergame
Elbow (Flexion and extension)	Improvement in fine motor control and arm strength for tasks such as opening doors or lifting light objects..	Destroying boxes with a hammer.
Shoulder (Flexion and extension)	Enhancement of shoulder mobility for overhead activities like reaching for shelves or hanging clothes.	Throwing Tejos.
Elbow (Interior and exterior extension)	Improved range and coordination for bimanual tasks such as cutting food or using tools.	Cutting grass branches with a machete.

The exergame is developed through three key phases (see Figure 1). The first phase focuses on destroying boxes by striking them, using the mechanics of elbow flexion and extension to promote motor recovery (Fig 1A). This initial phase not only emphasizes elbow strengthening but also introduces participants to the virtual environment, helping them adapt to the games

interface and controls. The use of elbow flexion and extension in this phase is carefully designed to improve elbow mobility and strength, which is crucial for many daily activities [9]. The second phase introduces the mechanics of shoulder flexion and extension through a virtual Tejo game, requiring controlled movements for precise throws (Fig 1B). In this phase, the game becomes more challenging, demanding greater shoulder control and coordination. The virtual Tejo serves not only as a physical exercise but also adds elements of precision and strategy, engaging both the mind and body of the participant. This type of activity helps improve hand-eye coordination and shoulder stability, which is essential for tasks requiring fine and precise control [9].

The third phase incorporates more challenging movements by combining elbow and shoulder movements, similar to Kabat diagonals, simulating the act of cutting branches while riding a virtual horse (Fig 1C). This final phase is designed to integrate and apply the skills developed in the previous phases. Combined elbow and shoulder movements are fundamental for many daily activities and require a high degree of coordination and muscular control. By simulating branch cutting, while riding a horse, participants practice complex movements in a controlled environment, which can translate to significant real-life improvements [9]. Additionally, this phase offers a culturally enriching experience, keeping participants motivated and engaged. These activities aim not only to improve upper limb functionality but also to provide a culturally enriching experience, motivating participants on their path to recovery. By combining physical exercises with elements of Colombian culture, Motion Health VR creates a unique and engaging rehabilitation experience that keeps participants motivated and committed throughout their recovery process [27].

Design of the Kinematic Difficulty Adaptation in the Exergame

Objective of the Kinematic Adaptation: The primary objective of difficulty adaptation in the Motion Health VR exergame is to dynamically adjust the complexity of therapeutic tasks based on kinematic parameters measured in real time. The purpose of this adjustment is to keep the fatigue of post-stroke participants within an optimal therapeutic range, ensuring that the exercises are challenging enough to promote motor improvements without causing excessive fatigue [28]. This therapeutic range has been established in collaboration with clinical experts, using the Borg scale of perceived exertion, which serves to quantify fatigue levels [20]. The kinematic adaptation is based on movement data captured by the sensors of the Virtual Reality (VR) headset and controllers, allowing the calculation of features correlated with perceived fatigue levels that are beneficial for post-stroke rehabilitation.

Implementation of the Inverse Kinematics (IK) Model: Since the headset and controllers only capture head and hand movements using Inertial Measurement Units (IMUs) sensors, an inverse kinematics (IK) model was implemented to reconstruct the positions of joints not directly measured [29], such as the elbows and shoulders. This model is crucial to ensure that virtual movements accurately reflect the motor capabilities of the participants [30]. Kinematic chains were configured from the head, to the hands, respecting the physiological limitations of the joints to ensure that the movements were natural and effective in the virtual environment [31]. Once the IK model was configured, the parameters were optimized to ensure the accuracy of the reconstructed movements. This optimization process balanced accuracy with computational efficiency, ensuring that calculations were performed in real time without compromising the participants immersive experience [32]. The data captured reflects the accelerations of the described joints in X, Y and Z as well as the rotation described in quaternions.

Fig 1. Game mechanics in Motion Health VR: Boxes, Tejos and Branches

Game Variables and Parameterization: To effectively implement kinematic adaptation, real-time changes in game difficulty are achieved by manipulating various exergame variables [35]. A base difficulty system was designed and implemented to adjust the complexity of activities according to the participants physical abilities. For example, in the box destruction activity, the number of hits required to break them can be increased; in the Tejo game, the throwing distance can be adjusted; and in the branch-cutting activity, the position of objects can be modified to improve rehabilitative gestures or movements [36]. Additionally, a graphical interface was developed that allows therapists to manually adjust the difficulty level before each session. Through a menu with sliders, therapists can customize the exergame difficulty according to the participants individual progress, ensuring that the exercises are motivating and do not lead to frustration or discouragement.

Pilot Study for Data Collection: In order to develop a kinematic adaptation system based on objective measurements, a pilot study was conducted with a cohort of 10 stroke survivors who were not included in the experimental or control groups of the main study. All participants were selected according to predefined inclusion criteria: age over 50, confirmed medical diagnosis of stroke with upper limb motor impairments, ability to follow simple instructions, and tolerance for immersive virtual reality sessions of at least 15 minutes. The data collection session took place in a supervised clinical setting, using the non-adaptive version of the Motion Health VR system and a standardized gameplay protocol across the three activities (Boxes, Tejos, Branches). During the session, movements of the shoulder and elbow were recorded using the inertial sensors embedded in the Meta Quest 2 controllers, allowing the acquisition of kinematic information without requiring any additional hardware. Simultaneously, at the end of each activity, participants were asked to rate their perceived fatigue using the modified Borg scale, a widely validated tool for assessing subjective physical effort in clinical settings. These subjective fatigue values were used as the dependent variable for building a prediction model based on the extracted kinematic features. The combination of objective and subjective data provided a robust dataset for developing a personalized adaptive system optimized for post-stroke patients.

Kinematic Feature Extraction and Selection: Once the pilot study data were collected, a comprehensive feature extraction process was performed to characterize the quality of upper limb movement during the three gameplay activities. Kinematic features were computed from the raw positional and rotational data obtained from the Meta Quest 2 sensors. The signals were first filtered using a tenth-order Butterworth filter with a cutoff frequency of 1 Hz to reduce high-frequency noise while preserving relevant motion patterns. The data were then segmented into one-second windows with 50 % overlap to capture short-term variations during each session.

From these segments, several time-domain features were extracted, including Root Mean Square (RMS), angular velocity, linear acceleration, standard deviation, and the dimensionless jerk. In addition, frequency-domain descriptors such as spectral entropy, average spectral power, spectral energy, and SPARC (Spectral Arc Length) were calculated to evaluate motion smoothness and efficiency. These features have been previously validated as relevant indicators in post-stroke rehabilitation contexts [33].

Among all computed features, the dimensionless jerk emerged as the most robust predictor of perceived fatigue. This feature quantifies movement smoothness by analyzing the rate of change of acceleration normalized by movement duration and amplitude. Its strong correlation with Borg fatigue scores in the pilot dataset was confirmed through a supervised machine learning pipeline using feature importance analysis and cross-validation techniques [34]. Consequently, the dimensionless jerk was selected as the key input variable for the adaptive model, given its theoretical relevance and empirical performance in predicting effort levels during gameplay.

Polynomial Regression Model for Fatigue Prediction: To implement real-time difficulty adaptation within the immersive exergame Motion Health VR, a kinematic-based system was developed using data collected from a pilot study involving 10 post-stroke participants over 14 sessions. The system aimed to dynamically adjust therapeutic task parameters according to the user's fatigue level, ensuring that activities remained sufficiently challenging to promote motor progress without inducing excessive exhaustion. Following a comprehensive evaluation, a second-degree polynomial regression model was selected as the

most appropriate method for predicting perceived fatigue (as measured by the Borg scale) from the dimensionless jerk, a feature identified as the most relevant during the feature selection process. The dimensionless jerk measures movement smoothness, where high values suggest abrupt, fatiguing motions and low values reflect smoother, more controlled movements. Since each game task (Boxes, Tejos, and Branches) exhibited a unique relationship between kinematic smoothness and perceived fatigue, separate polynomial models were developed for each activity. This modeling approach allowed the system to capture non-linear dynamics while maintaining the computational simplicity and execution speed required for deployment on a standalone VR headset like the Meta Quest 2. More complex approaches, such as neural networks, were considered but discarded due to their high computational demands, the risk of latency in real-time adaptation, and potential overfitting given the limited dataset [37][38]. A second-degree polynomial regression model was chosen as it offers an optimal balance between predictive accuracy and computational efficiency, which is critical for real-time implementation on a standalone VR headset like the Meta Quest 2. This decision was based on the constraints of the hardware platform and the need for stable, fast performance without introducing latency during gameplay. More complex models, such as neural networks or support vector machines, were considered during the design phase. However, these alternatives require significantly greater computational resources and longer inference times, which are not feasible for real-time adaptation on embedded systems. Furthermore, due to the relatively small dataset collected in the pilot study, using more complex models would increase the risk of overfitting and reduce generalizability. Thus, the polynomial model provided the best compromise between simplicity, responsiveness, and model robustness within the system's operational context. Once the dimensionless jerk was computed, the estimated fatigue value was fed into a real-time feedback loop implemented in Unity. The loop functioned as a proportional controller that recalibrated the difficulty of the exergame every 30 seconds based on the participant's updated kinematic data. During each cycle, the system captured the three-dimensional positions of the hand controllers at a rate of 30 Hz over 1-second intervals (see Figure 2), calculated the jerk, and then used the regression model to estimate the fatigue level on the Borg scale. Based on this value, the system adjusted task parameters in real time: the number of hits needed to destroy a box (Boxes), the throwing distance (Tejos), and the branch speed (Branches). If the fatigue level was below the optimal therapeutic range (less than 2), task difficulty increased; if it exceeded the upper threshold (more than 6), difficulty was decreased to allow recovery and maintain engagement.

Boxes: $y = 13591.0228x^2 - 27112.3547x + 13523.8283$ (1)
Tejos: $y = -1623.7301x^2 + 3209.7910x - 1583.5616$ (2)
Branches: $y = 3084.9736x^2 - 6055.5380x + 2973.0916$ (3)

Where

y = Borg fatigue value,   x = Dimensionless Jerk

The model achieved satisfactory predictive accuracy in cross-validation within the pilot dataset. A second-degree polynomial regression model was chosen as it provides an optimal balance between accuracy and computational efficiency, which is critical for real-time implementation on a standalone VR headset like the Meta Quest 2. More complex models, such as neural networks, while potentially more accurate, would require greater computational resources, introduce latency, and would be more prone to overfitting given the limited dataset from the pilot study. These equations were embedded into the real-time control loop of the exergame, executing every 30 seconds during gameplay. Each equation allowed the system to estimate fatigue dynamically and adjust difficulty according to the specific motion pattern of each task.

Proportional Control and Real-Time Feedback Loop: The dynamic adjustment of exergame difficulty in Motion Health VR was achieved through a real-time feedback system based on a proportional controller, developed within the Unity engine. This system recalibrated task difficulty every 30 seconds during gameplay by executing a cyclical evaluation and

adaptation process based on kinematic data and perceived fatigue. The feedback loop followed the steps below:

Kinematic data acquisition: The system continuously captured the three-dimensional positions (x, y, z) of the Meta Quest 2 controllers at a sampling rate of 30 Hz, segmented into 1-second sliding windows (see Figure 2).

- Processing of the dimensionless jerk: From the positional data, the system computed the dimensionless jerk-a unitless indicator of movement smoothness-averaged over the previous 30 seconds.

- Fatigue estimation using polynomial regression: The average dimensionless jerk was input into one of the three task-specific second-degree polynomial regression models (Eqs. 1–3) to estimate the participant's perceived fatigue on the Borg scale.
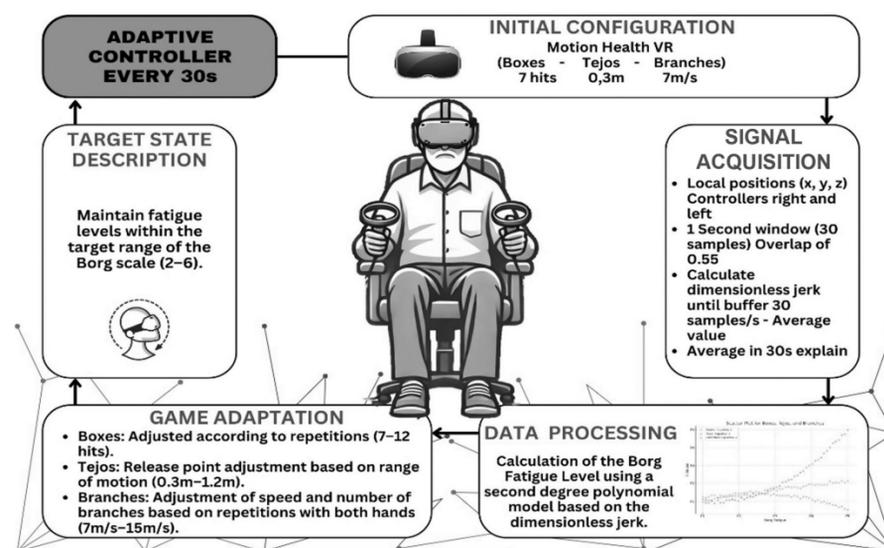

Fig 2. Adaptive System for Motion Health VR

- Difficulty adaptation: The predicted fatigue value was compared against a predefined therapeutic range (between 2 and 6 on the Borg scale), which is considered optimal for promoting therapeutic benefits while avoiding excessive strain. If the estimated value fell below 2, the system increased the task difficulty (e.g., smaller targets, faster object appearance, or greater reach distance). If the fatigue exceeded 6, task demands were reduced to facilitate recovery and avoid overload.

- Cycle repetition: This adaptive mechanism was executed every 30 seconds, allowing the game to respond continuously to intra-session changes in performance and effort.

This real-time feedback loop was designed to maintain participants in a therapeutic flow state, dynamically matching task challenge to motor capacity. The use of a proportional controller enabled smooth and progressive difficulty transitions, avoiding abrupt changes that could disrupt engagement or compromise the therapeutic rhythm of the session.

Real-Time Difficulty Adjustment: Real-time and adaptation is essential to ensure that the exergame tasks represent a constant but manageable challenge for the participant. This feedback system adjusts the difficulty of the activities according to the detected fatigue level, allowing the exergame to evolve with the participants physical state.

- Boxes: The number of hits required to destroy the boxes is adjusted according to the estimated fatigue value. As fatigue increases, the number of hits required also increases, up to a maximum of 12, adding more challenge to the task.

- Tejos: In this activity, the throwing distance varies between 0.3 and 1.2 meters. If the system detects a low level of fatigue, the distance increases, making the throw more demanding. On the contrary, if fatigue is high, the distance decreases, making the task easier.

- Branches: The speed of the branches varies between 7 and 15 meters per second, depending on the detected fatigue level. If the participant becomes fatigued, the speed decreases, making the activity easier to perform. If fatigue is low, the branches move faster, increasing the difficulty.

- Target State and Therapeutic Benefits: The main objective of the system is to keep the participant within a therapeutically safe range, where physical effort is controlled but sufficient to promote motor improvements. The use of the dimensionless jerk as a key

feature for difficulty adjustment allows for a precise personalization of the rehabilitation experience, optimizing therapeutic benefits and ensuring that the participant is working at a level appropriate for their physical capabilities. This approach ensures that the exergame provides a dynamic and personalized rehabilitation experience, tailored to the participants individual needs and adjusted in real-time to maximize therapeutic outcomes.

Adaptive System Design and Visualization (Figure 2): Figure 2 illustrates the full architecture of the kinematic adaptation system implemented in Motion Health VR. The system begins with signal acquisition, where raw kinematic data from the Meta Quest 2 sensors are collected in real time. These signals are segmented into 30-second moving windows and smoothed using a Butterworth filter to reduce noise while preserving meaningful motion dynamics. Next, the dimensionless jerk is computed from each window and used as the sole input to the task-specific polynomial regression model. The output is an estimated value of perceived fatigue, updated every 30 seconds. This prediction feeds into a proportional control unit, which compares the current fatigue level against a target range (Borg score between 2 and 6). Based on this comparison, the controller adjusts one or more task difficulty parameters in the next cycle—such as object size, target distance, or time constraints— allowing for continuous personalization of the rehabilitation challenge. All components of this adaptive loop were implemented using custom scripts in Unity and executed directly on the standalone Meta Quest 2 headset, enabling real-time processing without the need for external computing devices. In response to reviewer feedback, the "Signal Acquisition" box in Figure 2 has been improved by increasing the font size and simplifying the explanatory labels to enhance readability.

Evaluation of the Adaptive System: Playtesting with Post-Stroke Participants

Playtest with Post-Stroke Participants To validate the effectiveness of the adaptive system in Motion Health VR within a real rehabilitation setting, a playtest was conducted with 10 post-stroke participants. The primary goal of this playtest was to observe how the system adjusted the game mechanics in real-time according to participants' fatigue levels. The sessions were supervised by the lead researcher in collaboration with a physiotherapist, who was responsible for the safety and monitoring of the participants progress during the sessions.

Playtest Preparation: Before starting the sessions, participants were seated at a table and chair without armrests, ensuring they had sufficient mobility to interact with the game mechanics. Each participant used the Meta Quest 2 headset, and the internet connection was checked to avoid technical interruptions.

Interaction with Game Mechanics: Participants interacted with the three game mechanics: Boxes Tejos, and Branches. For each mechanic, the kinematic adaptive system dynamically adjusted the difficulty based on perceived fatigue levels, measured by the dimensionless jerk. This system ensured that participants consistently faced a challenge appropriate to their physical abilities, promoting more effective and safer rehabilitation.

a. In Boxes, the number of hits needed to break the boxes was automatically adjusted as fatigue increased or decreased, maintaining a constant level of challenge.

b. In Tejos, the throwing distance was modified, ensuring that participants could complete the task without causing excessive fatigue.

c. In Branches, the speed of the branches varied to match the participants real-time capacity, keeping the game mechanics challenging without overburdening the participant.

Playtest Observation and Results: The playtest allowed us to observe how the second-degree polynomial regression model, based on the dimensionless jerk, effectively adjusted the game mechanics. The adjustments were made in real-time, and overall, the system responded well to changes in the participants' physical states. Although formal data was not collected, observations indicated that the system kept participants within a safe therapeutic range without inducing fatigue levels that would negatively affect their performance or safety.

Playtest Results: The playtest demonstrated that the adaptive system in Motion Health VR could accurately adjust the game mechanics to maintain participants in a controlled physical exertion state. The dynamic adjustments allowed participants to progress in rehabilitation without being impacted by high levels of fatigue, which is essential for the success of post-stroke treatment. Additionally, the playtest provided valuable insights for potential future

improvements to the adaptive system, such as optimizing the adjustment range in some mechanics and ensuring greater precision in difficulty changes in certain scenarios. Despite some limitations observed, the results validated the effectiveness of the adaptive system in a real rehabilitation setting, ensuring participants could benefit from a personalized and dynamic therapeutic experience.

Objective and Therapeutic Benefits: The main objective of the system is to keep participants within a therapeutically safe range, where physical exertion is controlled but sufficient to promote motor improvements. Using the dimensionless jerk as a key feature for difficulty adjustment allows for a precise personalization of the rehabilitation experience, optimizing therapeutic benefits and ensuring that participants are working at a level suited to their physical capacities. This approach guarantees that the exergame provides a dynamic and personalized rehabilitation experience, tailored to the participant's individual needs and adjusted in real-time to maximize therapeutic outcomes.

Usability Study: Evaluation of the Adaptive System in Motion Health VR: To evaluate the real-time kinematic adaptation system implemented in Motion Health VR, a usability study was conducted with 20 post-stroke participants, equally divided into two groups: a control group and an experimental group. The aim of this study was to observe how the system adjusted the difficulty of therapeutic activities based on perceived fatigue and to assess the effectiveness of the adaptive version of the exergame compared to a non-adaptive version.

Participants: The sample size was informed by previous pilot studies in immersive neurorehabilitation technologies, which recommend exploratory groups of 8 to 15 participants per arm to assess feasibility, usability, and preliminary therapeutic effects [39]. Although a formal statistical power analysis was not conducted, the sample size was deemed appropriate for the exploratory nature of the study.

a. Control Group: Comprised of 10 participants with an average age of 58.1 years (SD: 7.5). These participants used a non-adaptive version of Motion Health VR, in which no automatic difficulty adjustments were made during activities.

b. Experimental Group: Included 10 participants with an average age of 64.6 years (SD: 12.45). This group interacted with the adaptive version of the exergame, where the system dynamically adjusted the difficulty of activities based on perceived fatigue, estimated through the dimensionless jerk—a key kinematic feature that measures movement smoothness.
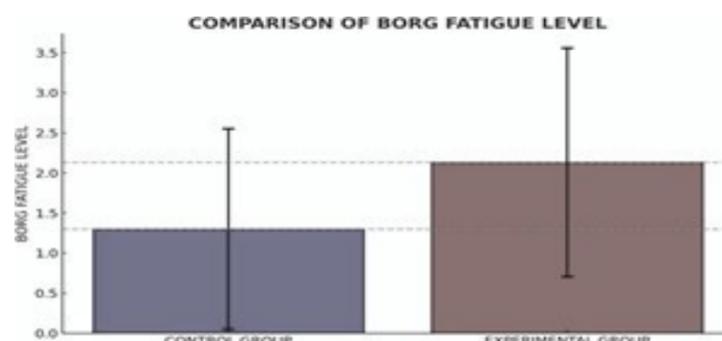

Fig 3. Comparison of Borg Fatigue level

The age difference between groups aligns with the epidemiological patterns of cerebrovascular disease, which disproportionately affects older adults [40]. This demographic factor was incorporated into the problem definition and study justification, emphasizing the need for adaptive rehabilitation strategies that improve therapeutic adherence in older post-stroke populations.

Tests Used: During the sessions for both groups, two evaluation tools were used to analyze participants experience and perceived fatigue:

- Borg Scale for Perceived Fatigue: The Borg scale allows participants to self-assess their fatigue level on a scale from 0 to 10, where "0" represents" no fatigue" and "10" indicates" extremely strong fatigue" [41]. This tool was used during sessions to continuously monitor participants fatigue and ensure they were not subjected to excessive physical load.

- Virtual Reality Neuroscience Questionnaire (VRNQ): The VRNQ is a questionnaire designed to assess user experience in VR environments. It consists of 20 questions organized

on a Likert scale from 0 to 5, evaluating aspects such as immersion, interaction, and support provided in the virtual environment [42].

Results

Comparison of Fatigue Levels (Borg Scale)

The Borg scale was used to measure the perception of fatigue in both the control and experimental groups. This scale allows participants to self-assess their level of physical exertion on a scale from 0 to 10, where "0" indicates no fatigue and "10" reflects extreme fatigue.

The results showed significant differences between the two groups. The control group, which used the non-adaptive version of the exergame, reported a mean fatigue level of 1.30 (SD = 1.25). On the other hand, the experimental group, which interacted with the adaptive version, recorded a mean of 2.13 (SD = 1.43). These results suggest that the adaptive system in Motion Health VR effectively increased the physical challenge for participants, which is beneficial in a rehabilitation context, as long as fatigue levels remain within a therapeutically appropriate range (See Figure 3).

The fact that the experimental group reported higher fatigue suggests that the dynamic adjustments made by the system successfully maintained a higher level of physical exertion, promoting greater physical engagement from participants without reaching dangerous levels of exhaustion. This is important in the context of post-stroke rehabilitation, as controlled effort can lead to more effective motor improvements.
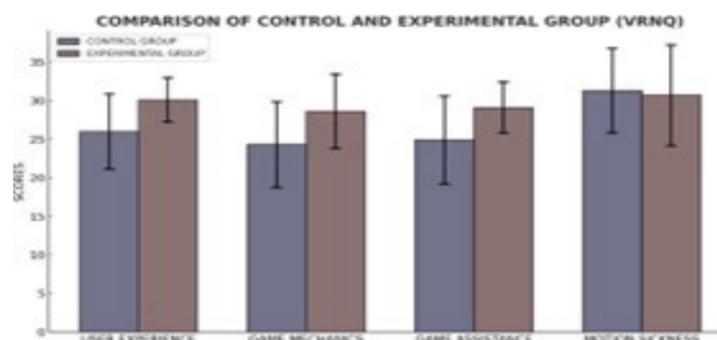

Fig 4. Virtual Reality Neuroscience Questionnaire

VRNQ Evaluation

The VRNQ was used to measure user experience in terms of immersion, interaction, and assistance during the use of Motion Health VR. In this evaluation, the experimental group, which used the adaptive version of the exergame, scored higher than the control group in several categories, reinforcing the idea that the adaptive system provided a more personalized and challenging experience. (See Figure 4).

- **User Experience:** The experimental group reported a mean score of 30.1 (SD = 2.88), while the control group achieved a mean of 26.0 (SD = 4.85). This indicates that participants in the adaptive group perceived a more positive and immersive experience compared to those using the static version of the exergame. The ability to adapt difficulty in real-time allowed participants to feel more connected to the game mechanics, making the experience more rewarding and personalized.

- **Game Mechanics:** In this category, the experimental group achieved a mean score of 28.6 (SD = 4.81), compared to 24.3 (SD = 5.54) in the control group. These figures highlight that the adaptive system not only improved the difficulty of game mechanics based on perceived fatigue but also made the tasks more challenging and motivating for participants. The systems dynamic adjustments ensured that participants faced challenges suitable to their physical level, resulting in a more positive perception of the overall game.

- **Game Assistance:** The experimental group also stood out in terms of in-game assistance, with a mean score of 29.1 (SD = 3.28) compared to 24.9 (SD = 5.69) in the control group. This suggests that participants who used the adaptive version of the exergame found the in-game aids and guidance more helpful, likely due to the mechanics adjusting in real-time to their capabilities, improving their learning experience and task execution.

- Motion Sickness: Regarding effects related to motion sickness, there were no significant differences between the two groups. The control group recorded a mean of 31.3 (SD = 5.46), while the experimental group reported 30.7 (SD = 6.52). This suggests that, regardless of real-time adaptation, both groups found the exergame equally comfortable and free of significant discomfort or nausea, which is crucial in the use of VR in rehabilitation contexts where patient safety and comfort are paramount (See Figure 4).

The results from both the Borg scale and the VRNQ confirm that the adaptive system implemented in Motion Health VR not only increased the perceived physical challenge for participants but also enhanced the overall quality of the immersive experience. The real-time adaptation system allowed for continuous and precise adjustments to the game mechanics, keeping participants within an appropriate exertion range to maximize therapeutic benefits without causing excessive fatigue or discomfort. The combination of higher fatigue in the experimental group, along with better evaluations of user experience and game mechanics, suggests that the adaptive system not only increased physical exertion but also improved overall participant satisfaction with the rehabilitation process. This supports the hypothesis that dynamic difficulty adaptation can create a more engaging and effective experience for participants in rehabilitation contexts.

Discussion

Evaluation of the Design and Achievements of the System

The Motion Health VR exergame was designed for post-stroke rehabilitation, integrating a real-time kinematic adaptive system that adjusts difficulty based on the measured dimensionless jerk (chosen due to its importance in predicting Borg levels), a key feature for evaluating movement smoothness and perceived fatigue [19], [43]. This approach allows the exercises to be sufficiently challenging to promote motor improvements without causing excessive fatigue, optimizing the upper limb rehabilitation process [44]. The system customizes the therapeutic experience for each participant by dynamically adjusting tasks throughout the session [18], providing a more efficient and tailored environment for post-stroke rehabilitation [45].

Comparison with Other Rehabilitation Approaches

Motion Health VR stands out compared to other exergames that use predefined difficulty levels. Its ability to adjust difficulty in real-time based on participants measured kinematic parameters in real-time using the embedded sensors in a commercially-available VR headset (Meta Quest 2). This offered greater precision in matching the level of effort, reducing the risk of overexertion or frustration [46], [47]. This facilitates a therapeutic intervention more aligned with the participants individual goals [48].

Evaluation of the Real-Time Adaptive System

The kinematically-adaptive system was piloted with ten participants with stroke and compared against its non-adaptive version. Results obtained from the Borg scale and the VRNQ from one session showed a significant advantage for the experimental group with greater physical effort and a more immersive experience in the adaptive exergame. The experimental group showed a higher level of fatigue compared to the control group, which is positive in therapeutic terms, as it kept participants within an appropriate effort range [49], [50]. Additionally, in the VRNQ, the adaptive group outperformed the control group in categories such as user experience and game mechanics, indicating better interaction with the system [51]. However, some limitations were observed in the range of difficulty adjustment, which was not always wide enough for advanced activities, affecting the perceived challenge [52]. Moreover, the VRNQ results showed that participants in the adaptive group reported a higher perception of "Game Assistance." This finding can be directly linked to the principles of flow theory, which suggests that motivation and engagement are enhanced when the challenge of a task is appropriately matched to the user's skill level. In this context, the implemented kinematic adaptation system may have helped participants feel more competent and supported during the experience, reinforcing their sense of control and enjoyment throughout the therapy. This also indicates that adaptive systems may not only

improve motor performance but also optimize key motivational aspects in immersive virtual rehabilitation settings.

Critique of the Adaptive System

While the polynomial model proved to be effective, participants in the experimental group mentioned that in some activities, such as box destruction, the difficulty adjustment did not seem to respond quickly. The use of more advanced algorithms, such as machine learning models, could improve adaptation to complex movement patterns and offer more precise and continuous adjustments [50], [53].

However, it is worth noting that some participants perceived the difficulty adjustments in the "Boxes" activity as slower or less responsive compared to the other tasks. This may be related to two possible factors. First, the regression model used for Boxes (Equation 1) may exhibit different sensitivity to variations in the dimensionless jerk, possibly due to the specific nature of the striking movements involved in this task. Unlike throwing (Tejos) or continuous reach motions (Branches), repetitive impact actions may generate kinematic signals that are more abrupt but less representative of actual fatigue accumulation, which could limit the predictive capacity of jerk-based estimation in this context. Second, it is possible that the frequency and type of motion in Boxes inherently delay the reflection of fatigue through kinematic smoothness, requiring longer periods to manifest meaningful changes. These factors highlight the need to further explore activity-specific calibration or consider the integration of additional kinematic or physiological features to enhance sensitivity in future iterations of the adaptive system.

Design Implications for Rehabilitation

The design of Motion Health VR provides a valuable tool for personalized rehabilitation. The ability to automatically adjust difficulty based on participants kinematic parameters is essential for delivering sessions aligned with individual needs [54]. Complex kinematic measures could also be key to discovering novel movement patterns associated with stroke physical recovery that can be unobtrusively recorded using modern VR and wearable systems. Moreover, the immersive environment and personalized interaction motivate participants to engage more with the treatment, improving long-term outcomes [55].

Future Perspectives

Custom-built, immersive, user-centered, adaptive, and kinematically-aware systems could benefit from improvements in the precision of dynamic task adjustments through more extensive evaluation process, involving multiple sessions and participants with other motor disabilities. Longitudinal studies would provide valuable insights into the long-term effects of this approach, allowing for design refinement and maximizing its clinical impact.

Limitations

One of the main limitations in the development and evaluation of Motion Health VR has been the difficulty in recruiting stroke participants. Post-stroke rehabilitation is a specialized process, and access to participants willing to participate in playtests of a VR system is limited. This has restricted the possibility of conducting broader tests, which would have allowed for a more robust evaluation of the adaptive system at various stages of rehabilitation.

Another significant limitation has been the limited number of playtests conducted. Although the preliminary results are promising regarding the systems ability to adjust difficulty in real time, the reduced number of tests makes it difficult to fully assess its responsiveness to different levels of fatigue and motor progress. For a comprehensive evaluation, more playtests with a larger and more diverse group of participants are needed, which would allow for refining the dynamic adjustment model and optimizing the therapeutic experience.

In addition to the commonly acknowledged limitations related to sample size and the number of playtest sessions, it is also important to consider the constraints of the adaptive model itself. The second-degree polynomial regression model, while providing a good balance between accuracy and computational efficiency, may not fully capture complex or non-linear relationships between kinematic features and perceived fatigue. This may limit

its responsiveness in certain task types, particularly those involving repetitive or abrupt motions. Another limitation is that the predictive model was derived from a specific cohort of 10 participants. Its generalizability to a broader and more diverse population of stroke survivors, with varying degrees of motor impairment, remains to be tested. Future work should focus on collecting data from larger and more heterogeneous samples to build a more robust and widely applicable adaptive model.

Conclusion

The design of Motion Health VR has demonstrated the value of IVR as an adaptable and effective tool for upper limb rehabilitation in post-stroke participants. Through its real-time kinematic adaptation system, the exergame dynamically adjusts activities based on complex kinematic parameters (e.g., dimensionless jerk), ensuring an appropriate balance between therapeutic challenge and fatigue. This approach is essential to promote effective and personalized rehabilitation, tailored to the participants changing needs throughout the recovery process. Moreover, we showed how the design of adaptive systems for stroke rehabilitation could benefit from early playtesting sessions by detecting important points of the system in real time and its usability. The exergames design, which allows for real-time difficulty customization, offers participants a dynamic environment that responds to their physical performance, enabling exercises to continuously adapt to their abilities. Additionally, the cultural personalization of virtual environments significantly enhances participants immersion, which contributes to increased adherence to therapy by creating a familiar and engaging environment that reinforces their motivation to continue treatment. Although improvement opportunities were identified, particularly regarding the systems ability to expand its adjustment range in advanced phases of rehabilitation, the use of advanced techniques such as machine learning algorithms could optimize the systems ability to more accurately adapt to participants individual progress. Furthermore, future collection of longitudinal data will be crucial to more thoroughly evaluate the sustained impact of Motion Health VR in post-stroke rehabilitation and improve its responsiveness over time. In conclusion, Motion Health VR offers an innovative and promising approach in the field of post-stroke physical rehabilitation, providing an adaptable and personalized framework that responds to the participants changing needs during the recovery process. This system has the potential to set new standards in the field of rehabilitation therapy, improving the effectiveness and accessibility of treatments for individuals who have suffered a stroke.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

J. Muñoz-Cardona: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – Review and editing, Supervision. J. Villada-Castillo: Conceptualization, Methodology, Validation, Formal analysis, Research, Writing—Original draft, Visualization, Supervision, Project management, Fund acquisition.

Financing

Declarations

This study was conducted in compliance with national and international ethical standards for research involving human subjects. The protocol was reviewed and approved by the Bioethics Committee of the Universidad Tecnológica de Pereira under Act No. 52, dated June 5, 2023. All participants provided written informed consent prior to their inclusion in the study, in accordance with the principles outlined in the Declaration of Helsinki (2013). To ensure the confidentiality and protection of sensitive health-related information, all clinical and kinematic data were anonymized and stored in secured databases with restricted access. The handling of personal data adhered to Colombian Law 1581 of 2012 on data protection, Law 23 of 1981 regarding medical secrecy, and Resolution 1995 of 1999 regulating clinical records management. Additionally, the use of emerging technologies such as immersive virtual reality and adaptive algorithms was aligned with the ethical principles of transparency, responsibility, and explicit consent, as recommended by the UNESCO 2021 Framework on the Ethics of Artificial Intelligence. Data were used exclusively for research purposes, and no personally identifiable information was shared or published.

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