

Article

Assessment of Fine Motor Skills Using Digital Serious Games: A Comparative Study with the Conventional Box and Block Test

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Abstract

The assessment and rehabilitation of fine motor skills are essential in clinical practice, particularly for individuals with neurological or musculoskeletal impairments. The Box and Block Test (BBT) is a widely used standard tool; however, it lacks digital capabilities for automated measurement and remote monitoring. This study presents two digital serious games designed to assess and support fine motor skills. The first game is a direct digital adaptation of the BBT, while the second mimics its core movements while introducing enhanced interaction features and flexibility. A total of 50 participants performed the conventional BBT and both digital games. The present evaluation represents a preliminary validation in healthy adults and provides a foundation for future clinical studies involving individuals with motor impairments. Performance metrics were collected and analyzed to compare outcomes and examine correlations between real-world and digital assessments. The results indicate significant correlations between BBT scores and performance in both digital serious games, supporting their validity as assessment tools. Additionally, the second game provided richer interaction data, suggesting potential for more comprehensive evaluation. These findings highlight the potential of serious games as reliable and engaging tools for fine motor assessment and rehabilitation in both clinical and remote settings.

Keywords: serious games; web applications; fine motor skills; the box and block test; digital assessment; motor rehabilitation; human-computer interaction; performance evaluation

1. Introduction

Fine motor skills are essential for performing everyday activities that require precision, coordination, and dexterity, such as grasping, manipulating objects, and writing. Impairments in these skills are commonly observed in individuals with neurological conditions, including stroke, Parkinson's disease, and cerebral palsy, as well as in patients recovering from injuries affecting the upper limbs. Accurate assessment of fine motor function is therefore critical for diagnosis, rehabilitation planning, and progress monitoring. A variety of standardized clinical tests have been developed to evaluate hand function, focusing on speed, coordination, and manual dexterity. Among these, the Box and Block Test (BBT) is widely recognized for its simplicity, reliability, and effectiveness in measuring gross manual dexterity through object transfer tasks [1–3].

In recent years, serious games have emerged as a promising approach to enhance rehabilitation processes by combining therapeutic exercises with engaging and interactive digital environments. Unlike conventional therapy, serious games can increase patient motivation, provide real-time feedback, and support repetitive task execution, which is



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essential for motor learning and recovery. Furthermore, advancements in human–computer interaction technologies have enabled the development of game-based systems that capture detailed performance data, facilitating objective assessment and personalized rehabilitation programs [4–6].

This paper proposes the design, implementation and validation of two digital and web-based serious games aimed at assessing and supporting fine motor skills. The first game represents a direct digital adaptation of the Box and Block Test, preserving its core mechanics in a virtual environment. The second game is designed to replicate the fundamental movements involved in the BBT while introducing enhanced interaction modalities and additional assessment features. The proposed approach aims to improve accessibility, portability, and inclusivity of motor skill assessment, while also enabling richer data collection and analysis compared to traditional methods.

The remainder of this paper is organized as follows: Section 2 reviews the state of the art in fine motor assessment and serious games for rehabilitation, highlighting also the main contributions of our research. Section 3 describes the design and implementation of the two digital games developed in this study. Section 4 presents the experimental evaluation, including a comparative analysis of results obtained from 50 participants performing both the traditional Box and Block Test and the proposed digital games. Section 5 discusses technical challenges, usability considerations, and practical recommendations identified during development and testing. Finally, Section 6 concludes the paper and outlines directions for future work.

2. State of the Art

The assessment and rehabilitation of fine motor skills have been extensively studied in clinical and research contexts, particularly in relation to neurological disorders and upper limb impairments. Standardized assessment tools such as the Box and Block Test (BBT), the Nine-Hole Peg Test (NHPT), and the Purdue Pegboard Test are commonly used to evaluate manual dexterity, coordination, and motor control [7–9]. Among these, the BBT is widely adopted due to its ease of administration, minimal equipment requirements, and strong reliability across different populations, including stroke survivors and elderly individuals [7,8]. However, traditional assessments are typically limited to outcome-based measures, such as the number of transferred objects, and do not capture detailed kinematic or temporal data that could provide deeper insights into motor performance. To address these limitations, researchers have explored the integration of digital technologies into motor assessment and rehabilitation.

2.1. Current Studies

Motion tracking systems, wearable sensors, and computer vision techniques have been employed to capture fine-grained movement data, enabling more objective and quantitative evaluation of motor function [10–12]. These approaches allow clinicians to monitor parameters such as movement speed, trajectory, smoothness, and coordination, which are difficult to assess using conventional methods. Despite these advantages, many digital assessment systems require specialized equipment or controlled environments, limiting their accessibility and scalability.

Serious games have emerged as a promising alternative for both assessment and rehabilitation of motor skills. By incorporating therapeutic tasks into interactive and engaging environments, serious games can increase patient motivation and adherence to rehabilitation protocols [13–16]. Studies have shown that game-based rehabilitation can lead to improvements in motor function comparable to, or in some cases exceeding, those achieved through traditional therapy [17]. In addition, serious games can provide real-time

feedback and adaptive difficulty, enabling personalized training experiences tailored to individual user needs [18].

Several research efforts have focused on developing serious games specifically targeting upper limb and fine motor rehabilitation. For example, virtual reality (VR) and augmented reality (AR) systems have been used to simulate real-world tasks and provide immersive training environments [19,20]. Other approaches utilize touchscreen devices, depth sensors, or haptic interfaces to facilitate interaction and track user performance [21,22]. While these systems demonstrate significant potential, many are designed primarily for rehabilitation rather than assessment, and few have been systematically validated against established clinical tests such as the BBT.

Recent studies have begun to investigate the digital adaptation of traditional assessment tools. Digital versions of dexterity tests aim to replicate the core mechanics of their physical counterparts while leveraging the advantages of digital platforms, such as automated data collection and remote accessibility [23,24]. Proposals on digitizing the BBT have shown that technological solutions can lead to increased engagement and enable remote supervision [25,26]. However, challenges remain in ensuring that these digital implementations maintain the validity and reliability of the original tests. Furthermore, there is a need for comparative studies that evaluate multiple game-based approaches and examine their correlation with real-world performance.

In summary, while significant progress has been made in the development of digital tools and serious games for motor rehabilitation, there is still a gap in validated, accessible, and versatile systems that combine assessment and training functionalities. This gap motivates the present study, which proposes and evaluates two serious games inspired by the Box and Block Test, with the aim of providing reliable digital alternatives for fine motor skill assessment and rehabilitation.

2.2. Research Gap and Contributions

Although previous studies have demonstrated the potential of virtual reality, augmented reality, computer vision, and serious games for upper-limb rehabilitation and fine motor assessment, several limitations remain. Many existing approaches rely on specialized hardware, such as depth cameras, wearable sensors, or immersive VR/AR equipment, which increases deployment cost and limits accessibility in home-based rehabilitation environments. Furthermore, a considerable proportion of the reported systems primarily target rehabilitation and user engagement rather than rigorous assessment, while only a limited number of studies have evaluated their performance against standardized clinical instruments such as the Box and Block Test (BBT). In addition, most existing digital implementations focus on a single interaction paradigm, making it difficult to determine whether alternative game designs can provide equally valid assessments while improving user engagement or offering richer performance information.

The present study addresses these limitations through the development and validation of two complementary web-based serious games that require only a standard webcam and a conventional personal computer, eliminating the need for specialized hardware. Unlike previous work that typically investigates a single digital implementation, this study compares two different game designs: one that closely reproduces the conventional BBT procedure and another that preserves the same underlying motor movements while incorporating additional cognitive interaction through object categorization. This comparison enables the investigation of whether increased cognitive engagement can be introduced without compromising assessment validity.

Another distinguishing characteristic of the proposed approach is its emphasis on accessibility and deployment. By implementing the applications entirely as browser-based

systems using standard web technologies and MediaPipe hand tracking, the proposed framework can be executed on widely available hardware without software installation or dedicated sensing devices. This architecture facilitates remote assessment scenarios and supports future large-scale deployment in home-based rehabilitation settings.

Finally, this work provides a systematic validation of both serious games through direct comparison with the conventional Box and Block Test using data collected from fifty healthy adult participants. The experimental evaluation combines correlation analysis, demographic comparisons, and usability assessment to investigate the concurrent validity, practicality, and user acceptance of the proposed digital assessment framework. Together, these contributions provide evidence that low-cost web-based serious games can serve as promising digital alternatives for fine motor skill assessment while simultaneously offering richer interaction data than conventional manual testing.

3. The Digital Serious Games

This study introduces two digital serious games designed to provide accessible and reliable alternatives for the assessment and rehabilitation of fine motor skills. Both applications aim to replicate and extend conventional therapeutic exercises by enabling accurate performance measurement within an interactive digital environment. A key advantage of the proposed systems is their low hardware requirement, as they operate using only a standard webcam and a midrange computer, eliminating the need for specialized equipment such as motion capture systems or wearable sensors. Furthermore, their web-based distribution enhances portability and accessibility, allowing deployment in clinical settings as well as home-based rehabilitation scenarios, which is particularly important for long-term therapy and remote monitoring. The first game closely imitates the movements and procedural logic of the Box and Block Test, providing a familiar and standardized framework for digital assessment. In contrast, the second game preserves the core movement patterns of the test while introducing alternative interaction mechanics, additional stimuli, and configurable parameters that support not only motor training but also cognitive engagement and user motivation. By combining fidelity to established clinical practices with the flexibility of digital environments, the proposed games aim to offer scalable, engaging, and data-rich tools that can enhance both assessment accuracy and rehabilitation effectiveness.

3.1. Games' Design

Both serious games were designed to operate using a standard webcam, through which hand movements and gestures are captured and interpreted in real time. By relying on vision-based interaction, the systems eliminate the need for specialized hardware, enabling a natural and intuitive user experience while maintaining low setup requirements. The design of both applications focuses on simplicity, clarity of visual feedback, and ease of use, ensuring that users of different ages and skill levels can interact effectively with the system.

The first game, referred to as Digital BBT, closely replicates the logic and movement patterns of the traditional Box and Block Test. In this environment, the live video feed from the webcam is augmented with virtual elements, including a central partition and multiple colored squares. At the beginning of each session, all squares are positioned on one side of the partition. Depending on the hand being assessed, the squares appear either on the right or the left side of the screen, and the user is required to “grasp” and transfer them one by one to the opposite side. When a square is successfully moved across the partition, it remains on the destination side and is immediately replaced by a new square at the starting position, ensuring continuous task flow. Each session lasts one minute, during which the user attempts to transfer as many squares as possible. At the end of the session, the total score is presented and can be stored for future reference and performance tracking. The

interaction design and timing constraints closely mirror those of the physical Box and Block Test, supporting comparability between digital and real-world assessments.

The second game, named Categorize, builds upon similar hand movement principles, and it is designed to assess manual dexterity while introducing additional cognitive and perceptual elements, including visual discrimination and decision-making. In this environment, the system generates three types of shapes—squares, circles, and triangles—which appear one at a time on the side of the screen corresponding to the active hand. The user must grasp each shape and move it across the screen to a designated area where three distinct target zones are displayed, each corresponding to one shape category. A point is awarded only when the shape is correctly matched to its respective zone, requiring the user to combine motor coordination with shape recognition and decision-making. As in the first game, each session has a duration of one minute, and users aim to correctly categorize as many shapes as possible within this time. Scores are displayed at the end of each session and can be saved for subsequent analysis.

For both games, visual guidance and real-time feedback are provided to support user interaction and ensure task clarity. Figures 1 and 2 present the user interface of the games Digital BBT and Categorize respectively. They demonstrate how users interact with the systems, specifically highlighting the process of grasping and moving virtual objects within each environment. Altogether, the design choices made for our applications aim to balance clinical relevance with user engagement, enabling both accurate assessment and effective training of fine motor skills.

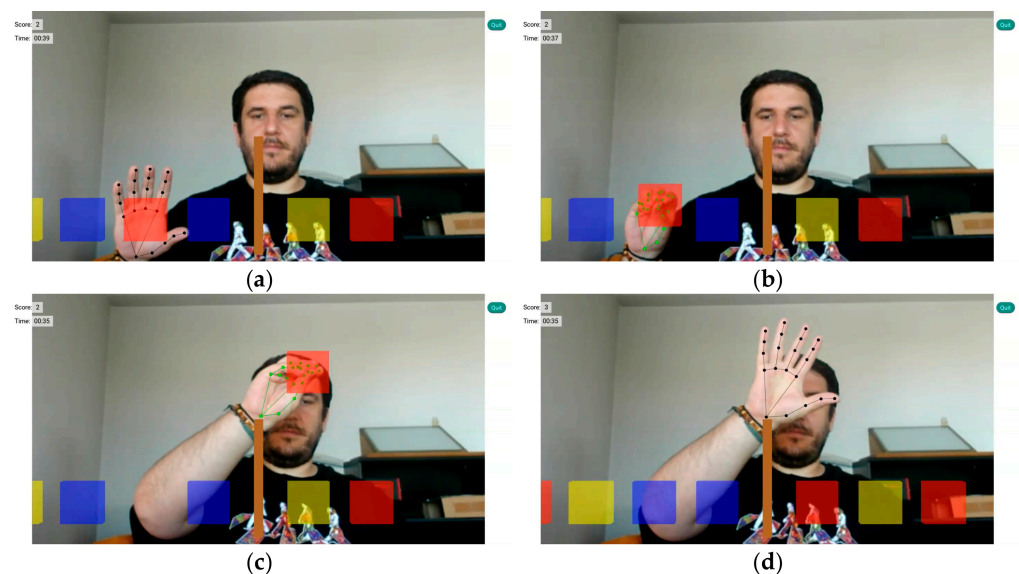


Figure 1. Example Demonstration of the Digital BBT Movements. (a) Placement of Hand over Block; (b) Gripping over Block and Grabbing it; (c) Moving Block to the other Side of the Partition; (d) Releasing Block and Scoring.

3.2. High-Level Architecture

The two digital serious games presented in this study share a common high-level architecture, designed to support real-time interaction, modular development, and efficient performance using low-cost hardware. The architecture follows a pipeline structure in which video input is captured, processed to detect and track hand movements, and subsequently translated into meaningful interactions within each game environment. This modular approach allows both applications to reuse core components while maintaining flexibility for game-specific logic and features.

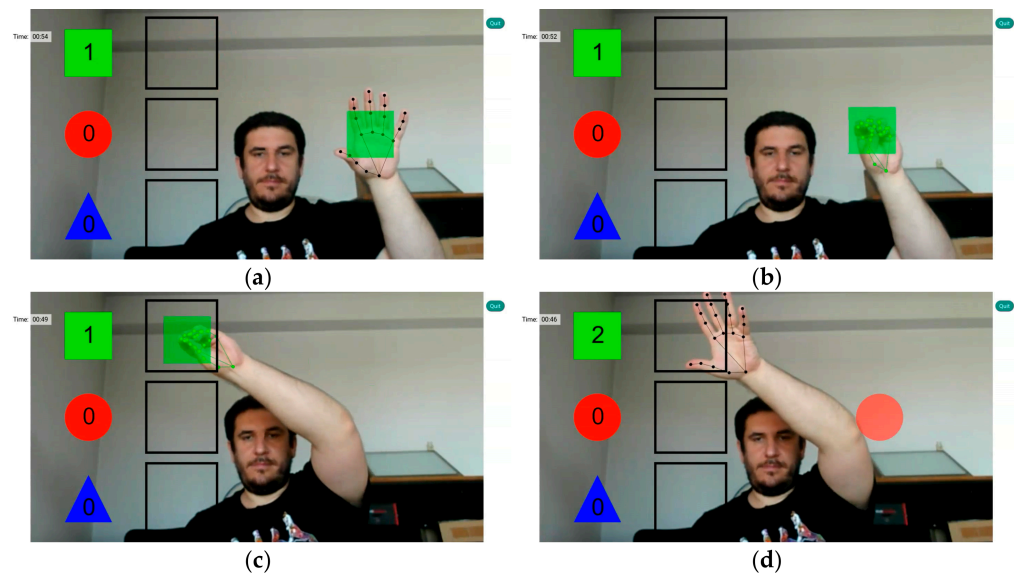


Figure 2. Example Demonstration of the Categorize Game Movements. (a) Placement of Hand over Shape; (b) Gripping over Shape and Grabbing it; (c) Moving Shape to the Specified Area; (d) Releasing Shape and Scoring.

At the input level, a standard webcam continuously captures video frames of the user's interaction space. These frames are forwarded to a hand detection and tracking module, which is responsible for identifying the position, orientation, and movement of the user's hand. This module extracts key features such as hand landmarks or bounding regions, enabling the system to interpret gestures such as grasping and releasing virtual objects. The accuracy and responsiveness of this component are critical, as they directly affect the usability and reliability of the games.

The processed hand data are then passed to the interaction and gesture recognition layer, where movement patterns are translated into game actions. For example, in the Digital BBT game, this layer determines when a user has “grasped” a square and whether it has been successfully transferred across the partition. Similarly, in the Categorize game, the system identifies object selection, movement, and correct placement within predefined target zones. This layer acts as a bridge between low-level motion tracking and high-level game logic.

Above this, the game logic module governs the rules, timing, scoring mechanisms, and progression of each game. It handles task initialization, object generation, collision detection, scoring updates, and session timing (e.g., the one-minute duration constraint). While both games share common timing and scoring structures, they differ in task logic, with the Digital BBT focusing on repetitive transfer actions and the Categorize game incorporating classification and decision-making processes.

The rendering and user interface module is responsible for overlaying virtual elements onto the live video feed and providing real-time visual feedback. This includes drawing shapes, partitions, target zones, and score indicators, as well as updating object positions dynamically based on user interaction. Clear and responsive visual feedback is essential to ensure that users can easily understand the system's state and their performance.

Finally, a data management component records performance metrics such as scores, timestamps, and interaction events. These data can be stored locally or transmitted to remote systems for further analysis, enabling longitudinal tracking of user performance and supporting both clinical evaluation and research purposes.

Figure 3 illustrates the high-level architecture of the proposed system, highlighting the main modules and the flow of data between them. The diagram emphasizes the modular

design and the interaction between video capture, hand tracking, game logic, rendering, and data storage components, which together enable the seamless operation of both serious games.

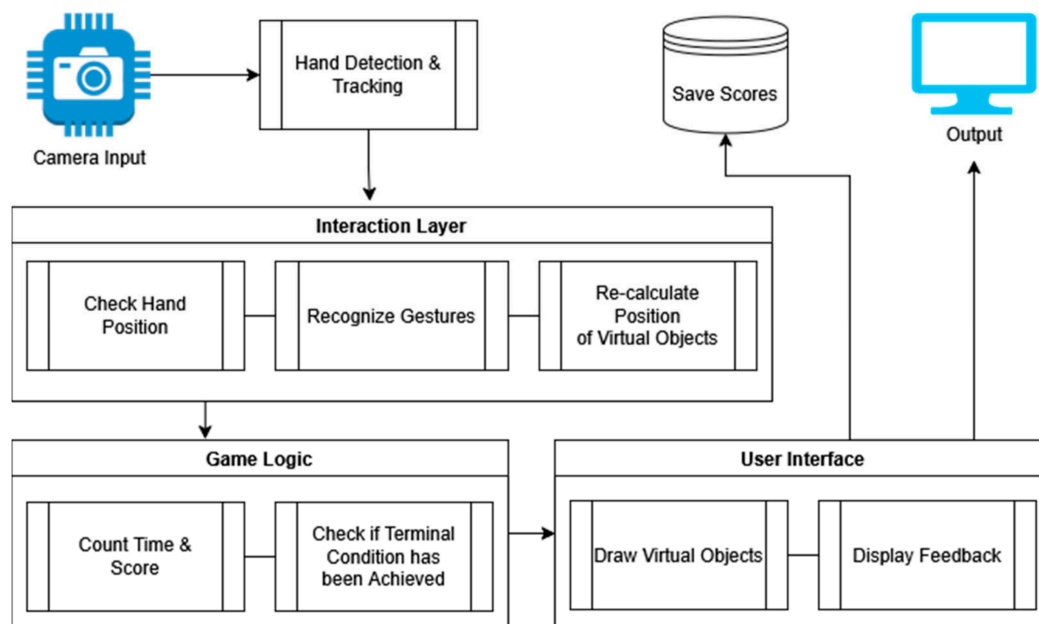


Figure 3. High-Level Architecture of the Digital Serious Games.

3.3. Implementation

The implementation of the proposed serious games was guided by the principles of accessibility, efficiency, and ease of deployment, aiming to ensure that the applications can be used in both clinical and home environments without specialized hardware or complex setup procedures. To achieve real-time hand detection and motion analysis, the system is built upon the MediaPipe framework [27], which provides robust and efficient hand-tracking capabilities through the extraction of detailed hand landmarks from video input. These landmarks, corresponding to key points on the hand (e.g., fingertips, joints, and palm center), are used to model hand posture and movement, enabling the recognition of interaction gestures such as grasping, holding, and releasing virtual objects. The applications operate in real time within a standard web browser using the MediaPipe inference pipeline executed locally on the client device. Under typical operating conditions using a conventional webcam (approximately 30 frames per second), the proposed interaction mechanism provides smooth visual feedback with minimal perceptible latency, enabling users to manipulate virtual objects in a natural manner without requiring dedicated sensing hardware or wearable devices.

The client-side of the applications is developed using standard web technologies, including HTML, CSS, and JavaScript, allowing the games to run directly within a web browser without the need for additional software installation. This approach enhances portability and cross-platform compatibility, making the system accessible from a wide range of devices equipped with a webcam. Real-time video processing and interaction handling are performed within the browser environment, ensuring immediate feedback and smooth user experience.

On the server-side, technologies such as PHP and MySQL are employed to manage user data, session results, and performance records. This backend infrastructure supports user authentication, data storage, and retrieval, enabling longitudinal tracking of user progress across multiple sessions. User privacy and data protection were considered

throughout the design of the proposed platform. Personally identifiable information is minimized, and participant records are stored using anonymized identifiers to prevent direct association between collected performance data and individual users. User authentication credentials are protected using the SHA-256 cryptographic hash function prior to storage, ensuring that passwords are never stored in plain text. Performance results and assessment scores are stored separately from authentication information, reducing the possibility of unauthorized linkage between identity and assessment records.

Gesture recognition is implemented by analyzing the spatial relationships and movement patterns of the hand landmarks provided by the MediaPipe framework. By calculating distances, angles, and positional changes between specific landmarks, the system determines when a user performs actions such as grasping or releasing virtual objects. This approach allows for reliable and efficient interaction without requiring additional input devices.

Figure 4 presents the set of hand landmarks detected by the MediaPipe framework, which form the basis for gesture recognition in both games. These landmarks enable precise tracking of finger and hand movements, supporting the accurate translation of physical actions into digital interactions within the game environments. The implementation of the gameplay and the interaction interface of our digital games is available as open-source software in [28].

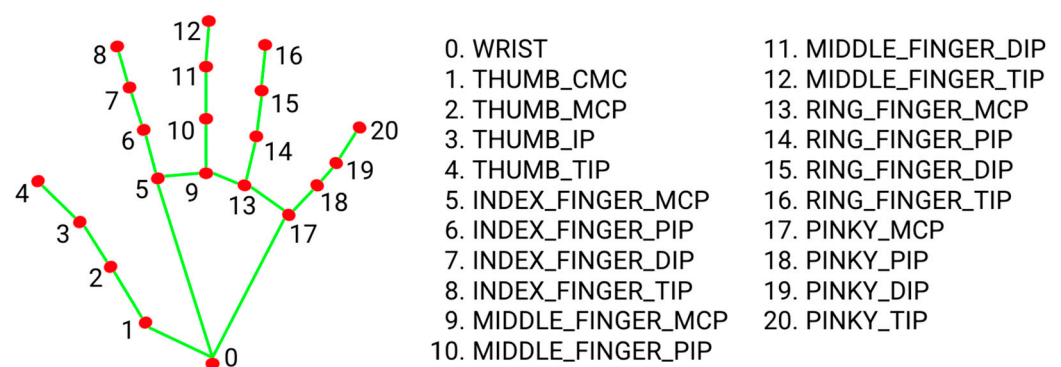


Figure 4. MediaPipe Hand Landmarks.

3.4. Gesture Recognition and Object Interaction

The proposed serious games employ the MediaPipe Hands framework to estimate twenty-one three-dimensional hand landmarks in real time from the webcam video stream. These landmarks are continuously updated for each captured frame and constitute the basis for all interaction between the user and the virtual environment. During gameplay, the system monitors the spatial relationships among selected fingertip landmarks to determine whether the user intends to grasp, transport, or release a virtual object.

Grasp detection is performed by monitoring the relative distance between the thumb tip (landmark 4) and the tip of the index finger (landmark 8). When the Euclidean distance between these landmarks becomes smaller than a predefined threshold while both landmarks are located inside the interaction region of a virtual object, the system considers the object to be successfully grasped and attaches it to the hand. The grabbing threshold is equivalent to 5% of the width of the frame by default, because it was identified as ideal for most users in order to replicate grasping—releasing actions similar to real world movements, but it can be readjusted based on the needs and preferences of each user. Once an object has been selected, its position is continuously updated according to the centroid of the tracked pinch position, allowing the object to move naturally with the user's hand.

Object release is detected when the distance between the thumb and index fingertips exceeds the predefined threshold while the object is located inside the target placement

region. If the release occurs within the valid destination area, the transfer is registered as successful and the system increments the corresponding performance score. Otherwise, the object is returned to its previous valid position, allowing the participant to attempt the movement again without interrupting the assessment session.

3.5. Collision Detection and Game Logic

Collision detection is implemented using two-dimensional bounding-box intersection tests between the tracked object position and predefined interaction regions within the game environment. Each virtual object is associated with a unique interaction area and can only be manipulated after a valid grasp event has been detected. During transport, the object remains linked to the tracked hand position until a release event occurs. The destination area is continuously monitored to determine whether the released object satisfies the placement criteria defined by the corresponding game.

In the Digital BBT game, a successful interaction is recorded only when the virtual block is released beyond the partition separating the two compartments, reproducing the functional principles of the conventional Box and Block Test. In the Categorize game, an additional logical verification step confirms that the released object has been placed inside the correct target container according to its assigned geometric shape. Incorrect placements are rejected, requiring the participant to repeat the movement before proceeding with the next object.

3.6. Calibration and Robustness

Before each assessment session, participants are instructed to position themselves at an appropriate distance from the webcam and to ensure adequate ambient illumination so that the complete working area remains visible throughout the task. A short initialization phase allows the MediaPipe hand-tracking model to detect the participant's dominant hand and establish stable landmark tracking before gameplay begins. This simple calibration procedure requires no specialized equipment or manual parameter adjustment and can typically be completed within a few seconds.

During execution, the system continuously evaluates the confidence of the detected hand landmarks. Temporary tracking failures caused by rapid hand movements, partial occlusions, or insufficient lighting are handled by maintaining the last valid object state until reliable landmark detection resumes. If hand tracking is completely lost, object manipulation is temporarily suspended to prevent unintended movements or erroneous score registration. Normal operation resumes automatically once stable hand tracking is re-established.

3.7. Privacy and Data Protection

The proposed web-based assessment platform was designed following fundamental privacy-by-design principles appropriate for research-oriented digital health applications. During each assessment session, MediaPipe hand landmarks are extracted in real time from the webcam stream and are used immediately for gesture recognition and game interaction. The system stores only the performance metrics required for assessment, including the number of successfully transferred objects, task completion information, and session statistics. Raw webcam video is not retained after processing, and the extracted hand landmarks are not permanently stored in the current implementation.

All participant data used during the experimental evaluation were anonymized prior to statistical analysis. Each participant was assigned a unique identifier that does not contain personally identifiable information. Consequently, the exported research dataset contains only anonymized demographic information and assessment results, thereby reducing privacy risks while allowing reproducibility of the reported analyses.

Access to the platform requires user authentication, while passwords are protected using the SHA-256 cryptographic hash function before storage in the database. Communication between the client and server can additionally be protected through standard HTTPS protocols during deployment, ensuring secure transmission of user credentials and assessment data over public networks.

4. Experimental Evaluation

The primary objective of the experimental evaluation was to investigate whether the proposed digital serious games can serve as reliable alternatives to the conventional Box and Block Test (BBT) for the assessment of fine motor skills. To achieve this objective, the performance of healthy adult participants was evaluated using the traditional BBT together with the two proposed digital games under controlled experimental conditions. Quantitative analyses were conducted to examine the degree of agreement between the conventional and digital assessments, while a usability evaluation was performed to investigate user acceptance and overall interaction quality. Also, testing our application with healthy people lays the foundation for extracting normative data that will serve as performance indicators in future evaluations which will include participants with motor impairments.

The experimental methodology was designed to answer the following research questions:

- RQ1: Can the Digital BBT reproduce the assessment results obtained using the conventional Box and Block Test?
- RQ2: Does the Categorize serious game provide assessment results that are significantly associated with conventional BBT performance despite incorporating additional cognitive elements?
- RQ3: Are the proposed serious games perceived by users as usable, intuitive, and appropriate for repeated assessment and rehabilitation sessions?

Based on these research questions, the following hypotheses were formulated:

H1. *Performance in the Digital BBT is positively correlated with performance in the conventional Box and Block Test.*

H2. *Performance in the Categorize game is positively correlated with performance in the conventional Box and Block Test.*

H3. *Participants will report high levels of usability, engagement, and satisfaction when interacting with the proposed digital serious games.*

The experimental study was designed not only to compare absolute performance scores between the conventional and digital assessments but also to investigate whether the proposed applications preserve the well-established behavioral patterns associated with manual dexterity, including the effects of age, gender, and hand dominance. Demonstrating these relationships would provide evidence supporting the construct validity of the proposed digital assessment framework.

4.1. Participants

A total of 50 healthy adult volunteers participated in the experimental study. The sample consisted of 20 males (40%) and 30 females (60%), with participant ages ranging from 20 to 70 years. For subsequent analyses, participants were divided into three age groups representing young, middle-aged, and older adults:

- 20–35 years: 15 participants;

- 36–55 years: 18 participants;
- 56–70 years: 17 participants.

Regarding handedness, 40 participants (80%) were right-handed, while 10 participants (20%) were left-handed. Since manual dexterity is known to differ between dominant and non-dominant hands, both hands were evaluated independently throughout the experimental procedure. Participants were recruited through convenience sampling from the local academic community and surrounding population. Participation was entirely voluntary, and no financial compensation was provided.

Prior to participation, volunteers received a detailed explanation of the objectives of the study, the testing procedure, and the expected duration of the experiment. All participants agreed to participate voluntarily after being informed that they could withdraw from the study at any stage without consequence.

To ensure that the experimental results reflected normal fine motor performance, participants were required to satisfy the following inclusion criteria:

- Age between 20 and 70 years;
- Ability to understand the experimental procedure and follow verbal instructions;
- Normal or corrected-to-normal vision;
- Ability to perform upper-limb movements without assistance.

Participants were excluded if they reported any diagnosed neurological, musculoskeletal, or upper-limb disorders that could affect manual dexterity, including stroke, Parkinson's disease, multiple sclerosis, cerebral palsy, severe arthritis, recent upper-limb injuries, or any other condition known to impair motor performance. Consequently, all participants included in the present study were considered healthy adults without known motor impairments.

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approval was obtained from the Institutional Research Ethics Committee of the University of Peloponnese (Approval No. 20366/8 September 2022) before participant recruitment commenced. All participants provided written informed consent prior to data collection. Personal information was treated confidentially, and all recorded performance data were anonymized before statistical analysis to ensure participant privacy.

4.2. Experimental Protocol

All experiments were performed under identical laboratory conditions in order to minimize external sources of variability. The digital applications were executed on a desktop computer equipped with a standard webcam positioned directly in front of each participant. The webcam continuously captured hand movements while the proposed computer vision algorithms detected hand landmarks and translated user movements into game interactions in real time. All experimental sessions were conducted using a standard mid-range desktop computer equipped with an Intel Core i5-10400 processor (2.90 GHz), 16 GB RAM, integrated Intel UHD Graphics 630, running Windows 11 Pro (64-bit). Video acquisition was performed using a Logitech C270 HD webcam, manufactured by Logitech International S.A., located in Lausanne, Switzerland, configured at a resolution of 1280 × 720 pixels and a frame rate of approximately 30 frames per second (fps). The webcam was positioned on top of the monitor at an approximate distance of 60–80 cm from the participant, providing a frontal view of the upper body and hands throughout the assessment. This hardware configuration was intentionally selected to demonstrate that the proposed assessment system can operate reliably on affordable, widely available consumer equipment without requiring specialized sensors or high-performance computing resources.

The sample size was determined based on the primary objective of the study, namely the evaluation of the correlation between the conventional Box and Block Test and the

proposed digital serious games. Assuming a large expected correlation ($r \approx 0.50$), consistent with previous validation studies of digital motor assessment tools, a two-sided significance level of $\alpha = 0.05$, and a statistical power of 80%, an a priori power analysis, performed using G*Power (version 3.1.9.7), indicated that approximately 29 participants would be sufficient to detect such an association. Consequently, the inclusion of 50 participants exceeded this minimum requirement, providing adequate statistical power while also allowing subgroup analyses according to age, gender, and hand dominance.

Before formal testing began, participants received standardized verbal instructions describing the objectives and rules of each assessment. Demonstrations of both digital games were provided to ensure that all participants clearly understood the interaction mechanisms before data collection commenced.

To minimize the influence of unfamiliarity with the applications, every participant completed two familiarization trials for each assessment task using both the dominant and the non-dominant hand. These practice trials allowed participants to become accustomed to the interaction mechanics of the digital environment and were not included in the statistical analyses.

Following familiarization, participants completed five recorded trials for each assessment modality using both hands. The three assessment modalities were:

1. The conventional Box and Block Test (BBT);
2. The Digital BBT serious game;
3. The Categorize serious game.

Each assessment lasted 60 s, following the standard administration procedure of the conventional BBT. Performance was quantified as the total number of successfully completed actions during each one-minute session. Specifically, for the conventional BBT and the Digital BBT, the recorded score corresponded to the number of successfully transferred blocks, whereas for the Categorize game the score represented the number of correctly categorized geometric objects.

To reduce fatigue, participants were allowed to rest briefly between consecutive trials and between different assessment modalities whenever requested. Since all assessment tasks required repetitive upper-limb movements, these short recovery periods helped maintain consistent performance throughout the experimental session.

For every participant, the same experimental procedure was followed to ensure consistency across the collected dataset. The resulting protocol generated a comprehensive set of performance measurements covering conventional assessment, digital assessment, dominant and non-dominant hand performance, demographic characteristics, and subjective usability evaluation.

4.3. Outcome Measures

The experimental evaluation aimed to compare participants' performance across three assessment modalities: the conventional Box and Block Test (BBT), the proposed Digital BBT serious game, and the Categorize serious game. To ensure objective comparison, identical testing durations and standardized scoring procedures were employed across all modalities.

The primary outcome measure for all three assessment modalities was the participant's task performance score, defined as the total number of successfully completed actions during a one-minute assessment period.

For each assessment modality, the score was calculated as follows:

- Conventional BBT: number of wooden blocks successfully transferred across the partition within 60 s.

- Digital BBT: number of virtual blocks successfully transferred across the virtual partition within 60 s.
- Categorize game: number of geometric objects correctly categorized into their corresponding target areas within 60 s.

These outcome measures were selected because they directly quantify manual dexterity while maintaining consistency between the conventional assessment and its digital implementations. Since every participant completed the assessments using both the dominant and the non-dominant hand, separate performance scores were recorded for each hand.

For every participant, the final score used in the statistical analysis corresponded to the arithmetic mean of the five recorded trials performed for each hand and assessment modality. Averaging multiple trials reduces the influence of random performance fluctuations and provides a more reliable estimate of each participant's actual motor ability.

In addition to the primary performance measures, several participant characteristics were recorded in order to investigate whether known factors affecting manual dexterity were preserved by the proposed digital assessments. The recorded demographic variables included:

- Age;
- Age group;
- Gender;
- Handedness;
- Dominant hand;
- Non-dominant hand.

These variables enabled subgroup analyses examining performance differences across demographic categories and allowed direct comparison with established normative findings reported in the literature for the conventional Box and Block Test.

Following completion of all assessment tasks, participants completed a usability questionnaire designed to evaluate their overall experience with the proposed digital serious games. The questionnaire consisted of two parts. The first part included eleven statements evaluated using a five-point Likert scale, where

- 1 = Strongly disagree;
- 2 = Disagree;
- 3 = Neither agree nor disagree;
- 4 = Agree;
- 5 = Strongly agree.

The statements investigated several usability dimensions, including ease of learning, clarity of instructions, ease of interaction, responsiveness, naturalness of movement, perceived reliability, physical effort, mental effort, enjoyment, willingness for repeated use, and perceived assessment validity.

The second part consisted of three multiple-choice questions that asked participants to identify their preferred assessment, the most engaging assessment and the assessment they perceived as the most difficult.

Together, these measures provided complementary qualitative information regarding user acceptance of the proposed digital assessment framework.

4.4. Statistical Analysis

To evaluate the validity of the proposed digital serious games as assessment tools for fine motor skills, both descriptive and inferential statistical analyses were performed. Prior to inferential statistical analysis, the distribution of the continuous outcome variables was

examined using the Shapiro–Wilk test for normality. Since the assumptions of approximate normality were satisfied for all primary outcome measures, parametric statistical methods were considered appropriate for the subsequent analyses. Descriptive statistics are reported as arithmetic mean, standard deviation (SD), median, interquartile range (IQR), minimum, maximum, and 95% confidence intervals where appropriate. All statistical tests were two-tailed, and statistical significance was established at $\alpha = 0.05$.

Initially, descriptive statistics were calculated for every assessment modality. For each group of participants, the following statistics were computed:

- Arithmetic mean;
- Standard deviation (SD);
- Minimum score;
- Maximum score;
- Median;
- Interquartile range (IQR).

These descriptive measures provide an overview of participant performance and facilitate comparison between the conventional BBT and the proposed digital games. Furthermore, descriptive statistics were calculated separately for dominant hand, non-dominant hand, gender and age group, allowing investigation of demographic influences on assessment performance.

The principal objective of this study was to determine whether performance in the proposed digital serious games was significantly associated with performance in the conventional Box and Block Test. Accordingly, Pearson's product-moment correlation coefficient (r) was calculated between conventional BBT—digital BBT, and conventional BBT—categorize game, for both dominant and non-dominant hands. Pearson correlation analysis was selected because the outcome variables are continuous and the purpose of the analysis was to evaluate the strength and direction of linear relationships between the conventional and digital assessments. For every calculated correlation coefficient, the following statistics were reported:

- Pearson correlation coefficient (r);
- Corresponding p -value;
- 95% confidence interval;
- Coefficient of determination (R^2).

The strength of the observed correlations was interpreted according to Cohen's widely accepted guidelines, presented in Table 1.

Table 1. Cohen's guidelines.

Pearson Coefficient	Interpretation
0.10–0.29	Weak
0.30–0.49	Moderate
0.50–0.69	Strong
≥ 0.70	Very strong

Scatter plots with fitted linear regression lines were generated for each comparison between the conventional BBT and the two digital assessment modalities in order to provide a visual representation of the observed linear relationships. In addition to Pearson's correlation coefficient, the coefficient of determination (R^2) was calculated to quantify the proportion of variance in digital performance explained by the conventional assessment. Confidence intervals were computed using Fisher's z -transformation, providing an estimate of the precision of the reported correlation coefficients.

To investigate whether the digital games preserved the behavioral characteristics observed in the conventional Box and Block Test, participant performance was compared across demographic groups. Separate analyses were performed according to age group, gender and hand dominance. These comparisons allowed evaluation of whether the digital assessments reproduced the well-established effects of age and dominant-hand superiority that have consistently been reported in previous BBT studies. Table 2 presents the summary of the experimental variables we use, while the statistical analyses performed are showcased in Table 3.

Table 2. Summary of Experimental Variables Included in the Statistical Analysis.

Category	Variable	Type
Conventional assessment	Real BBT score (dominant hand)	Continuous
Conventional assessment	Real BBT score (non-dominant hand)	Continuous
Digital assessment	Digital BBT score (dominant hand)	Continuous
Digital assessment	Digital BBT score (non-dominant hand)	Continuous
Digital assessment	Categorize score (dominant hand)	Continuous
Digital assessment	Categorize score (non-dominant hand)	Continuous
Participant information	Age	Continuous
Participant information	Gender	Categorical
Participant information	Handedness	Categorical
Questionnaire	Likert-scale responses	Ordinal
Questionnaire	Preferred task	Categorical
Questionnaire	Most engaging task	Categorical
Questionnaire	Most difficult task	Categorical

Table 3. Statistical Analyses Performed.

Analysis	Purpose
Descriptive statistics	Summarize participant performance
Pearson correlation	Evaluate association between conventional and digital assessments
95% Confidence intervals	Estimate precision of correlation coefficients
Coefficient of determination (R^2)	Quantify explained variance
Frequency analysis	Analyse questionnaire responses
Group comparisons	Examine effects of age, gender and hand dominance

Responses to the usability questionnaire were analyzed using descriptive statistics. For each Likert-scale question, the frequency distribution of participant responses was calculated together with the corresponding response percentages. The multiple-choice questions were analyzed by computing the frequency with which each assessment modality was selected. These analyses were intended to evaluate participants' perceived usability, engagement, responsiveness, realism, and overall acceptance of the proposed digital serious games.

4.5. Experimental Results

A total of fifty healthy adults successfully completed the experimental protocol. All participants completed the conventional Box and Block Test (BBT), the Digital BBT serious game, and the Categorize serious game using both the dominant and the non-dominant hand. No participant withdrew from the study, and no technical failures or incomplete measurements were recorded during data collection.

First, we should mention that the collected results in the traditional BBT are consistent with healthy adult norms appearing in former research. The mean and median scores we recorded per group, dividing participants based on age, gender and hand dominance,

do not differentiate more than 3 units over or under the expected scores given in commonly accepted normative data [29]. This is a strong indicator that our experimental study was conducted under circumstances that can provide valid conclusions about potential tendencies, without ignoring the fact that further research is necessary to solidify our results.

The descriptive statistics indicate that participant performance followed similar trends across the three assessment modalities. As expected, the highest scores were observed in the conventional BBT, followed by the Digital BBT and the Categorize game. This difference is expected because the digital environments introduce additional interaction constraints associated with computer vision processing, while the Categorize game additionally incorporates cognitive decision-making through object classification.

Nevertheless, despite the differences in absolute scores, participants who achieved higher performance in the conventional BBT consistently obtained higher scores in both digital serious games. Similarly, participants exhibiting lower manual dexterity in the conventional assessment demonstrated correspondingly lower performance in the digital environments. This behaviour suggests that both digital games preserve the ranking of participants according to their motor abilities.

Furthermore, the expected superiority of the dominant hand was consistently observed across all three assessment modalities. Likewise, younger participants generally achieved higher performance scores than middle-aged and older participants, reproducing the well-established age-related decline in manual dexterity reported in previous BBT studies. Table 4 summarizes the descriptive statistics for each assessment modality. Also, in Appendix A we present the means scores achieved per age group, gender and hand dominance in every assessment test.

Table 4. Descriptive statistics of participant performance across the three assessment modalities.

Assessment	Hand	Mean	SD	Median	Min	Max
Conventional BBT	Dominant	80.82	8.75	78	69	102
Conventional BBT	Non-Dominant	77.82	8.20	76	67	99
Digital BBT	Dominant	46.18	5.35	45	38	59
Digital BBT	Non-Dominant	44.34	5.32	43	36	57
Categorize	Dominant	37.56	4.39	37	31	48
Categorize	Non-Dominant	35.86	4.60	34	29	47

The principal objective of the present study was to determine whether performance in the proposed digital serious games accurately reflects manual dexterity as measured by the conventional Box and Block Test. Pearson's product-moment correlation analysis revealed very strong positive correlations between the conventional BBT and both digital assessment modalities. For the dominant hand, performance in the Digital BBT demonstrated a Pearson correlation coefficient of $r = 0.958$ ($p < 0.001$) with the conventional BBT. Similarly, the Categorize game demonstrated an even slightly stronger relationship with the conventional assessment ($r = 0.967$ ($p < 0.001$)). Analysis of the non-dominant hand produced similarly strong relationships. The Digital BBT yielded $r = 0.932$ ($p < 0.001$) while the Categorize game demonstrated $r = 0.930$ ($p < 0.001$).

According to Cohen's interpretation guidelines, all observed correlations are classified as very strong, indicating that participant performance in both digital environments closely follows performance obtained using the standardized clinical assessment.

These findings provide strong evidence supporting hypotheses H1 and H2, demonstrating that the proposed serious games preserve the relative ranking of participants

according to their fine motor abilities. In Table 5 we present the Pearson correlation analysis between the conventional BBT and the proposed digital assessments.

Table 5. Pearson correlation analysis between the conventional BBT and the proposed digital assessments.

Comparison	Pearson r	95% CI	p-Value	Interpretation
Conventional BBT vs. Digital BBT (Dominant)	0.958	[0.928, 0.976]	<0.001	Very strong
Conventional BBT vs. Categorize (Dominant)	0.967	[0.943, 0.981]	<0.001	Very strong
Conventional BBT vs. Digital BBT (Non-dominant)	0.932	[0.881, 0.961]	<0.001	Very strong
Conventional BBT vs. Categorize (Non-dominant)	0.930	[0.878, 0.960]	<0.001	Very strong

Figure 5 further illustrates the relationship between the conventional BBT and the two digital serious games. In all four comparisons, the data points are closely distributed around the fitted regression lines, indicating strong positive linear associations between conventional and digital assessment scores. No substantial deviations from linearity or influential outliers were observed, further supporting the suitability of Pearson correlation analysis for evaluating the relationships between assessment modalities.

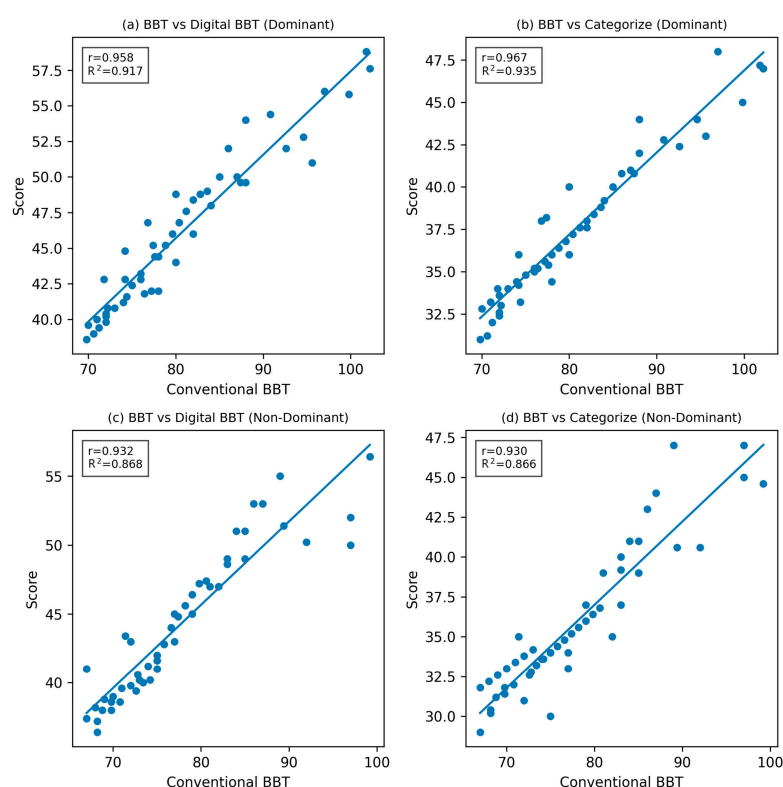


Figure 5. Scatter plots illustrating the relationships between the conventional Box and Block Test (BBT) and the proposed digital assessment modalities.

The corresponding coefficients of determination indicate that a substantial proportion of the variability observed in the digital assessments can be explained by performance in the conventional BBT. Specifically:

- Digital BBT (dominant): $R^2 \approx 0.918$;
- Categorize (dominant): $R^2 \approx 0.935$;
- Digital BBT (non-dominant): $R^2 \approx 0.869$;
- Categorize (non-dominant): $R^2 \approx 0.865$.

These results indicate that approximately 87–94% of the variability in digital performance is associated with manual dexterity measured using the conventional clinical assessment.

Performance differences across age groups followed the expected trends reported in normative Box and Block Test studies. Participants aged 20–35 years consistently achieved the highest performance scores across all three assessment modalities, followed by the 36–55 years group, while participants aged 56–70 years demonstrated the lowest average performance. Importantly, although absolute scores differed between the conventional and digital assessments, the relative differences between age groups remained remarkably consistent. This observation indicates that both serious games preserve the age-related characteristics of manual dexterity that have been extensively documented in the literature. Similarly, dominant-hand performance exceeded non-dominant-hand performance across every participant subgroup. These findings further support the construct validity of the proposed digital assessment framework. Table 6 presents the comparison of mean performances of participants, grouped by age and hand dominance.

Table 6. Mean performance according to participant characteristics.

Variable	Conventional BBT	Digital BBT	Categorize
Young adults (20–35)	Highest	Highest	Highest
Middle-aged (36–55)	Intermediate	Intermediate	Intermediate
Older adults (56–70)	Lowest	Lowest	Lowest
Dominant hand	Higher	Higher	Higher
Non-dominant hand	Lower	Lower	Lower

The experimental findings demonstrate that both proposed digital serious games successfully reproduce the behavioural characteristics measured by the conventional Box and Block Test. Although the Digital BBT and Categorize game naturally produce lower absolute scores due to differences in interaction modality and computer vision constraints, the exceptionally high correlation coefficients indicate that participants preserve nearly identical performance rankings across all assessment modalities. Consequently, individuals demonstrating superior manual dexterity in the conventional assessment also perform better in both digital environments, while participants with lower dexterity exhibit proportionally lower digital performance. These observations strongly support the validity of the proposed games as digital alternatives for assessing fine motor skills.

Moreover, the Categorize game achieved correlations comparable to those obtained by the Digital BBT despite incorporating additional cognitive processing requirements. This finding suggests that integrating cognitive tasks into serious games can enrich the assessment process without substantially compromising their ability to evaluate underlying motor performance.

Overall, the statistical analyses provide robust quantitative evidence supporting the validity of the proposed serious games, considerably strengthening the conclusions of this study compared with analyses based solely on descriptive statistics.

4.6. Usability Evaluation

In addition to evaluating the validity of the proposed serious games as assessment tools, a usability study was conducted to investigate participants' perceptions regarding the interaction quality, ease of use, responsiveness, and overall acceptance of the proposed digital applications. Since the long-term success of digital rehabilitation systems depends not only on their measurement accuracy but also on user acceptance and engagement, usability constitutes an important aspect of their practical applicability.

Immediately after completing all experimental tasks, participants completed a post-experimental questionnaire specifically designed for this exploratory study. The questionnaire consisted of eleven statements evaluated using a five-point Likert scale (1 = Strongly disagree to 5 = Strongly agree), together with three multiple-choice questions investigating user preferences among the three assessment modalities. The questionnaire focused on five principal usability dimensions:

- Learnability;
- Ease of interaction;
- Perceived system responsiveness;
- Perceived workload;
- Overall user satisfaction and acceptance.

The questionnaire was developed to obtain qualitative feedback regarding the usability of the proposed applications rather than to provide a standardized psychometric assessment. Consequently, the results should be interpreted as exploratory measures of user acceptance.

To reduce the potential influence of social desirability bias, questionnaire responses were collected anonymously, and participants were informed that their answers would be used exclusively for research purposes and would not affect the evaluation of their performance. The questionnaire employed neutral, non-leading statements describing different aspects of usability and user experience, allowing participants to express either positive or negative opinions without suggesting preferred responses. Furthermore, participants completed the questionnaire independently after finishing all assessment tasks, minimizing potential influence from the investigators during data collection. The summary of the questionnaire responses can be found in Appendix A.

Participants reported exceptionally high levels of learnability and ease of interaction for both proposed serious games. All participants (100%) strongly agreed that they quickly understood the objectives of the applications, considered the provided instructions clear, and found the interaction process easy to learn. These findings indicate that the proposed interfaces require minimal familiarization before effective use and therefore appear suitable for users with varying levels of computer experience.

Similarly, all participants strongly agreed that the hand movements required during interaction felt natural and closely resembled real-world object manipulation. Since both games rely exclusively on vision-based hand tracking without requiring wearable devices or additional controllers, this result demonstrates that the interaction design successfully reproduces intuitive hand movements while maintaining a low hardware barrier.

Overall, these findings suggest that the proposed digital environments provide a user experience that is straightforward, intuitive, and immediately understandable, characteristics that are particularly important for rehabilitation applications intended for repeated long-term use.

Real-time responsiveness represents a critical requirement for interactive rehabilitation systems because delayed visual feedback can negatively affect both user engagement and motor performance. The majority of participants (86%) strongly agreed that the proposed applications responded immediately to their actions, while an additional 10% agreed with this statement. Only 4% of participants expressed a neutral opinion, and none reported disagreement. These findings indicate that the combination of MediaPipe hand tracking and browser-based implementation provides sufficient computational performance to support smooth interaction under the experimental conditions.

The absence of negative evaluations regarding system responsiveness further suggests that the latency introduced by the computer vision algorithms was sufficiently low to avoid noticeable disruption of the interaction process.

An important objective of the usability evaluation was to determine whether the proposed games introduced unnecessary physical or cognitive burden that could interfere with the assessment of manual dexterity. The questionnaire responses indicate that participants generally perceived both applications as physically comfortable. Regarding physical effort, 86% of participants strongly disagreed that the games were physically tiring, while the remaining participants disagreed with this statement. No participant reported neutral or positive agreement. Similarly, participants reported very low mental workload. For the Digital BBT, 96% strongly disagreed that the task was mentally demanding, while only 4% disagreed. The Categorize game produced slightly higher perceived cognitive effort, as expected due to the additional object-classification task. Nevertheless, the overwhelming majority of participants still reported low levels of mental workload.

These observations suggest that the additional cognitive component incorporated into the Categorize game modestly increases task complexity without substantially increasing user burden, thereby supporting its suitability for combined motor-cognitive rehabilitation exercises.

Participants expressed highly positive opinions regarding the overall user experience provided by both digital serious games. Most participants strongly agreed that they enjoyed interacting with the applications and indicated that they would be willing to use the proposed games regularly if available for rehabilitation or self-assessment purposes. Similarly, the majority of participants strongly agreed that their performance within the digital environments accurately reflected their real-world manual abilities. This finding is particularly noteworthy because perceived assessment validity is an important factor influencing user trust in digital healthcare applications.

Overall, these responses demonstrate a high level of acceptance of the proposed interaction paradigm and indicate that users considered the digital assessments both enjoyable and credible. Nevertheless, because usability outcomes were based on participant self-report, the consistently high ratings should be interpreted alongside the possibility of residual response bias, despite the use of anonymous questionnaires and neutral survey wording.

The multiple-choice questions provided additional insight into participant preferences among the three assessment modalities. The Categorize game emerged as the preferred application, being selected by 80% of participants as their favourite assessment. Similarly, 80% of participants identified the Categorize game as the most engaging application. Interestingly, the same game was also perceived as the most difficult by 70% of participants. This finding suggests that increased cognitive challenge does not necessarily reduce user enjoyment. On the contrary, introducing decision-making elements appears to increase participant engagement while preserving usability. The Digital BBT and the conventional BBT received substantially fewer preferences in all questionnaire categories.

These findings indicate that although the Digital BBT successfully reproduces the traditional assessment procedure, the additional interaction complexity incorporated into the Categorize game may improve long-term user motivation, an important consideration for home-based rehabilitation programs requiring repeated use over extended periods.

Table 7 presents the summary of the usability questionnaire responses, while Table 8 shows the participants' preferences among the assessment modalities.

The usability evaluation demonstrates that the proposed digital serious games achieved a high level of user acceptance while maintaining intuitive interaction and minimal physical burden. Particularly noteworthy is the observation that the Categorize game was simultaneously perceived as the most engaging and the most challenging application. This combination suggests that incorporating additional cognitive elements may increase user motivation without negatively affecting overall usability. Such characteristics

are highly desirable in rehabilitation environments, where sustained user engagement is essential for long-term adherence to therapeutic programs.

Table 7. Summary of usability questionnaire responses.

Usability Dimension	Main Finding
Learnability	100% immediately understood the games
Ease of Use	100% found the interaction easy
Natural Interaction	100% reported natural hand movements
Responsiveness	96% agreed or strongly agreed that the system responded immediately
Physical Workload	100% disagreed that the games were physically tiring
Mental Workload	Very low for both games; slightly higher for Categorize
Enjoyment	Majority strongly agreed
Willingness for Repeated Use	Majority strongly agreed
Perceived Assessment Validity	Majority believed the games reflected their real abilities

Table 8. Participant preferences among the assessment modalities.

Question	Conventional BBT	Digital BBT	Categorize
Preferred assessment	5	5	40
Most engaging assessment	5	5	40
Most difficult assessment	10	5	35

Furthermore, the positive evaluations regarding natural interaction, responsiveness, and perceived assessment validity indicate that the proposed computer vision-based interaction paradigm successfully reproduces manual manipulation tasks without requiring specialized hardware or wearable sensors.

Overall, the usability findings complement the quantitative validation results presented in the Section 4.5, demonstrating that the proposed serious games not only exhibit strong agreement with the conventional Box and Block Test but are also perceived by users as intuitive, reliable, and suitable for repeated use.

4.7. Study Limitations

Despite the encouraging findings obtained in the present study, several limitations should be acknowledged.

First, the experimental evaluation was conducted exclusively with healthy adult participants without diagnosed neurological or musculoskeletal disorders affecting upper-limb function. Although this approach was appropriate for establishing the initial validity of the proposed digital assessments, it does not allow direct conclusions regarding clinical populations. Since the intended application of the proposed serious games includes assessment and rehabilitation of individuals with motor impairments, future studies should investigate their performance in patients affected by conditions such as stroke, Parkinson's disease, cerebral palsy, multiple sclerosis, or traumatic upper-limb injuries.

Second, although the study included fifty participants covering a relatively broad age range, the sample size remains modest from a statistical perspective. The performed a priori power analysis indicated that the recruited sample exceeded the minimum number of participants required to detect the expected association between the conventional and digital assessment methods, but larger participant cohorts would increase statistical power, improve the precision of estimated correlations, and facilitate more detailed subgroup analyses.

A further limitation concerns the participant recruitment strategy. Since volunteers were recruited using convenience sampling, the study population may not fully represent

the broader population of potential users. Future multicentre studies involving participants from different demographic and clinical backgrounds would improve the generalizability of the findings. In addition, despite the measures taken to reduce response bias through anonymous data collection and neutral questionnaire wording, the usability evaluation relied on self-reported responses and therefore cannot completely exclude the possibility of social desirability bias.

Another potential limitation involves learning effects. Although participants completed familiarization trials before the recorded measurements, repeated exposure to similar motor tasks may have slightly influenced subsequent performance. Future studies may further reduce this possibility by employing randomized or counterbalanced assessment orders across participants.

The present evaluation focused primarily on the number of successfully completed actions during one-minute assessment sessions. While this metric is consistent with the conventional Box and Block Test and therefore facilitates direct comparison, digital environments are capable of capturing substantially richer information, including movement trajectories, reaction times, object manipulation speed, movement smoothness, and error characteristics. Incorporating these additional metrics into future analyses could provide a more comprehensive assessment of fine motor performance than is possible using traditional clinical instruments.

Moreover, although the current implementation minimizes privacy risks by storing only anonymized assessment outcomes rather than raw video recordings, future deployments involving clinical populations should further evaluate long-term privacy preservation, secure data governance, and compliance with institutional and national healthcare regulations.

Finally, the current implementation relies on a standard webcam and computer vision algorithms for hand tracking. Although the experimental evaluation demonstrated reliable performance under controlled laboratory conditions, environmental factors such as lighting conditions, camera quality, background complexity, and hardware performance may influence interaction accuracy in real-world home environments. Future versions of the system will investigate adaptive calibration techniques and more robust computer vision algorithms to improve reliability under diverse operating conditions.

Although these limitations should be considered when interpreting the present findings, they do not diminish the primary contribution of this work, namely the demonstration that the proposed digital serious games exhibit strong agreement with the conventional Box and Block Test while providing additional flexibility, accessibility, and opportunities for automated data collection.

4.8. Implications for Digital Assessment and Rehabilitation

The present findings have several practical implications for both clinical assessment and rehabilitation. From an assessment perspective, the proposed digital serious games demonstrate that standardized manual dexterity evaluations can be successfully translated into accessible computer vision-based environments without requiring specialized motion capture systems, wearable sensors, or dedicated rehabilitation hardware. This considerably reduces deployment costs while increasing accessibility for both healthcare professionals and patients.

Furthermore, the ability to automatically record assessment results and store longitudinal performance data provides opportunities for objective monitoring of rehabilitation progress over extended periods. Such functionality may support more personalized treatment planning and facilitate remote supervision by clinicians, particularly in home-based rehabilitation settings where regular clinical visits may not be feasible.

The Categorize game also illustrates the potential advantages of combining motor assessment with cognitive training within a unified digital environment. Integrating motor and cognitive exercises may improve user engagement while simultaneously expanding the range of behavioural information collected during assessment.

More broadly, the proposed framework demonstrates how serious games can extend conventional clinical assessments beyond simple outcome measures by enabling continuous digital monitoring, richer performance analytics, and scalable deployment through web technologies.

4.9. Summary of Experimental Findings

The experimental evaluation demonstrated that both proposed serious games provide reliable digital representations of the conventional Box and Block Test for assessing fine motor skills.

Strong positive correlations between the conventional BBT and the two digital games indicate that participant performance is preserved across physical and virtual environments, supporting the validity of the proposed assessment framework. In addition, the usability evaluation demonstrated high levels of participant acceptance, intuitive interaction, and sustained engagement, suggesting that the proposed applications are well suited for repeated use in both assessment and rehabilitation scenarios.

The lower performance observed in the Categorize game compared with the conventional and digital Box and Block Tests is likely attributable to its additional cognitive requirements rather than reduced motor capability alone. Unlike the conventional BBT, which primarily evaluates gross manual dexterity through repetitive object transfer, the Categorize game requires participants to identify object shapes, select the appropriate target location, and make rapid decisions while performing the motor task. Consequently, the measured performance reflects an interaction between motor execution and cognitive processes such as attention, visual discrimination, and decision-making. This distinction is particularly relevant for clinical applications. When the primary objective is the assessment of pure motor function, the Digital BBT provides a closer functional analogue to the conventional Box and Block Test. In contrast, the Categorize game may be more suitable for evaluating motor performance under cognitively demanding conditions, thereby offering complementary information regarding functional abilities encountered during activities of daily living.

Although additional validation involving larger participant cohorts and clinical populations is required, the present results provide encouraging evidence that computer vision-based serious games can serve as accessible, low-cost, and scalable tools for digital fine motor assessment. These findings establish a solid foundation for the continued development of intelligent rehabilitation platforms capable of supporting both clinical practice and home-based healthcare. It should be emphasized that the present experimental evaluation was conducted exclusively with healthy adult participants and was designed as a preliminary validation of the proposed assessment framework. Consequently, the reported findings primarily demonstrate the feasibility, usability, and concurrent validity of the proposed digital serious games under controlled experimental conditions. Although the observed correlations with the conventional Box and Block Test are encouraging, the current study does not establish clinical effectiveness or diagnostic validity for individuals with neurological or musculoskeletal impairments.

5. Technical Issues & Usage Recommendations

During the design, development, and evaluation of the proposed digital serious games, several technical challenges and practical considerations were identified. Addressing these

issues is essential to ensure reliable performance, accurate assessment, and a positive user experience, particularly when the applications are deployed in non-controlled environments such as patients' homes.

One of the primary technical challenges relates to the accuracy and robustness of hand detection using a standard webcam. Although the MediaPipe framework provides reliable real-time tracking, its performance can be affected by environmental conditions such as lighting, background complexity, and camera quality. Poor illumination or highly cluttered backgrounds may reduce detection accuracy, leading to incorrect gesture recognition or temporary loss of tracking. To mitigate these issues, it is recommended that users operate the system in well-lit environments with minimal background distractions and position the camera at an appropriate angle and distance to ensure clear visibility of the hand.

Another important consideration is system performance and latency. Since the applications rely on real-time video processing within a web browser, performance may vary depending on the computational capabilities of the user's device. Lower-end systems may experience reduced frame rates or delayed responses, which can negatively impact interaction quality and user engagement. It is therefore advisable to use a midrange or higher-performance computer and a modern web browser optimized for real-time multimedia processing. Additionally, closing unnecessary background applications can help improve system responsiveness.

Gesture recognition reliability also presents certain limitations. The current implementation is based on predefined thresholds and geometric relationships between hand landmarks, which may not fully capture the variability of hand sizes, movement styles, or user-specific motor impairments. This can occasionally result in false positives or missed interactions, particularly for users with limited motor control. Future improvements could incorporate adaptive algorithms or machine learning techniques to better accommodate individual differences and enhance recognition accuracy.

From a usability perspective, user familiarity with the system plays a significant role in performance outcomes. Participants typically require a short familiarization period to understand how to position their hand, perform gestures, and interact with virtual objects effectively. Providing clear on-screen instructions, visual cues, and possibly a brief training session before assessment is recommended to ensure consistent and reliable results.

Network-related factors should also be considered, particularly for systems that store data remotely or are accessed online. While the core functionality of the games operates locally within the browser, saving results and retrieving user data depend on stable internet connectivity. In cases of poor or intermittent connections, delays or failures in data transmission may occur. Implementing local buffering mechanisms and retry strategies can improve reliability in such scenarios.

Finally, from a data management and security standpoint, the use of SHA-256 encryption enhances the protection of user information and performance records. However, it is also important to ensure compliance with relevant data protection regulations and to adopt best practices such as secure communication protocols (e.g., HTTPS), user consent mechanisms, and proper data anonymization when used in clinical or research contexts.

Based on these observations, several usage recommendations can be proposed. Users should ensure appropriate environmental conditions (lighting and background), utilize adequate hardware, and undergo a brief familiarization process before engaging in assessment or training sessions. Clinicians and researchers are encouraged to interpret results in conjunction with traditional assessment methods, particularly in early stages of adoption. By considering these factors, the proposed serious games can be effectively utilized as accessible and practical tools for fine motor skill assessment and rehabilitation.

6. Discussion and Further Development

This paper presented the design, implementation, and evaluation of two digital serious games aimed at assessing and supporting fine motor skills. The proposed systems were developed as accessible, low-cost alternatives to traditional assessment methods, requiring only a standard webcam and a midrange computer while being distributed through web technologies. One of the games closely replicates the logic and procedure of the Box and Block Test (BBT), while the second introduces an alternative interaction paradigm that combines motor activity with cognitive elements.

The primary objective of this experimental study was to investigate whether the proposed digital serious games can provide valid assessments of fine motor skills comparable to those obtained using the conventional Box and Block Test. The statistical analyses presented in the previous sections provide strong evidence supporting this objective. Moreover, testing our digital games with healthy people lays the foundation for extracting normative data which can later serve as measurements for identifying unregular performance.

The correlation analyses demonstrated exceptionally strong positive relationships between the conventional BBT and both proposed digital assessment modalities. Pearson correlation coefficients exceeded 0.93 in every comparison and reached values as high as 0.967, indicating that participant performance in the digital environments closely follows performance measured using the standardized clinical assessment. These findings support both H1 and H2, suggesting that the proposed digital games successfully preserve the behavioural characteristics of manual dexterity evaluated by the conventional BBT.

An important observation is that both digital games reproduced well-established performance patterns associated with manual dexterity. Younger participants consistently achieved higher scores than older participants, while dominant-hand performance exceeded non-dominant-hand performance across all assessment modalities. These findings agree with previously published normative studies of the Box and Block Test and therefore provide additional evidence supporting the construct validity of the proposed digital assessment framework.

Although the Digital BBT and the Categorize game produced lower absolute scores than the conventional BBT, these differences should not be interpreted as reduced assessment accuracy. Unlike the physical BBT, both digital environments rely on computer vision algorithms, virtual object manipulation, and visual feedback presented through a two-dimensional display. The Categorize game additionally introduces cognitive processing through object recognition and decision-making, naturally increasing task complexity. Consequently, absolute performance differences between physical and digital environments are expected. However, because participant rankings remain highly consistent across all assessment modalities, the digital games appear capable of evaluating relative motor performance with high reliability. In addition, the two digital assessments should be viewed as complementary rather than interchangeable, with the Digital BBT serving as the more direct measure of manual dexterity and the Categorize game extending the assessment to include cognitive-motor interaction.

The usability evaluation further supports the practical applicability of the proposed framework. Participants consistently reported that both applications were intuitive, responsive, and enjoyable to use. Particularly noteworthy is the observation that the Categorize game was simultaneously perceived as the most engaging and the most challenging application. This finding suggests that incorporating cognitive components into rehabilitation exercises may increase user motivation while preserving their ability to evaluate fine motor performance. Since long-term rehabilitation success depends heavily on patient adherence, maintaining user engagement represents an important advantage of serious game-based rehabilitation systems.

Overall, the quantitative validation results and the positive usability evaluation indicate that the proposed digital serious games represent promising alternatives to conventional manual dexterity assessment, particularly in scenarios where remote assessment, automated data collection, or home-based rehabilitation are desirable. Nevertheless, these findings should be interpreted within the context of a preliminary validation study and should not be considered evidence of clinical effectiveness in patient populations.

The statistical analyses performed in this study were selected to evaluate the concurrent validity of the proposed digital assessments with respect to the conventional Box and Block Test. Pearson correlation analysis was considered appropriate because the primary objective was to determine whether participant performance rankings were preserved across the conventional and digital assessment modalities. While additional agreement analyses, such as Bland–Altman plots and Intraclass Correlation Coefficients (ICC), could provide complementary information regarding systematic measurement bias, limits of agreement, and reliability, these analyses are generally more informative during later validation stages when larger and more diverse participant cohorts are available and when the objective is to evaluate the interchangeability of measurement methods. Similarly, repeated-measures analysis of variance (ANOVA) could be employed in future studies involving larger cohorts to investigate systematic differences between assessment modalities while accounting for within-subject variability. Consequently, analyses such as Bland–Altman plots, ICC and repeated-measures ANOVA constitute an important direction for future work and will be incorporated in subsequent validation studies involving larger samples and clinical populations.

Beyond assessment, the developed applications also show promise as rehabilitation tools, offering an interactive environment that can motivate users to perform repetitive motor exercises. Their portability and ease of deployment make them particularly suitable for home-based rehabilitation, addressing limitations associated with access to clinical facilities. At the same time, the ability to record and store detailed performance data enables longitudinal monitoring and opens new possibilities for data-driven evaluation of motor recovery.

The gesture recognition strategy adopted in this work intentionally relies on simple geometric relationships between a small number of hand landmarks rather than complex machine learning classifiers. This design choice improves computational efficiency, simplifies deployment within standard web browsers, and facilitates reproducibility across different hardware configurations. Although more sophisticated gesture-recognition approaches could further improve robustness under challenging environmental conditions, the current implementation demonstrated reliable real-time performance throughout the experimental evaluation involving healthy adult participants.

Several directions for further development are identified. Although the proposed platform stores only anonymized assessment results rather than raw video recordings, recent research has shown that human motor behavior and movement patterns may constitute behavioral biometric characteristics capable of supporting user re-identification under certain circumstances. Consequently, protecting fine motor assessment data remains an important consideration for future large-scale telehealth platforms. Future versions of the proposed system will further strengthen privacy protection by incorporating enhanced anonymization techniques, encrypted storage of sensitive assessment records, role-based access control, and compliance with evolving healthcare data protection standards such as the General Data Protection Regulation (GDPR). Similar privacy concerns have been reported in studies demonstrating that behavioral characteristics, including handwriting style, may reveal stable identity-related information even after abstraction of the origi-

nal input, highlighting the importance of protecting movement-derived data in remote assessment systems [30].

Another key enhancement involves the integration of remote monitoring capabilities, allowing medical professionals to create accounts, access user data, and track patient progress over time. This would facilitate more personalized and adaptive rehabilitation programs, as well as improved communication between patients and clinicians. In addition, future versions of the system will explore the use of alternative technologies to improve performance and scalability, such as transitioning from PHP-based back-end services to more efficient runtime environments (e.g., Node.js) and adopting NoSQL databases for handling larger and more flexible datasets.

Further work will also focus on expanding the range of serious games, incorporating new interaction scenarios that target different aspects of motor and cognitive function. The development of mobile-compatible versions is another important goal, enabling broader accessibility through smartphones and tablets.

Vital for our applications is testing with larger groups of healthy people in order to extract normative data. To assess properly the condition of patients we need to be able to specify a scoring range that is considered acceptable for healthy people.

Moreover, extended evaluation studies involving healthcare professionals and patients will be conducted to better understand the clinical applicability of the system and its potential impact on treatment planning and rehabilitation outcomes. We will focus on comprehensive clinical validation of the proposed framework in collaboration with rehabilitation professionals and healthcare institutions. In particular, the system will be evaluated with individuals affected by stroke, Parkinson's disease, multiple sclerosis, cerebral palsy, age-related dexterity decline, and other neurological or musculoskeletal conditions associated with impaired upper-limb motor function. These studies will investigate not only concurrent validity but also test–retest reliability, responsiveness to rehabilitation interventions, and long-term usability in home-based tele-rehabilitation environments. Future validation studies will also incorporate Bland–Altman agreement analysis, together with additional reliability measures such as Intraclass Correlation Coefficients, to further evaluate systematic bias, limits of agreement, and the interchangeability of the proposed digital assessments with the conventional Box and Block Test.

Finally, future research may investigate the integration of adaptive algorithms and machine learning techniques to personalize difficulty levels and improve gesture recognition accuracy, as well as the incorporation of multimodal feedback (e.g., auditory or haptic cues) to enhance user engagement. By addressing these directions, the proposed framework can evolve into a comprehensive platform for digital motor assessment and rehabilitation, contributing to more accessible and effective healthcare solutions.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis Of Variance
AR	Augmented Reality
BBT	The Box and Blocks Test
CI	Confidence Intervals
CSS	Cascading Style Sheets
HTML	Hypertext Markup Language
HTTPS	Hypertext Transfer Protocol Secure
ICC	Intraclass Correlation Coefficients
MySQL	My Structured Query Language
NoSQL	Not only Structured Query Language
SD	Standard Deviation
SHA-256	Secure Hash Algorithm 256-bit
VR	Virtual Reality

Appendix A

Table A1 shows the mean scores of the participants in the experimental study per hand dominance and task, grouped by age and gender, while Table A2 shows the way the answers were distributed at each question of the questionnaire that was given to the participants after executing all given tasks.

Table A1. Testing results in the Real World BBT, the Digital BBT, and the Categorize game.

Age Group	Gender	No of Users	Real World BBT		Digital BBT		Categorize	
			Dominant Hand *	Non-Dominant Hand *	Dominant Hand *	Non-Dominant Hand *	Dominant Hand *	Non-Dominant Hand *
20–35	Male	5	90	87	52	50	42	40
	Female	10	87	83	50	48	41	38
36–55	Male	8	85	82	49	48	40	39
	Female	10	80	77	46	44	37	35
56–70	Male	7	73	70	41	39	34	33
	Female	10	73	71	41	39	33	32

* Mean scores.

Table A2. Questionnaire responses.

Question	No. of Answers (Digital BBT)					No. of Answers (Categorize)				
	5	4	3	2	1	5	4	3	2	1
I quickly understood what I had to do	50	0	0	0	0	50	0	0	0	0
The instructions were clear	50	0	0	0	0	50	0	0	0	0
The game was easy to use	50	0	0	0	0	50	0	0	0	0
The system responded instantly to my actions	43	5	2	0	0	43	5	2	0	0

Table A2. Cont.

Question	No. of Answers (Digital BBT)					No. of Answers (Categorize)				
	5	4	3	2	1	5	4	3	2	1
The movements I made felt natural	50	0	0	0	0	50	0	0	0	0
I made mistakes due to system issues	0	0	0	5	45	0	0	0	5	45
The tasks were physically tiring	0	0	0	7	43	0	0	0	7	43
The tasks were mentally demanding	0	0	0	2	48	0	0	0	6	44
I found the games enjoyable	45	3	2	0	0	45	3	2	0	0
I would be willing to use these games regularly	43	5	2	0	0	43	5	2	0	0
I felt that my performance reflects my real ability	43	4	3	0	0	43	4	3	0	0
Question	Real World BBT					Digital BBT				
Which task did you prefer	5					5				
Which task felt the most difficult	10					5				
Which task was the most engaging	5					5				

Evaluation explanation: 5 = I strongly agree with the statement; 4 = I agree with the statement; 3 = I neither agree nor disagree with the statement; 2 = I disagree with the statement; 1 = I strongly disagree with the statement.

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