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RESEARCH ARTICLE

User Experience of a Serious Game for Physical Rehabilitation Using Wearable Motion Capture Technology

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ABSTRACT This paper presents a wearable motion capture (MoCap)-based serious game (SG) for physical rehabilitation and evaluates its user experience. Conventional physical rehabilitation relies on professional trainers, equipment, and facilities, which are time-consuming and expensive for users. It often reduces the users' motivation to perform exercises. It can be difficult for users to continue their physical rehabilitation through the conventional model. However, recent studies demonstrate that serious games have the potential to improve the effectiveness of rehabilitation training through a more engaged and immersive game design. Most of those studies focus on technology and the development of a specific MoCap sensor-based SG design for users with motor deficiencies, rather than emphasizing the users' experience impacting the effect of performance in physical rehabilitation. This study developed a prototype of a physical rehabilitation exercise game that considers user experience. This game employs a wearable inertial MoCap sensor enabling users to interact intuitively with the game to promote physical activities for health. We analyze and discuss user satisfaction and game experience through user experience questionnaires. The results suggest that most users were satisfied with the SG-based rehabilitation, and found the game was enjoyable and engaging. Based on the implications, we discuss possible future research to improve user experience of the highly accurate real-time MoCap-based serious game. This can enable users with motor disabilities to undertake physical exercises in a home environment.

INDEX TERMS Serious games, motion capture, physical rehabilitation, user experience, usability.

I. INTRODUCTION

In the last decade, motion capture (MoCap) has become a promising tool applied in various contexts, such as healthcare and clinical settings for the diagnosis and treatment of physical ailments [1] industrial settings for entertainment [2], the gaming industry [3], sports training [4], and intangible heritage conservation [5]. In particular, in the healthcare context, MoCap has been widely used in physical rehabilitation that assists people with motor disabilities. People who have motor deficiencies often encounter problems that largely limit their ability to perform daily activities independently. Moreover, these deficits impact their quality of life, level of independence, and even occupational perspective [6], [7]. It has been demonstrated that physical rehabilitation can assist people with motor deficiencies in fully or partially recovering [8]. Physical rehabilitation has become a primary method to treat people with motor deficiencies. Due to the various motor deficiencies (neurological disorder or body injury), physical rehabilitation can be a complex process that utilizes various facilities to correct undesired motion behaviours and meet specific goals. Rehabilitation aims to

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restore or return a patient to a state of optimal functioning in interaction with his environment [9]. This typically involves rigorous exercise routines tailored to the patient's needs, whether for musculoskeletal or neuromuscular rehabilitation [10]. These activities usually require a professional therapist to monitor the patients' exercise and provide an assessment of the progress at the end of the training [11]. The process of standard physical rehabilitation typically happens in clinical settings. Considering the inconvenience of travel and time costs, however, patients do not periodically visit healthcare clinics to train and monitor their motor flexibility. Only 31% of patients with motor disabilities regularly exercise [12]. Obviously, lack of motivation is a major barrier to patients performing exercise routinely [13]. Other issues of standard physical rehabilitation include an insufficient number of exercises in therapy sessions [14]. Given the ongoing COVID-19 pandemic, furthermore, the situation has become worse, and the development of home-based rehabilitation is necessary.

Much research demonstrates that a MoCap-based serious game (SGs) has the potential to offer a rehabilitation tool to address these issues [15]. Firstly, MoCap-based SGs allow users to have physical exercise at home for safe non-contact rehabilitation. Secondly, users can have free interaction with full-body 3D motion capture in a natural interactive interface. Different from the Graphic User Interface (GUI), which adopts a mouse and keyboard to interact with a computer system, the Natural User Interface (NUI) adopts cameras or sensors to capture human body gestures interacting with the computer [16]. The NUI allows users to be more engaged and motivated during physical exercises, which can effectively promote rehabilitation. Lastly, the enjoyment of a game could attract users and reduce boredom during rehabilitation [17].

Recent research focuses on the hardware and software of motion capture technology for developing various MoCap devices. Two types of MoCap device have been developed for physical rehabilitation. One is an inertial measurement unit (IMU), which is a wearable sensor-based device and another is a camera-based device [18]. Another is a markerless camera-based device, such as the Microsoft Kinect sensor that has been widely used in rehabilitation-related training or exercises for patients with motor disabilities. Despite its cost-effective, affordable, and flexible method enabling it to become an important tool to improve training performance [19], using a Kinect-based game system for physical rehabilitation has certain limitations. One of the key issues is that tracking with the Kinect sensor is not precise enough to be completely reliable, which causes some problems when interacting with games and produces an incorrect outcome [20]. However, a wearable MoCap system with an IMU sensor has high accuracy that can accurately estimate angles at a higher degree of precision [21]. This wearable MoCap system is also a portable, affordable device with interactive functionality.

Although the wearable MoCap system brings a new perspective to physical rehabilitation, most recent studies only focus on technological applications and methodologies for specific purposes, such as elderly care and stroke rehabilitation [22], [23]. There is little research on user experience of the wearable MoCap system, and it is still unclear how satisfactory users' experience of the wearable MoCap system is for physical rehabilitation. Furthermore, a MoCap-based SG provides users an enjoyable experience, an aspect that has been ignored in studies [24]. A well-designed study of user experience demonstrating objective benefits is required to demonstrate the applicability of MoCap in physical rehabilitation.

A review study of physical rehabilitation using MoCap systems indicates that 42% of motion capture systems reported in the MoCap rehabilitation research used IMUs [25]. Thus, considering its high accuracy and potential, IMU suits were used as a motion capture tool in the design of our SGs.

This study aims to investigate the user experience of wearable MoCap-based SGs as a robust tool for physical rehabilitation. We first designed a wearable MoCap-based SG and then assessed user experience of enjoyment and game usability quantitatively. The study aims to provide objective evaluations of how wearable MoCap SGs could help improve the outcomes of physical rehabilitation. This study has made significant contributions to research areas in MoCap-based games and physical rehabilitation by adding a dimension of user experience studies. It has offered objective guidelines for home-based rehabilitation practice, enhancing its overall impact.

II. RELATED WORKS

This section explores current research on wearable MoCap-based serious games and provides an overview of related studies on physical rehabilitation using MoCap sensors. It addresses the issues of user experience of MoCap and how seriously the game facilitates the improvement of physical rehabilitation.

A. WEARABLE MOCAP-BASED RESEARCH

Motion capture is a process of digitally tracking and recording the movement of a human body in a given space of time [26]. It often employs an outfit or similar apparatus fitted on users. The suit has markers that are determined by sensors, cables, or a series of cameras previously prepared for this function [27]. The reference points pick up and map the body of the users, scanning this data to translate their movements into a virtual body. Specific software is available to triangulate the points raised and reconstruct the body movement digitally [28]. A previous study underscores the benefit of MoCap technology in physical rehabilitation work through an unprecedented analysis of how a patient performed his movements and where he exerted more strength to identify points in the body where a workload is happening [29].

Various MoCap sensors or devices have been developed since was the first successful application of MoCap technology in the 1980s [30]. These include magnetic, mechanical and optical sensors, with optical further divided into passive, active, and marker-less systems [31]. Except in the marker-less system, these systems require a user to wear either a suit with sensors or markers on the person's body. Wearable MoCap sensors were first used for physical rehabilitation research; however, most of these studies focus on technological development, new methodology, monitoring, and measurement for effects and accuracy of rehabilitation. Many studies adopt novel interactive motion capture technology for normal stroke care rehabilitation [32], [33], [34]. The results from these studies indicate that MoCap technology can effectively improve inpatients' post-stroke produced function, which was similar to the results of normal stroke rehabilitation. Furthermore, some studies focus on physical rehabilitation to prevent or treat musculoskeletal-type injuries along with physical rehabilitation enhancement [35]. They utilize inertial motion tracking sensors incorporated in a wearable body suit. The results demonstrate that the system has the potential to help an athlete stay updated on biodata to analyze their exercise performance [36]. Additionally, Mirabella et al. present a MoCap system consisting of a few MEMS inertial sensors, for accurate measurement of a user's arm. This study suggests the value of using MoCap in training and rehabilitation [37]. More recently, an Android-based image sensor, the Nively MentorAge, has been used to assess the movement of patients with Parkinson's disease [38]. It captures the patients' physical motion and provides an interface for recording and analyzing their body posture and gestures while they play a game. Nonetheless, it lacks an emphasis on user experience of physical rehabilitation through wearable MoCap sensors.

Most of the studies that explore user experience utilize marker-less camera-based game devices, such as Microsoft Kinect, Nintendo Wii, and PlayStation [39]. In particular, Kinect has demonstrated the potential to create an enjoyable setting for physical activity in previous research [40]. For example, some studies highlight the use of Kinect to train people recovering from minor upper limb burns [40]. These studies indicate that Kinect can effectively enhance rehabilitation and users' satisfaction, resulting in a more positive rehabilitation outcome compared to conventional physiotherapy [41]. Some studies, moreover, focus on the elderly population. Sáenz-de-Urturi et al. evaluate elders' experience of computer usability through Kinect-based games [42]. The study demonstrates that the elderly can engage with the game and reports a willingness among older users to engage with the Kinect system at home. Pedraza-Hueso et al. outline a serious game combining Kinect and virtual reality for physical and cognitive rehabilitation therapies [15]. During the exercise programme, patients were monitored and received feedback in real-time, so they knew if they performed the exercises correctly. Existing studies show that using MoCap technology for physical rehabilitation can lead to remarkable outcomes if integrated with serious games.

B. SERIOUS GAMES AND PHYSICAL REHABILITATION

Serious games are distinguished from entertainment-focused goal games based on goals and objectives [43]. The objective of a serious game is not associated with entertainment but with education, as they are often linked to perceptual, cognitive, behavioural, affective, and motivational development and result in knowledge acquisition or understanding [44]. SGs have been shown to have a positive impact on the development of personal skills through the use of a natural user interface, for example, in health care and physical rehabilitation. This particular type of game has been described as "edutainment", which is education through entertainment [45]. Corti suggests that SGs are about leveraging the power of video games to captivate and engage users for the specific purpose of developing new skills [46]. Ritterfeld et al. [47] define serious games as "any form of interactive computer-based game software for one or multiple players to be used on any platform and that has been developed with the intention to be more than entertainment" (p. 6). One advantage of SGs is that they simulate users' body mobility through a series of exercises. The players of SGs acquire skills by overcoming serious challenges related to real-world situations, such as physical therapy programmes [48]. This type of SG focuses is designed for exercise, training, simulation, education, or solving real-life problems through a game approach that runs on a computer or game console [49]. This approach can effectively improve exercise action performance [50]. Furthermore, this type of SG refers to "exergames" (exercise games) that are particularly useful in the training of physical rehabilitation, providing an immersive experience for the improvement of users' physical and cognitive functions. In addition to providing an enjoyable experience, a serious game has always a practical goal. The design of a serious game needs to carefully connect both aspects so that the resulting game is both enjoyable and meaningful.

Compared with conventional physical rehabilitation, SG-based rehabilitation can create engagement and enjoyment during the playing of the game [51]. SG-based rehabilitation depends on various game elements including competition, chance, role play, rules, goals, interactivity, and story [52]. Those elements can motivate players during a game [53]. According to Mildner and Florian Mueller, when SGs are used as a tool, they can provide "an extrinsic motivation to players who do not have an intrinsic motivation to engage with a topic otherwise" (p. 60). In the conventional mode of physical rehabilitation, patients may not have a high intrinsic motivation to exercise to improve their condition. However, they might be interested in playing a game in which they can compete against other players or virtual avatars. This is extrinsic motivation, in which the game is considered a tool to help players accomplish a goal. Prensky [54] argues that enjoyment in a game experience refers to being engaged. This also suggests that fun is a crucial part of learning, as it provides a relaxed atmosphere for active learning [55].

Fun is considered essential for most games, and it can largely promote the central objectives of a serious game [56].

Recent studies point to the trend of developing MoCap-based SGs for physical rehabilitation purposes. Combining MoCap technologies with SGs can create more engagement and enjoyment for users through a natural human-computer interface rather than using a mouse and keyboard. Applying these technologies to physical exercise programmes can facilitate the development of body mobilization skills. In fact, however, there is little research on how users experience MoCap-based games including the characteristics of playability, engagement, and enjoyment. In this study, user experiences of a serious game are analyzed with the aim of providing a positive game experience. We adopted a wearable MoCap suit with embedded sensors to develop a serious game "Dungeon Quest Adventure" for the purpose of promoting therapeutic exercises while having fun. The game was designed for pervasive physical rehabilitation, which includes post-stroke conditions, motor disabilities, and upper limb motor problems. Wearable MoCap is a non-visual tracking system that allows users to interact without an intermediary device such as a game controller. It provides users with great advantages and new experiences that conventional approaches to physical therapy cannot achieve. The wearable MoCap-based SG aims to provide individuals who have experienced motion deficiencies rehabilitation exercises. The objectives of the SG emphasized improving the performance of rehabilitation exercises by making them more enjoyable and enhancing the user's experience.

III. METHODS

The game system developed for this research adopted a Noitom wearable MoCap device connected to a PC with a large LCD screen. It is based on inertial measurement units (IMUs) with a natural user interface (NUI) using the Windows operating system. This wearable MoCap captures users' body movements in a 3D environment conducive to interaction. The system uses the participant's body as a game controller interactive within the 3D environment. The game can track multiple users simultaneously in real-time.

A. PARTICIPANTS

We consulted an occupational therapist for suggestion when selecting participants in this study. The participants were selected based on a set of eligibility criteria: the cognitive ability to understand the game and the instructions from the physiotherapists; basic physical conditions with minimum movement in either both arms or one arm. The detailed selection criteria for participants are presented in Table 1. Twenty-five participants (15 men and 10 women) aged between 25 and 50 (M = 35.52, SD = 8.07) were recruited for this study. The Mini Mental Status Examination (MMSE) was used for measuring participants' cognitive impairment. The score of MMSE (M = 28.27, SD = 2.54) indicated that all participants had a normal mental state. Most of the participants had limited experience with computer games. Eight participants had previous experience with game consoles, such as Kinect and Wii. None had previous experience with wearable MoCap suits. Seventeen participants had musculoskeletal injuries, while eight participants reported experiencing chronic pain in their arms.

TABLE 1. Inclusion and exclusion criteria for selecting participants.

Inclusion	Exclusion
-18 years and above -Motion deficiencies with limited mobility in either arm. - Ability to stand with normal lower limb function or with assistance. - Basic literacy.	-Participants with existing cognitive impairment (MMSE scores less than 25) -Visual or hearing impairment -Currently in some treatment -Other medical condition, such as cardiovascular or respiratory conditions -Participants with serious disorder or motion issues

B. DESIGN PROCEDURE

All participants were asked to sign a consent form before the study. The testing was located at a university lab in Shanghai, China. After the test, all participants needed to complete questionnaires. The game had three levels with different tasks that were easy, moderate, and difficult. Each participant took part in a game and passed three levels during a session. Three sessions were held on different days, and the whole testing process was completed in one week. Before participants played the game, they were provided explanations and instructions on the game tasks and what they needed to do during the session. Subsequently, the participants were given assistance with the MoCap suits. It is crucial to allow the participants to become familiar with the MoCap system. A physiotherapist was available to assist them when needed. Researchers provided questionnaires after the participants completed the game.

C. GAME DESIGN

The game was developed using the Unreal Engine 4 (UE4) game engine combined with Axis Neuron Pro software to record the participants' body motion data in a virtual environment. The approach aimed to assign participants to undertake specific exercises by analyzing their movement performance and providing evaluation of their experience of playing the game. This study adopted UE4 to create game modules and game rules. The rules of the game were designed to require participants to collect golden coins flying from the front to enhance their upper limb rehabilitation (upper limb horizontal abduction, shoulder abduction 90°) at the optimal level to develop strength (Figure. 1). In this study, we emphasized upper extremity rehabilitation exercises, which were based on Brunnstrom's upper limb function. Upper extremity rehabilitation is a common treatment and intervention for many people who have suffered from strokes, hemiparesis, and other conditions. Clinical research demonstrates that physical rehabilitation can assist people with motor deficiencies in

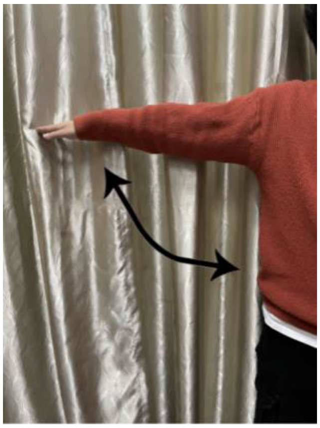

FIGURE 1. A participant is trying to perform an upper limb exercise with his shoulder at a 90° abduction.

fully or partially recovering [57]. Brunnstrom's approach to rehabilitation involves the use of reflexes to develop movement behavior via functional retraining to enhance movement control [58]. Three different exercises were possible during the playing of the game: right upper limb, left upper limb, or both upper limbs. Although Brunnstrom's scale was mainly used for stroke rehabilitation, it can be applied to improving general physical health [59].

The scene of the game ''Dungeon Quest Adventure'' was a virtual underground castle, similar to a medieval castle, featuring 3D elements such as skeletons, statues, and torches (Figure. 2). It was designed with an adventure-oriented approach aimed at capturing users' attention and providing an immersive experience. The dungeon was designed to be as realistic as possible to create an immersive, mysterious atmosphere to inspire an experience of engagement for the players. The game encouraged players to explore the mythical world and attracted them to play the game. The avatar was designed as a knight-errant that challenged the user to complete tasks. The movements of players were transferred to the knight-errant in the game (Figure. 3). The left image of Figure. 3 shows a player wearing MoCap; the middle image depicts a model created with Axis Neuron Pro software while the right image features the avatar created by MotionBuilder software. The movement of the subject mapped instantaneously to the avatars. Thus, the players could immediately see how the avatar played every move they made. This encouraged the mobility of players during the exercises. For players who had limited mobility in either arm, the game was configured in a way that allowed players to choose to play the game with their left or right arm.

Figure 4 shows a participant playing the game showing the time the player took, an energy bar, life, and tasks displayed on the screen. There are three objects: a golden coin, a flying axe, and a heart. The golden coin represents energy, the flying axe represents life reduction, and the heart represents health. In the game, players use their arms to collect flying golden coins to gain energy and lower their arms to avoid touching the flying axe that can harm the avatar. Figure 5 depicts these objects. The energy bar in the game is very important, as it decides if the game will move to the next level. The player needs to concentrate on the flying objects and attempts to collect as many golden coins as possible. Each time the player collects a golden coin, the player's energy grows until becoming full. When the energy is full, the task is achieved, and the players move to the next level. When the axe is flying overhead, the players need to lower their upper limbs to avoid being hit. If they are hit, the health bar becomes smaller. When the health bar is empty, the player fails and

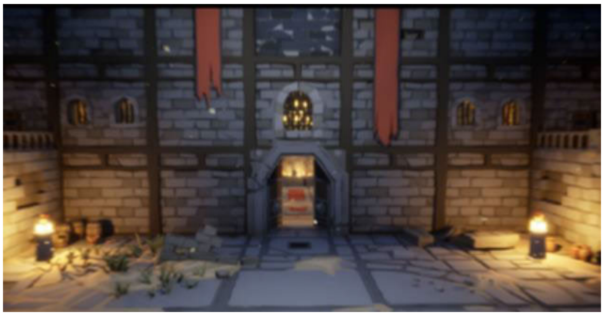

FIGURE 2. A screenshot of the game showing the game environment.

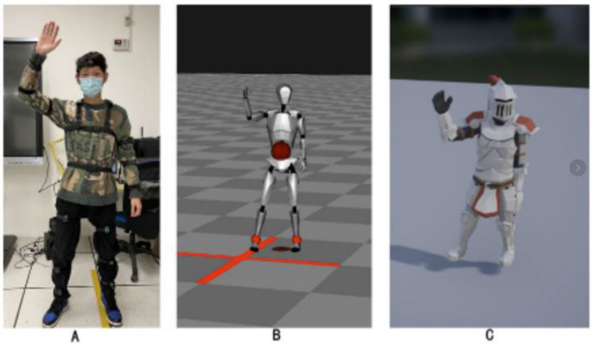

FIGURE 3. Excerpt from the rehabilitation game "Dungeon Quest Adventure". (A) A player wearing a MoCap suit to play the game. (B) The avatar is shown in the Axis Neuron Pro software. (C) The avatar with game costume in MotionBuilder software.

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FIGURE 4. The screenshot displays the game interface and environment as a player attempts to collect a flying golden coin. The timer at the top of the screen indicates the duration of the game. Additionally, two bars located at the top left represent the player's life and energy levels. The objectives are displayed on the left side of the screen, which involve avoiding axe attacks and collecting the golden coins to escape from the dungeon.

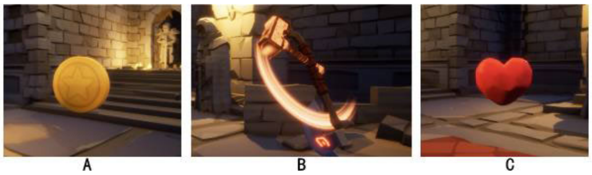

FIGURE 5. The screenshot from the game shows the objects of a golden coin (A); a flying axe (B) and a heart (C).

the game needs to be restarted. Hearts are used to restore health, preserving the players' vitality and allowing the game to continue.

The game has a total of three different levels of two minutes for each level. The design aims to avoid player fatigue during training. However, the time for each player varies depending on how fast they collect golden coins. The first level is easy because the speed of flying objects is very slow. This can help players familiarize themselves with the game rules and begin to exercise slowly. In the first level, the objects follow a horizontal path. In the second level, the objects follow a horizontal angle that is slightly different from the first level. The third level has a faster speed with a different angle. The players need to focus on the flying objects and distinguish the objects to collect, from those to avoid. This design aims to enhance their sense of immersion and cognitive engagement, characteristics highlighted by Hookham and Nesbitt [60]. After finishing the three levels, the players receive a medal as a final reward. Figure 6 shows the architecture of this game element.

IV. RESULTS AND DISCUSSION

A. GAME USABILITY

The study adopted a system usability scale (SUS) to evaluate game usability [61]. The scale consists of ten items. In this study, the scale is altered by replacing the word "system" with "game system" and "use" with "play." It adopted a 5-point Likert Scale for the evaluation with the scores from 0 to 100. The SUS was applied to assess game usability after participants played the game for three sessions. The participants were asked to complete the SUS questionnaires immediately after the game sessions. The scores of the first session were good (M = 74.24, SD = 3.15); those of the second session were also good (M = 75.8, SD = 3.5) similar to the first one. The third session had the highest score (M = 88.60, SD = 2.79). The scores indicated the game usability was good.

Apart from the SUS questionnaires, we also evaluated usability according to the following four criteria: user satisfaction, task completion time, the experience of MoCap-based SG, and the feeling of wearing MoCap suits. Except for the SUS score, this study classified the ratings into three levels of satisfaction including dissatisfaction (poor or worse), neutral (ok), and satisfaction (good or better) scores [62]. Table 2 summarizes the results of the experiment. The table indicates that the three sessions improved overall user satisfaction with a mean score of over 60%, indicating that user satisfaction was good [63]. The SUS score increased between sessions, and then we performed a post-hoc test. We found that the mean difference was significant ($p < 0.05$). Furthermore, most of the participants reported that they were satisfied with their gaming experience. A comparison between dissatisfaction and satisfaction reflected a significant difference (from 20% dissatisfaction in S1 to 8% in S3 and from 48% satisfaction in S1 to 64% in S3). This result suggests that overall the participants were satisfied with the physical game exercises. We assume that this may be due to the fact that the game is enjoyable, relaxing, and reduces the monotony of regularly repeating prescribed exercises. Thus, adopting the wearable MoCap-based SG may positively add benefit to rehabilitation for the patients.

TABLE 2. Results of a user satisfaction assessment measured with SUS.

Sessions	N	Mean (SD)	Dis		Neu		Sat	
			N	%	N	%	N	%
S1	25	72.91(8.69)	5	20	8	32	12	48
S2	25	76.79(9.67)	4	16	6	24	15	60
S3	25	83.26(5.31)	2	8	7	28	16	64

Dis: dissatisfaction, Neu: neutral, Sat: satisfaction

1) TASK COMPLETION TIME

For a further evaluation of the benefits of the "Dungeon Quest Adventure" game for physical rehabilitation, this study investigated the time a participant took to complete tasks using the wearable MoCap. Firstly, we allowed the participants to finish the game and recorded the completion time. Then we compared task completion time with satisfaction regarding the MoCap suits to determine if there was a correlation. The duration of the game was two minutes. Most of the players completed the game within two minutes. The score for the first session was (M=1.624, SD=0.24); the score for the second session was (M=1.71, SD=0.21); and the score for the third session was (M=1.78, SD=0.15). The mean score of the three sessions was (M=1.70, SD=2.15). A Pearson's correlation test was used to determine if there was a correlation between task completion time and satisfaction. The results indicated that there was a significant difference between users' satisfaction with playing games and the time to complete the tasks ($p = 0.00$). We also analyzed and compared the average task completion time between men and women using an unpaired t-test. The results demonstrated that there was significant difference ($p < 0.05$) (Table 3). This result suggests that higher satisfaction leads to more time being taken to complete the game. This could be because MoCap-based gameplay was enjoyable and engaging, which ultimately increased participants' motivation to play the game. This increased enjoyment and engagement motivated players to perform exercises. The results also show that female participants spent more time to complete game than male participants.

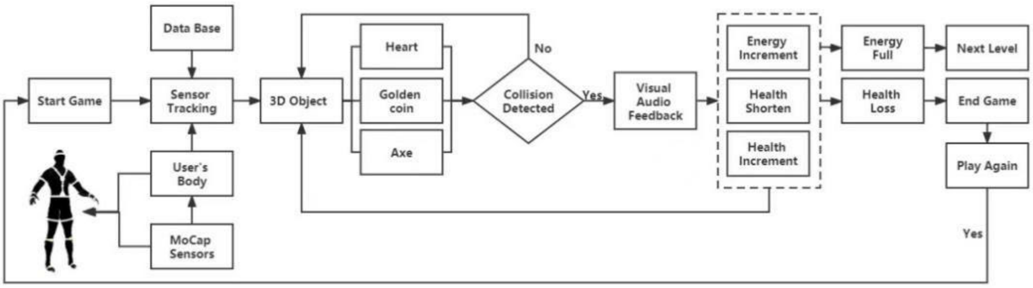

FIGURE 6. An overview of the game architecture.

TABLE 3. Task time for game completion between men and women.

	F	Sig.	t	df	Sig. (2-tailed)	Mean Differ	Std. Error Difference
Equal variances assumed	0.11	0.73	3.17	23	0.004	0.141	0.0466
Equal variances not assumed			2.97	15.3	0.009	0.141	0.04758

2) USERS' EXPERIENCE OF MOCAP-BASED SG

As a serious game provides an enjoyable method of training for physical rehabilitation, it is critical to understand whether the players realize they are actually exercising while they are playing a game using a wearable MoCap suit. To investigate the correlation between the physical exercises they performed in the game and awareness of the exercise they were performing while playing, the participants were asked to rate the overall level of physical exercise during the game sessions. Meanwhile, the participants' awareness level was assessed in order to evaluate if they were aware of the exercise they performed while playing the game. The evaluation used a seven-point Likert scale to assess the level of physical exercise. The questionnaire regarding the level of awareness ranged from number 1 for 'not aware', number 4 for 'moderately aware' and number 7 for 'extremely aware'. The 'moderately' level indicated they were 'fairly aware'. The results from the questionnaire demonstrate that the physical exercise score was moderate (M=5.50, SD=0.74), and the awareness score was (M=2.14, SD=0.92). The results highlight that the participants had a low level of awareness of the exercise they were doing while playing the game. We also applied a Pearson correlation test to see if there was a significant difference between the exercise and awareness scores. The results indicate there is no significant correlation ($p = 0.902$).

3) USERS' EXPERIENCE OF WEARABLE MOCAP SUITS

In addition, the participants were requested to rate the experience level of the MoCap suits they were wearing while playing. In this study, we attempted to investigate if wearable MoCap suits affected the performance of the physical rehabilitation exercises. The rating scale was a seven-point Likert scale, in which number 1 refers to 'no effect', number 4 is 'moderate', and number 7 is 'strong effect'. The results of these questionnaires indicate that there was little feeling of effect about the suits they wore while playing the game (M=1.88, SD=0.94). No significant correlation was found between the physical exercises and the experience level of the wearable suits ($p = 0.469$). Previous studies point out that one of the disadvantages of using wearable MoCap suits is the time spent wearing the suits, which could cause users discomfort and inconvenience in long-term rehabilitation contexts [64]. In this study, we recorded the time (minutes) spent wearing suits for each participant in the three sessions. One-way ANOVA was used to analyze the results. The time wearing the suits in the first session (M=18.08, SD=1.80) was more than in the third session (M=11.28, SD=2.18). The results indicate there was a significant difference between the first session and the third session in time spent wearing the suits ($p < 0.05$). Figure 7 indicates the difference between session 1 and session 3. This suggests that the time wearing the MoCap sensors can be significantly less than the normal time in long term training. Through our observation, the time wearing the MoCap suits was variable, depending on the individuals and the environment. The results show that the wearable MoCap suits themselves did not greatly influence the performance of physical rehabilitation. In terms of user experience, this implies that a wearable MoCap system based on inertial sensors has a comparable performance to camera-based systems, such as Microsoft Kinect. The result accords with Milosevic, Leardini, and Farella's research, which indicates that wearable inertial sensors and Kinect have similar performances for motor rehabilitation [65].

In addition, the participants rated their opinion as to whether the MoCap suits were inconvenient to use during physical rehabilitation. A five-point Likert scale was used for this survey. Most of the participants reported moderate inconvenience (M=3.84, SD = 0.8), and they could accept the time spent wearing the MoCap suits. Our results suggest that using wearable MoCap suits for rehabilitation did not cause users inconvenience and discomfort, which is contrary to other research findings, such as a study by Chang et al. [64].

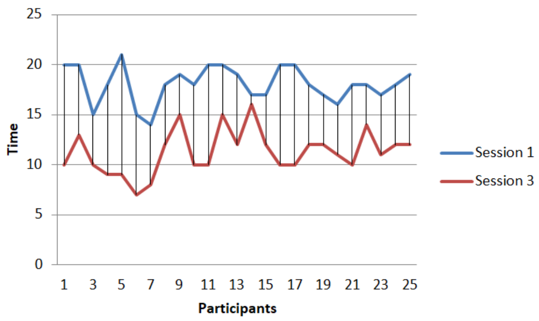

FIGURE 7. **The diagram illustrates the duration for which participants wore the MoCap suits between the first and third sessions.**

Moreover, the participants were asked to rate their feeling about wearing MoCap suits during the gameplay. As this study attempted to assess the user experience of the wearable MoCap-based serious game for physical rehabilitation, it was important to assess whether the participants were aware of the exercises they performed while wearing the MoCap suit. In other words, we were interested in whether or not the participants experienced discomfort during the training due to wearing the suits. The rating scale was a seven-point Likert scale, in which number 1 represents "not at all", number 4 represents "moderate" and number 7 is "extreme discomfort". The results of the questionnaire indicate that participants in the physical exercise programme experienced nominal feelings of wearing the suit (M=2.26, SD=1.08). This could be because players experienced "flow" during the playing. The concept of flow signifies the feeling of complete and energized focus on an activity, with a high level of enjoyment and achievement [66]. This suggests that the level of the players' focus maximizes their performance in and pleasurable feeling from playing, during which players lose track of their worries [67]. This also indicates that participants had an experience of pleasure while gaming.

Overall, when participants played the game, they experienced little awareness of the exercises and few were overly self-conscious of the suits they were wearing. This result suggests that the wearable MoCap did not impact the performance of the physical exercises, and the system may provide a user experience comparable to marker-less MoCap devices. However, comparing user experience between a wearable MoCap and Kinect requires further investigation. Our findings suggest that a wearable MoCap system can be utilized as a dependable tool for home rehabilitation. Aside from those studies, we also conducted a gaming player experience study which is detailed in the following section.

B. GAMING PLAYER EXPERIENCE

In the past decade, user experience has become a dynamic research area in entertainment media such as video games. However, standard usability testing is not enough for testing games because its metrics, such as effectiveness measured by task completion or efficiency measured by error rate, do not map directly to game evaluation [68]. According to Wiemeyer, Nacke and Moser, the evaluation of a game needs to have a strong focus on the players. Thus measuring and understanding player experience (PE) has become key to studies of gaming users. This study adopted the core element of the gaming experience model to understand PE for serious games [69]. In this study, we used the Core Element of the Gaming Experience Questionnaire to evaluate players' experience. Calvillo-Gámez et al. similarly developed a questionnaire for gaming experience. It has 10 scales: Enjoyment, Frustration, CEGE, Puppetry, Video-game, Control, Facilitators, Ownership, Environment, and Game-play [70]. Our questionnaire model includes 38 items with a 7-point Likert scale. The outcome of user experience shows that participants were very positive about the game with an average score of (M = 6.32, SD = 0.94). Most of the participants said that they enjoyed the game and their score (M=6.52, SD = 0.66) out of a maximum score of 21. However, most of the participants indicated that they did not experience frustration while gaming, and the average Frustration score was (M = 1.41, SD = 0.6) out of a maximum score of 14. For the video game, the average Video-game score was (M = 5.14, SD = 1.15). Moreover, participants stated that they were in control of the game with an average Control score of (M= 6.23, SD=0.85).

The results indicate that the scores for the Video-game and Enjoyment scales were positive and encouraging. The overall results of PE were encouraging, as they showed that most participants rated the game as challenging and fun. When comparing male and female participants, male participants considered the game to be easy. Aches and fatigue were significant barriers to recovery. However, the findings indicate that there is no evidence that wearable MoCap-based exercises cause aches or fatigue after movement. The majority of participants reported not experiencing aches or fatigue in their arms after each session. This may be attributed to the gameplay we designed within a reasonable timeframe. However, if the duration of the gameplay is increased, the level of aches and fatigue experienced by the participants may also increase. This finding implies that customized games should be used for rehabilitation instead of commercial games. This issue requires further investigation utilizing appropriate measurement methods in the specific patients.

This study aimed to evaluate the user experience of using a wearable motion capture (MoCap)-based serious game in order to enhance the effectiveness of physical rehabilitation. We assessed the user experience using the System Usability Scale (SUS) test and the Core Elements of the Gaming Experience Questionnaire. These findings can potentially be utilized in the creation of the MoCap-based serious games for home based rehabilitation of various motor deficiencies. This study focused on patients with upper limb issues. The results suggest that the wearable Motion Capture-based serious game could potentially be applied to other types of motor deficiencies in the upper extremity.

The qualitative results of this study indicate potential clinical applications for patients with motor disabilities in the future. Our findings indicate that completing rehabilitation at home is comparable to undergoing rehabilitation as an inpatient or at a clinic. Although remote rehabilitation for motor disabilities has not been extensively explored, our studies provide support for the potential use of a wearable MoCap system in enhancing the effectiveness of home-based rehabilitation.

C. LIMITATIONS AND FUTURE STUDIES

This study employed an inertial measurement unit for serious game design which may be a limitation. Other commercial devices should be explored for a more comprehensive understanding of users' experience across different platforms. This is one avenue for further research.

Future studies should investigate physiological measures of galvanic skin response, heart rate, and other variables for testing user experiences. Adopting a biometric approach has the benefit of increased accuracy in recording information without disturbing the player. In addition, user experience across different motion capture platforms will need to be compared and evaluated. It will help researchers and physiotherapists to have better knowledge of different rehabilitation tools. Future studies, moreover, should adopt a more accurate wearable MoCap system measuring"flow" and immersion experience. The aim of subsequent research should be to enable players to achieve a strong feeling of presence in game environments, allowing users to realize a higher level of physical rehabilitation.

V. CONCLUSION

This study introduced a serious game that utilizes a wearable MoCap system, along with an integrated user experience evaluation component within the process. The results from the study were encouraging and suggested a high game performance. The results from the study have the following contributions. (1) The findings demonstrate that wearable MoCap-based serious games have the potential to become a useful tool for improving physical rehabilitation and aiding patient recovery. (2) The use of wearable MoCap-based serious games improved users' satisfaction during upper limb exercises, making the gameplay more enjoyable and engaging. (3) The wearable MoCap-based game had positive effects on patients' attention and enhanced motivation, leading to improvements in upper limb performance. (4) Serious games using wearable MoCap technology in physical rehabilitation provide an immersive and enjoyable experience, which may enhance the effectiveness of the exercises. (5) A wearable MoCap suit performs similarly to other marker-less camera-based game devices for motor rehabilitation. (6) The wearable MoCap may not cause users' inconvenience and discomfort during the exercises. The participants in this study were interested in the gameplay and indicated a willingness to use it in their home environment in the future.

ETHICAL STATEMENT

This study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Shanghai University of Engineering Science (EST-2023-017).

APPENDIX

Questionnaires of system usability scale (SUS)

1. I think that I would like to play this game frequently.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

2. I found the game unnecessarily complex.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

3. I thought the game was easy to play.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

4. I think that I would like the support of a technical person to be able to use this game.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

5. I found the various functions in the game were well integrated.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

6. I thought there was too much inconsistency in this game.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

7. I imagine that most people would learn to use this game very quickly.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

8. I found the game very awkward to use.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

9. I felt very confident playing the game.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

10. I needed to learn a lot of things before I could get going with this game.

Strongly Disagree				Strongly Agree
☐	☐	☐	☐	☐
1	2	3	4	5

I am aware that the game I am playing is actually an exercise.

not awareness **moderate** **extreme**
○ ○ ○ ○ ○ ○ ○

I feel uncomfortable playing the game while wearing a MoCap suit.

strongly Disagree **agree** **strongly Agree**
○ ○ ○ ○ ○ ○ ○

I think that I would like to use the MoCap suit to play the game again.

strongly Disagree **agree** **strongly Agree**
○ ○ ○ ○ ○ ○ ○

The Core Element of the Gaming Experience Questionnaire

1. I enjoyed playing the game
2. I was frustrated at the end of the game
3. I was frustrated whilst playing the game
4. I liked the game
5. I would play this game again
6. I was in control of the game
7. The controllers responded as I expected
8. I remember the actions the controllers performed
9. I was able to see in the screen everything I needed during the game
10. The point of view of the game is that I had spoiled my gaming
11. I knew what I was supposed to do to win the game
12. There was a time when I was doing nothing in the game
13. I liked the way the game looked
14. The graphics of the game were plain
15. I do not like this type of game
16. I like to spend a lot of time playing this game
17. I got bored playing this game
18. I usually do not choose this type of game
19. I did not have a strategy to win the game
20. The game kept constantly motivating me to keep playing
21. I felt what was happening in the game was my own doing
22. I challenged myself even if the game did not require it
23. I played with my own rules
24. I felt guilty for the actions in the game
25. I knew how to manipulate the game to move forward
26. The graphics were appropriate for the type of game
27. The sound effects of the game were appropriate
28. I did not like the music of the game
29. The graphics of the game were related to the scenario
30. The graphics and sound effects of the game were related
31. The sound of the game affected the way I was playing
32. The game was unfair
33. I understood the rules of the game
34. The game was challenging
35. The game was difficult
36. The scenario of the game was interesting
37. I did not like the scenario of the game
38. I knew all the actions that could be performed in the game.

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