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DESIGNING FOR REHABILITATION MOVEMENT RECOGNITION AND MEASUREMENT IN VIRTUAL REALITY

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ABSTRACT

Virtual reality (VR)-based rehabilitation has been widely implemented to maintain and increase patient motivation during therapy sessions. Researchers nowadays design VR-based rehabilitation by leveraging off-the-shelf VR devices for easy access and application. However, researchers need to implement additional custom hardware or incorporate a specific algorithm to perform a real-time evaluation of each therapeutic movement. This study aims to design and develop a system with features for recognizing and measuring the upper limb rehabilitation movement in VR using off-the-shelf VR devices such as VR headsets, controllers, and trackers. This system is bundled and distributed as a single toolkit to accommodate other researchers in providing the evaluation feature for their VR-based rehabilitation system. The user experiment was conducted to verify the usability of this proposed design system. The experiment results show that the system can recognize 16 upper limb movements and provide several measurement data that researchers can use in providing the evaluation feature based on their design requirements.

Keywords: Virtual reality, Innovation, Evaluation, Rehabilitation, Toolkit

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1 INTRODUCTION

Rehabilitation is defined as "a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions in interaction with their environment" (World Health Organization, 2019). Following this definition, researchers have proposed multiple healthcare interventions to aid in rehabilitation, including virtual reality (VR) technology (Georgiev et al., 2021). With the rapid development of VR devices, the trend of utilizing VR-based interventions for healthcare has gained significant attention among researchers. In this sense, VR technology has been implemented for several therapy purposes, such as to treat a mental disorder (Georgieva and Georgiev, 2022) or physical disability (Lee et al., 2020). A prior study focusing on implementing VR in physical rehabilitation has demonstrated a positive impact, particularly in improving patients' motivation during rehabilitation (Huang et al., 2019).

However, despite the many existing VR-based rehabilitation studies, a survey by Tuah et al. (2021) noted several possible directions for future exploration. One of the challenges mentioned is related to the extensive evaluation. Measuring the effectiveness of the training is one of the evaluation approaches that can provide feedback about the patients' progress to the therapist and maintain the patients' motivation by showing the impact of their therapy (Yoshioka, 2020). For this reason, the evaluation process becomes essential while designing the VR-based intervention for rehabilitation. Several prior research in VR-based rehabilitation that utilize off-the-shelf VR devices did not provide performance evaluation, such as achieved range of motion (ROM), angular speed, and real-time feedback of the performed movement (Lim et al., 2020; Huang et al., 2019; Weber et al., 2019).

This paper designs a system that provides a ready-to-use function for real-time upper limb movement evaluation in VR. To test the usability of the designed system, a virtual environment (VE) is built, leveraging previous interaction characteristics in each upper limb rehabilitation movement. The movement interactions on the VE are implemented to perform the 16 upper limb movements. The study's main contribution is to present a system that provides a function for recognizing and measuring upper limb movements in rehabilitation using off-the-shelf VR devices. Researchers in this field can utilize the system to provide real-time evaluation features in their developed system. Additionally, a standard mapping interaction to manipulate a 3-dimensional (3D) object in VE based on the 16 upper limb movements is equipped in this system.

The paper is organized as follows. The related work is discussed in the next section. A description of the interaction and evaluation toolkit design is then introduced, followed by the toolkit implementation and test. A discussion section provides further explanation of the system testing results and the implication of the design for health. Finally, we conclude the work and summarize this study approach's results.

2 RELATED WORK

Designing custom rehabilitation hardware. To design the hardware device for rehabilitation purposes, the researchers utilized user-centered design (UCD) to collect the requirement and perform the evaluation (Ghazali et al., 2014). Researchers can either leverage the off-the-shelf devices and modify them to meet the users' condition (Shirzad et al., 2015) or fully design custom hardware (Soomro et al., 2022) to fit the required shape and function based on the treated limb (Callegaro et al., 2016). In another study, a rehabilitation system was proposed by incorporating IoT-based wearable devices and serious games to improve the rehabilitation experience and provide users with precise measurements and real-time feedback (Song et al., 2016).

Designing gamification for rehabilitation. Game-based applications for rehabilitation utilized an interactive game to engage the patients' motivation (Dias et al., 2019) or tried to simulate daily living activities (Weber et al., 2019). Leveraging commercial video games that are designed for healthy users without the therapy requirement causes more fatigue during the therapy session (Gustavsson et al., 2021). Considering therapy movement has a specific requirement to meet the patients' conditions, previous research focused on developing a different game to fulfill the requirement for each therapy movement. For instance, the research of Pereira et al. (2021) proposed hand therapy, and the research of AlMousa et al. (2020) focused on elbow and shoulder for stroke patients.

Designing VR-based rehabilitation with off-the-shelf devices. VR-based rehabilitation has become a trend to provide exciting therapy sessions to improve the patients' motivation during rehabilitation (Yoshioka, 2020). Moreover, the rapid development of VR devices commercialized in the market can

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help the researcher omit the device development process. The previous study demonstrated VR-based upper limb rehabilitation by completing the gamified tasks using the headset and controller from HTC Vive (Huang et al., 2019) and Oculus (Weber et al., 2019) resulted in positive feedback of increasing patients' motivation to undergo the training.

Research Aim. Although the implementation of off-the-shelf VR devices fulfills the research approach, providing a real-time feature to evaluate the movement with these devices takes time and effort. To the best of our knowledge, no unified system can serve as the entry point for VR researchers to implement the movement evaluation feature in their VR-based rehabilitation systems. Therefore, this study designed and developed a system that provides a ready-to-use function for evaluating the performance of upper limb rehabilitation using off-the-shelf VR devices. Additionally, a standard movement mapping feature is added to the toolkit, which researchers can use to manipulate the 3D object in the VE based on the movement in the physical world.

3 VR SYSTEM DEVELOPMENT

The VR system developed in this study consists of the toolkit and the VE for experimental purposes. The toolkit provides two features: performance evaluation and mapping interactions. The toolkit covers 16 movements from the upper body part, which are grouped based on the asses function of the arm, including the shoulder, elbow, and wrist. The toolkit is developed using the Unity game engine and utilizes the widely-used VR plugin SteamVR[1] to leverage several commercial VR devices in the market. Moreover, the toolkit will be implemented in a designed mapping interaction, which can improve the feeling of user interaction with the 3D object in the developed VE.

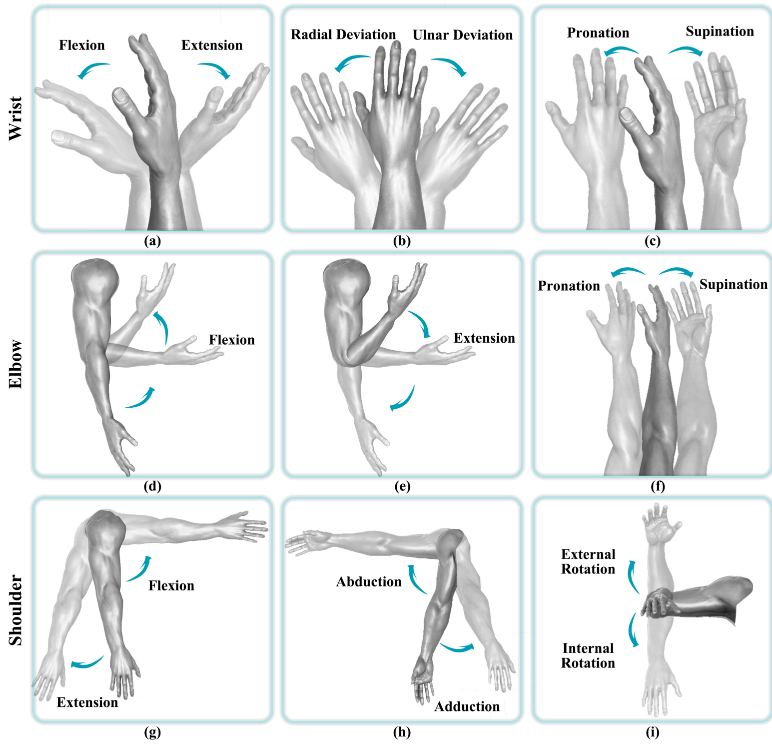

Figure 1. 16 upper limb movements

3.1 Movement evaluation

The toolkit generates a CSV file as an evaluation report based on the performed movement. The report consists of several movement data, such as movement recognition, start and end timestamp, moving duration, ROM, angular speed, repetition number, and level. Figure 1 shows the 16 movements and describes how the movement is identified in each part of the upper limb. From the figure, the darker

[1] https://store.steampowered.com/app/250820/SteamVR/

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shade represents the movement's neutral position or start position. The arrow shows in which direction the limb is moving in each movement. This study chooses these 16 upper limb movements as the focus of the movements.

In order to obtain measurements from the participant's movements, the system requires 3D position and rotation data from the shoulder, elbow, and wrist within the VE. To achieve this, the study compares the position and rotation of the shoulder based on the VR headset's position and rotation, while the position and rotation of the elbow and wrist are obtained using a tracker near the elbow and a controller in hand, respectively. By utilizing the SteamVR plugin, the system is able to track the position and rotation of each device within the physical room in real time, enabling the collection of accurate and reliable data.

3.1.1 Movement recognition

The movement recognition feature of this toolkit serves to identify the specific upper limb movement performed by patients. This feature has the capability to recognize 16 different upper limb movements, as depicted in Figure 1. The recognition process involves performing calculations to determine the direction of movement based on input data obtained from tracking the position and rotation of the patient's shoulders, elbows, and wrists in 3D coordinates within the VE.

For wrist movement recognition, the toolkit utilizes the 3D coordinates of the patient's wrist within the VE obtained from controller tracking data. This data includes the position and rotation of the user's hand in the physical world, which can be estimated as the palm position and rotation within the VE. The toolkit captures the initial position and rotation data from the 3D wrist and palm coordinates within the VE. It compares them with the final position and rotation data at the end of the movement to recognize wrist movement.

Elbow and shoulder movement recognition use all 3D coordinates within the VE derived from the tracked shoulder, elbow, and wrist. By analyzing the 3D coordinates captured at the start and end of the movement, the toolkit is able to recognize the specific upper limb movement performed by the patient in the physical world.

3.1.2 Movement measurement

The movement measurement feature of the toolkit performs various measurements to generate a movement evaluation report in the form of a CSV file. To obtain this data, the toolkit captures multiple parameters at the start and end of each movement. These parameters include the current timestamp, position, and rotation of the three 3D coordinates obtained from the tracked devices.

Using the start and end timestamps, the toolkit can calculate the duration of each movement. Additionally, the three 3D coordinate data are used to calculate the ROM, which indicates how far the part of the body can be moved around a joint or a fixed point. With both duration and ROM data available for each movement, the toolkit can also calculate the angular speed of the movement.

The recognized movement and corresponding measurement results are written to a temporary file within the system at the end of each movement. Once the patient performs all required movements, the toolkit generates a CSV file containing the complete movement evaluation report. Researchers can use this file to evaluate and analyze the results of the movements performed during rehabilitation sessions. Furthermore, researchers can create visualization tools to report on performance evaluations obtained from the CSV file.

3.2 Designing interaction

The primary challenge in designing effective interaction within virtual environments lies in identifying metaphors that can effectively map user movements in 3D space to object movements. In addition to ensuring the naturalness of the movement, it is essential to consider the effectiveness of the movement itself. To address this challenge, this study conducts a comprehensive survey of existing research and leverages related rehabilitation movements as a reference for designing interaction within VEs. To facilitate this process, the study breaks down the activity performed in physical environments that affects the transformation of a 3D object inside the VE into several axes.

Table 1 summarizes existing research in immersive upper limb rehabilitation based on the affected limb in the movement. The Movement Description column details the specific activity performed that manipulates the 3D object within the VE. The coordinate axis in the table defines several directions for 3D object transformation, including translation along the x-axis for right and left movement, along the y-axis for up and down movement, and along the z-axis for front and back movement. Another translation is moving a 3D object in a two-dimensional coordinate plane, such as the xy, xz, and yz planes. Finally, the last movement is rotation, which refers to the circular movement of a 3D object around a central axis.

Table 1. Previous related approach

Affected Limb	Movements	Movement Description	Translation			Translation			Rotation			References
			x-axis	y-axis	z-axis	xy-plane	xz-plane	yz-plane	x-axis	y-axis	z-axis	
Wrist	Flexion/Extension	Grate carrot by bending wrist to the right and left	×									(Colomer et al., 2016)
	Ulnar/radial deviation	Wiping movement, remove the scribble on the table	×									(Jung et al., 2017)
	Pronation/supination	Turn on/off stove (turn knob)									×	(Proffitt et al., 2015)
Elbow	Flexion/Extension	Lift weight to a specified height		×								(Dias et al., 2019)
	Pronation/supination	Cup pouring									×	(Lim et al., 2020)
Shoulder	Flexion/Extension	Throwing ball in bowling			×							(Liao et al., 2021)
	Abduction/Adduction	Move the cube from the upper side to the right and left				×						(AlMousa et al., 2020)
	Internal/External Rotation	Move paddle in table tennis					×					(Zirbel et al., 2018)

To manipulate the 3D object along specific axes, this study utilized mid-air input and single depth of field (DOF) manipulation on custom axes, following the MAiOR's (Mid-Air Objects on Rails) techniques introduced by Mendes et al. (2017). Using these techniques, the rehabilitation for a specific upper limb movement can focus on performing the primary gesture while manipulating the 3D object in the VE along the moving limb direction in a particular axis.
For the user experiment, this study implemented 3D object manipulation for each upper limb movement based on the results described in Table 1. However, this study designed a different activity for all movement pairs in the same scenario to familiarize participants during the evaluation session. This study chose to leverage the activity at a dining table inside VE, where participants could serve plates to the left and right sides of the table or rotate cups to stand straight.

4 VR SYSTEM IMPLEMENTATION AND TEST

In order to assess the usability of the developed system, a user experiment was conducted to gather movement data as described in section 3.1.2, and the resulting angular speed graphs were analyzed. The expected trend was for the speed to increase gradually from the first to the third repetition as participants became more familiar with the movements. Any unexpected results were further investigated and discussed in section 5.

4.1 Participants

This study recruited 13 participants (7 females and 6 males), ages between 20 and 34. These participants are university students from various academic backgrounds, including engineering, education, business, humanities, and medical. All participants confirmed that they were in good health and could perform multiple repetitions of upper limb movements during the experiment's sessions, which lasted between 50-60 minutes. Among the participants, 11 (84.6%) reported having prior experience using various VR devices such as Oculus Rift, Oculus Quest, HTC Vive, and Valve Index. Additionally, 8 participants (61%) reported prior experience with movement-based interactions using Nintendo Wii or Microsoft Kinect. Notably, none of the participants in this study were left-handed.

4.2 Experiment procedure and tasks

There are 16 movements task that need to be performed by participants in this experiment. Participants had to accomplish three correct repetitions in three difficulty levels for each movement. Therefore, the experiment was divided into three sessions with five minutes break between sessions, focusing on the wrist, elbow, and shoulder movements task for the first, second, and third sessions, respectively. The

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movement queue is randomized in each level and session to prevent participants from remembering the previous level's movement order.

Before the beginning of each session, participants were given a clear explanation and demonstration of the movement tasks. Once they thoroughly understood, they were instructed to put on the VR headset and attach the tracker and controller on their preferred arm side. For this experiment, a Valve Index VR headset and a controller were utilized, along with one tracking device from the HTC Vive brand. These devices were selected based on their shape and compatibility with the SteamVR plugin. The design of the Valve Index controller is beneficial for rehabilitation movements as it can be used without requiring the user to grip the controller body. Additionally, the HTC Vive tracker was positioned 5cm under the elbow joint to avoid discomfort while moving the arm. As a result, adjustments were made to the system to ensure that the elbow joint position in the VE matched the position in the physical environment.

Once the participant was prepared and comfortable with the attached VR devices, the session began. During the session, participants were given sequential instructions to perform the task scenario inside the VE. After completing all the sessions, participants filled out a post-study survey form. Finally, each participant was interviewed to gather their opinions and identify any challenges encountered while performing upper limb movements in the VE.

In order to complete the task, participants were required to move their limbs at a specific angle as instructed. To ensure the safety and suitability of the angles used in each movement, this study adopts the maximum ROM approach advocated by prior research (Zwerus et al., 2019; Rahman et al., 2009; Namdari et al., 2012). The movements were divided into three levels, with corresponding distribution thresholds: 70% for the easy level, 80% for the medium level, and 90% for the hard level, based on the maximum ROM established in previous studies. Participants had to accomplish three correct repetitions at each level to progress to the next level or movement task.

4.3 Result

The experiment collected 1872 correct movement data (13 participants × 16 movements × 3 levels × 3 repetitions) from 13 participants. In addition, our results include pre-questionnaire data and post-questionnaire data. Several movement data collected from the toolkit consist of the movement recognition results, movement status (correct/incorrect), timestamps recorded at the start and end of movements, moving duration, bending angle, repetition, and level. By collecting the moving duration and bending angle in each movement, a calculation can be done to get the angular speed data shown in Figure 2 (a.Wrist, b.Elbow, c.Shoulder).

Moreover, participants were asked to complete questionnaires on their comfort level wearing the devices (Knight et al., 2002) and the ease of remembering and performing the movements. A Spearman's rank-order correlation analysis was run to assess the relationship between the comfort assessment and ease of remembering and performing the movements. Table 2 shows there was a statistically significant, moderate negative correlation between easy-to-remember and perceived change ($r_s = -.725$), easy-to-perform and emotion ($r_s = -.666$), and easy-to-perform and perceived change ($r_s = -.621$).

5 DISCUSSION

Previous research on technology intervention proposed either the design focusing on the device for rapid feedback movement therapy (Callegaro et al., 2016) or leveraging the off-the-shelf devices to engage the patients' motivation (Shirzad et al., 2015). In this study, we drew inspiration from the work of Afyouni et al. (2020) and designed a system that can be implemented in off-the-shelf VR devices and provide real-time evaluation during the therapy session. Additionally, to leverage the system's rapid evaluation, we designed a mapping interaction in VE using MAiOR's technique for 3D object manipulation

Table 2. Correlation comfort wearing device and easiness to remember and perform

	Emotion	Attachment	Harm	Perceived Change	Movement	Anxiety
Easy to remember	-.397	-.231	.239	-.725**	-.514	-.536
Easy to perform	-.666*	-.467	-.260	-.621*	-.500	-.467

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

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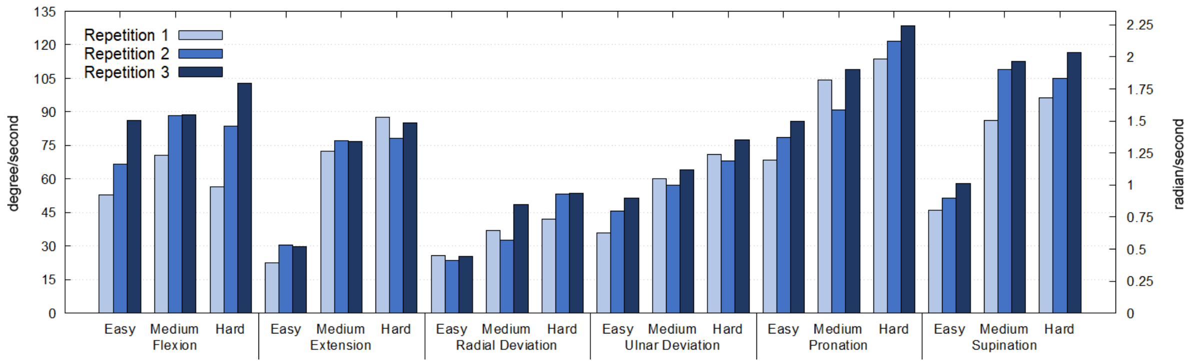
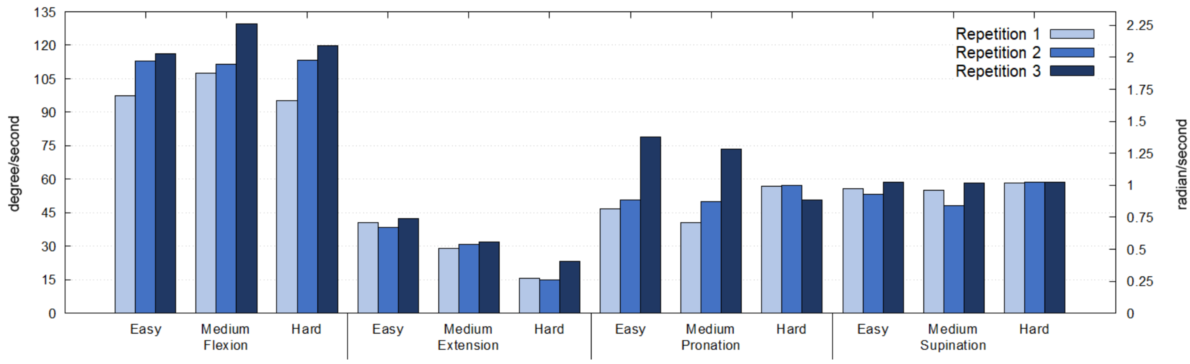
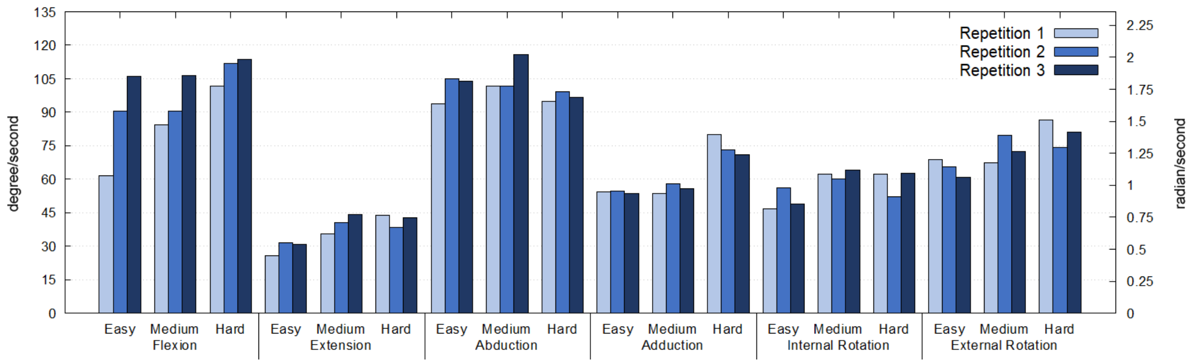


(a) Wrist angular speed



(b) Elbow angular speed



(c) Shoulder angular speed

Figure 2. Angular speeds

based on the 16 upper limb movements. We further packaged our system as a single toolkit, making it accessible to other researchers working in similar fields to implement these features.

5.1 Principal finding

The results of the experiment are presented in Figure 2, which displays the average angular speed divided into three body parts. The figures indicate a general trend of increasing angular speed from repetition 1 to 3 in movement-level pairs. This trend is most evident in Figure 2a, which relates to the wrist movement, involving only the wrist and hand parts and happening within a small range compared to the elbow and shoulder movements. Consequently, it is considered easier to perform than other body part movements, as there is no need to change the full arm position when initiating the movement. The slower angular speed in the figures indicates a more challenging task. However, Figure 2b on the extension movement showed low angular speeds in all the levels compared to other movements. After careful observation and discussion with the participants, they reported having reached their maximum ROM, but the 3D object did not reach the correct position. This was because their starting position was not at

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the lowest degree, and updating the logic in the system for movement distance was required to address the issue.

Other than elbow extension, the shoulder extension in Figure 2c also resulted in a low angular speed. Through interviews with the participants, it was concluded that the virtual interaction designed for this movement had affected their confidence in moving their arms. Specifically, participants were hesitant to perform the movement as they were asked to pull a virtual chair toward their bodies, which gave them the impression that the chair would collide with their body. This finding suggests that future research should carefully consider the design of interactions for fully immersive VR to avoid similar issues. Despite this challenge, the experiment successfully provided angular speed data for all 16 upper limb movements, demonstrating the efficacy of the designed system for movement recognition and measurement.

Aside from the movement data collected from the system, the post-questionnaire data is analyzed to determine correlations between variables. As shown in Table 2, a negative correlation was found between the variables of easy-to-remember and easy-to-perform with emotion and perceived change dimensions. The emotion dimension refers to the users' concerns about appearance and relaxation, while the perceived change dimension refers to the user's feeling physically different, which can be upsetting while wearing VR devices. The results indicate that when the user's feeling of physically different is higher, it will decrease their ability to remember and perform the movements. Similarly, when the user is more concerned about the appearance of wearing the device, it can decrease their ability to perform the movements. With this finding, the researcher needs to consider the implemented devices while designing the VR rehabilitation, as they can affect the user's achievement in remembering and performing the movements.

5.2 Implication for design for health

The system proposed in this study offers several advantages to researchers in the field of VR rehabilitation. Firstly, it provides a ready-to-use function for evaluating upper limb movement in VR. It can serve as a starting point for researchers to incorporate movement evaluation functionality in their VR-based rehabilitation systems. Secondly, the performance report data obtained from the system can be visualized in various ways, such as providing a user interface for the therapist and patients to observe the performance in a matrix or graph, enabling an easy understanding of the results. Additionally, the data can be centralized in a hospital or rehabilitation center, allowing for evaluation at any time and place.

With the given performance report data, researchers can design the visualization performance result in many ways. For example, providing a user interface to the therapist and patients to observe the performance in a matrix or graph, providing an easy understanding in evaluating the results. Additionally, this data can be stored centralized in a hospital or rehabilitation center, enabling the evaluation at any time and place.

Some patients may encounter various difficulties, including mobility limitations and low support from caregivers or family, that may impede them from visiting hospitals or rehabilitation centers (Jack et al., 2010). To address this issue, home-based rehabilitation can provide patients with continuous therapy. Researchers can design home-based rehabilitation systems using off-the-shelf VR devices, eliminating the need for additional custom hardware during the evaluation process. The vast proliferation of off-the-shelf VR devices, combined with their user-friendly des, have made them a convenient and practical solution that does not necessarily require professional experience or expertise. By enabling therapists to monitor performance from a distance, patients' caregivers can save time and travel costs to the rehabilitation center. Moreover, patients can perform therapy more frequently in the comfort of their homes and keep track of their progress and performance in each session.

6 CONCLUSION

This study designed and developed a single toolkit for recognizing and measuring 16 upper limb movements in VR-based rehabilitation. The toolkit is designed to work with the widely-used VR plugin SteamVR to support VR devices that are commercialized in the market. This study aims to accommodate a researcher with a ready-to-use function for providing real-time evaluation during the therapy session. By implementing this toolkit into their VR-based rehabilitation system, researchers do not have to design custom hardware or utilize a specific algorithm for performing movement evaluation.

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