Research Paper

A Virtual reality-based System for Hand Rehabilitation and Its Impact on the Emotional and Physiological Responses of Users

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ABSTRACT

Introduction: Maintaining motivation is one of the most important characteristics of rehabilitation strategies for successful treatment. Understanding the underlying mechanism of mental state helps develop new therapeutic methods based on virtual reality (VR) and serious game technologies. The present study develops a cost-benefit game-based hand rehabilitation system and assesses the influence on the psychological state of subjects when they interact with a VR environment in different task difficulty levels.

Methods: First, we introduced a low-cost smart hand rehabilitation system based on the Leap Motion Tracker. Subsequently, the experimental study was performed with 20 healthy participants. Their mental states were evoked using interaction with two separate games in four different difficulty levels. Three measures from the self-assessment manikin (SAM) self-reported test were described as a psychological response to this condition, and four features were extracted from the photoplethysmogram signal to quantify psychophysiological responses of the autonomic nervous system (ANS).

Results: Comparison of the different difficulty levels revealed significant changes in arousal and dominance corresponding to the under-challenging and over-challenging conditions, respectively. The results of psychophysiological feature analysis showed significant differences only for the standard deviation of intervals between consecutive heartbeats.

Conclusion: The developed system is a low-cost smart solution that can be useful for upper limb neurological rehabilitation. Regulating difficulty parameters of the implemented game can be used to influence the motivation of users through rehabilitation procedures. Photoplethysmogram is an appropriate psychophysiological indicator of mental states, but further studies are required.

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Highlights

- VR-based systems can be used for improving the motivation of patients to perform the rehabilitation exercises.
- A game-based system using the Leap Motion tracker was designed for hand rehabilitation.
- The designed system could improve the arousal and dominance of users.
- The designed system could reduce the user's standard deviation of intervals between consecutive heartbeats.

Plain Language Summary

Maintaining the motivation and commitment of patients is crucial for preventing boredom during the rehabilitation process. In this regard, VR-based rehabilitation systems can be used to improve the motivation of patients to perform the rehabilitation exercises. In this study, a game-based system using the Leap Motion tracker was designed for hand rehabilitation. Then, it was tested on healthy people by measuring their emotional and physiological (Heart rate variability) reactions. The results showed that the VR-based hand rehabilitation system improved the arousal and dominance domains of the self-assessment manikin questionnaire (SAM), and reduced the standard deviation of NN intervals during a photoplethysmography-based heart activity monitoring. The developed system is a low-cost smart solution that can be useful for hand rehabilitation. This game-based system can be used to influence the motivation of users.

1. Introduction

Recovery of normal hand function has a considerable effect on individuals' sense of independence and quality of life. The functional and anatomical complexities of the human hand put some constraints on its rehabilitation. The current methods of neurological rehabilitation usually involve performing repetitive and intensive exercises based on specific regular tasks (Alankus et al., 2010). However, studies have shown that only about 30% of patients follow the recommended exercise routine by therapists (Benvenuti et al. 2014). Thus, one challenge in this process is an increase in motivation levels in patients. A higher motivation level will increase patients' acceptance, intensity, and amount of exercise, leading to improved motor learning (Novak, 2018). Restrictions and challenges of rehabilitation have prompted rehabilitation based on virtual reality (VR) and serious games in recent years (Donoso Brown et al., 2015; Muri et al., 2013; Weiss et al., 2014; Henderson et al., 2007; Langhorne et al., 2009; Nissler et al., 2019; Omedes et al., 2018).

Maintaining the motivation and commitment of patients is are primary determinant of preventing boredom of the rehabilitation procedure. This can be achieved by improving the patient experience by allowing them to have a challenge proportionate to their level of skills without it leading to disappointment (Novak et al., 2011c). Serious games in a VR-based rehabilitation system include adaptive parameters that could adjust the difficulty level of the given task (Grimm et al., 2016). If the system is appropriately designed, changing these parameters should change the person's psychological state. We also need to know how the difficulty level regulation modulates various perceived cognitive states. Psychological dimensions are some criteria, such as dominance, arousal, and valence, to describe a person's response to events and situations. These dimensions are usually measured using subjective questionnaire reports; however, self-reported measures are not an adequate solution, as they are subjective and impose intervention to be interrupted. Psychophysiological measurements (originating from the ANS) can be taken objectively and determined as an indirect method of estimating psychological state. One of the best-known psychophysiological responses is the index extracted from heart activity (Tiberio et al., 2013).

Accordingly, this study develops a VR-based hand rehabilitation system (VR-HRS) and investigates how it affects users' psychological states and motivation. We considered the following essential points in the design of this system: 1) Measuring hand joints angles accurately, 2) Providing meaningful exercises for the hand, 3) Using low-cost instrumentation, and 4) Maintaining motivation through the rehabilitation exercise.

In the first part, the VR-HRS set up was revealed. We designed and implemented VR-HRS, comprising different parts as follows: A hand motion tracker, a psychophysiological measurement unit, and serious game scenarios in a VR environment. The hand motion tracker unit is developed based on "Leap Motion" (a new generation of marker-free hand visual-tracker technologies that have been introduced in recent years). It is low-cost and has sufficient accuracy, so these devices have attracted the attention of researchers in the rehabilitation field (Pastor et al., 2012; Da Gama et al., 2015). Photoplethysmography (PPG)-based heart activity monitoring was used as a cheap and feasible way to measure a person's psychophysiological indexes while performing a VR-based task. VR environments that run two games were designed based on two common wrist mobility exercises, extension and ulnar-radial deviation.

In the latter part of this research, we carried out experiments on 20 healthy participants to measure subjective and objective participants' psychological states during the VR tasks. Each of them performs eight experimental sections (four different levels of difficulties in two scenarios). We examined the effect of changes in the difficulty level of tasks on the dominance, valence, and arousal reported by their users. In the following step, we assessed whether these changes could be observed indirectly by objective psychophysiological measurements extracted from cardiovascular activity.

2. Materials and Methods

Hand rehabilitation hardware system

The developed system consists of a central unit and a subordinate system (Figure 1). The central unit task is the data acquisition and control of the other system compartments. This unit is connected to a hand tracking system (Leap Motion) and PPG and carries out synchronization and input data analysis. The subordinate system received the wrist anatomical angles to control objects' position in the game and sent game information to the central unit.

Hand movement tracking

The movements are the main part of controlling the game. They have to be usable for rehabilitation intervention. There is a collection of hand rehabilitation movements in studies (Grubišić et al., 2015; Krukowski et al., 2016) for developing VR and gaming–based rehabilitation systems. Here, we chose ulnar–radial deviation and extension of the wrist and designed two separate game scenarios for each of them. Figures 2a and b shows a schematic of the motion tracking system, in which Leap Motion was placed at a 30-cm distance above the hand. The forearm is fixed in the Z–axis direction of the Leap Motion coordination system. We extracted the anatomical points using a dedicated Software Development Kit (SDK) of Leap Motion. The devia-

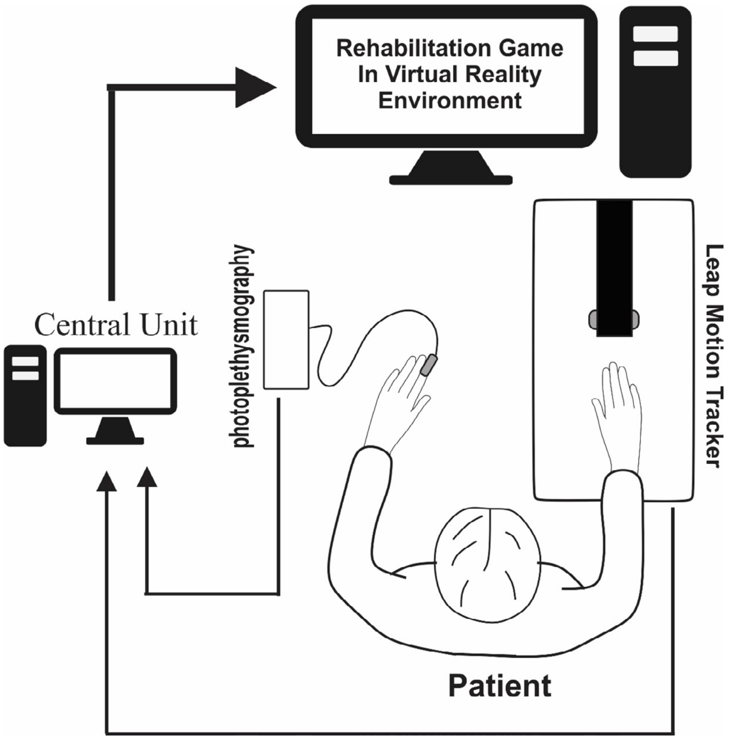

Figure 1. Schematic of the developed hand rehabilitation system

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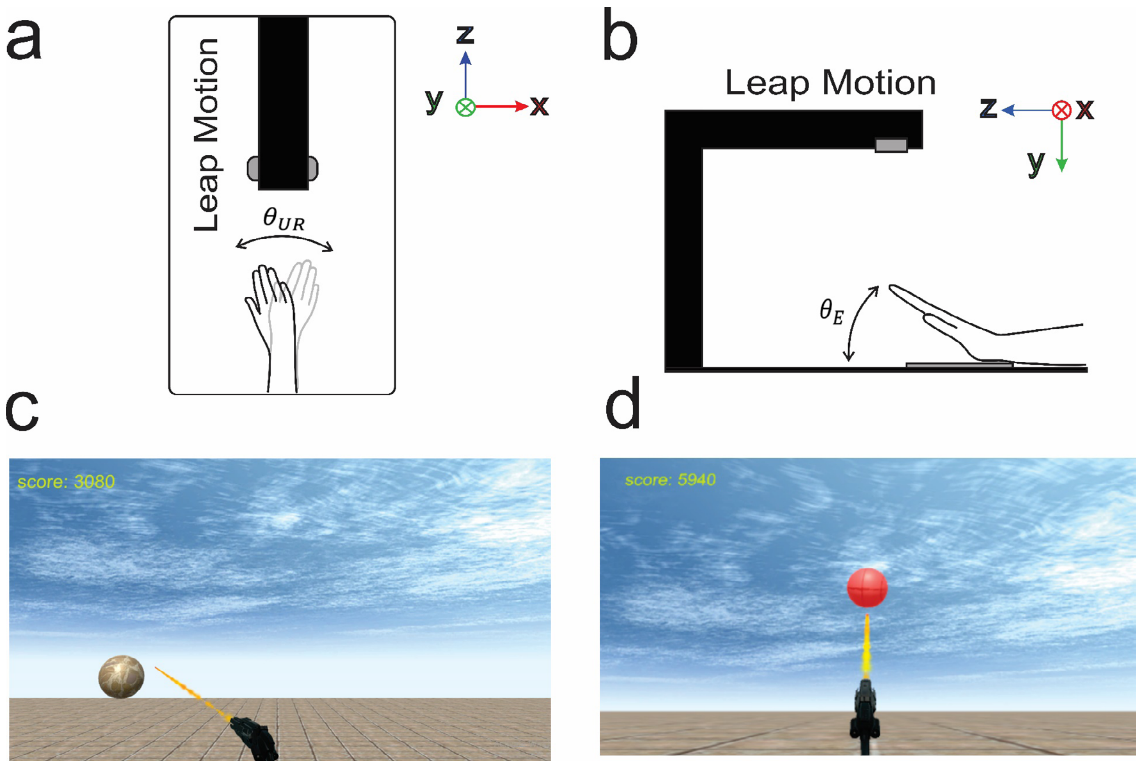

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Figure 2. The structure of the hand tracking system and the controlling movements VR game environments, ulnar-radial deviation (a & c) and extension (b &d)

Note: The forearm is fixed using two straps to have the least movement in comparison to the leap motion coordination system.

tion and extension were defined as the angle between the middle finger metacarpal bone direction to the z-axis on the x-z plane and the Y-axis on the Y-Z plane.

Psychophysiological data acquisition

Mental and emotional states produce somatic responses using the autonomic nervous system (ANS). These responses (e.g. electrocardiogram, galvanic skin response, and skin temperature) are more comfortable to record. A variety of signals related to cardiac function have been considered in previous studies (Novak et al., 2011c; Tiberio et al., 2013). This time series is affected by the sympathetic and parasympathetic nervous systems (Tiberio et al., 2013), and used as physical effort (Bernardi et al., 1996), as well as stress (Rani et al., 2002) measurements. In this study, we used PPG to consider psychophysiological features as inputs of dynamic difficulty adaptation. PPG recording tools are inexpensive, easy to use, and contain information about cardiovascular function. We designed the data acquisition unit of PPG using the Maxim MAX 30100 chip set up by SAM3X8E ARM CORTEX-M3 microcontroller with the sampling rate fixed to 100 Hz. The performance and temporal accuracy of this sensor have been investigated (Wu et al., 2017; Xuedan et al., 2019).

Game scenarios in VR

The Unity game engine was used to fulfil the implementation of the VR environment of the game and the dynamic interplay of objects. We designed two games for performing hand movement tasks. The scenarios in both of the games are the same, and the only difference is in the direction of gun movement (horizontal for ulnar/radial deviation and vertical for extension) in the VR environment. During the game, spheres with random sizes (10 to 100 pixels) and in different positions appear in the game environment. The participants have to point at the sphere for a certain amount of time (which is the control parameter of the game difficulty). This time alternates in the range of 0.5 to 2 s. Every time the participant explodes a sphere before the end of this period, they will gain 100 scores (lose 50 otherwise).

Study protocol

A total of 20 healthy subjects in the age range of 25±3 years participated in the experiment (12 males and eight females). All of them were right-handed. During the game, participants were sitting in front of the screen. They placed their dominant hand on a table so that it was in the Leap Motion field of view. We attached the pulse oximeter recording probe to the other hand (Figure 1). When the game was started, they experienced the VR environment and attempted to steer the gun's direction by changing their wrists.

The participants played two different sessions for ulnar-radial deviation and extension games. Each session lasted about 30 min, including 5 min of warm-up and four games with different difficulty levels presented in random order. The running time of each game was about 5 min, depending on the speed of the person.

Self-assessment measures

At the end of each level, participants filled out the self-assessment manikin (SAM) questionnaire (Bradley & Lang, 1994). It is a non-verbal evaluation method to measure the psychological dimension directly. Dimensions are represented by ordered figures arranged increasingly from left to right of the paper (or screen) that indicate the level of personal response to experience. The validity and reliability of SAM for Persian speakers have been examined in (Nabizadeh Chianeh et al., 2012) to assess the level of emotional dimensions, including arousal, valence, and dominance. In rehabilitation research, this tool has been repeatedly used to record the individuals' subjective responses to their emotional situations while interacting with robotic or VR-based instruments (Villar et al., 2020).

Psychophysiological measures

Heart rate variability (HRV) signal is a time series extracted from the intervals between two normal heartbeats. The sympathetic and parasympathetic nervous systems regulate the dynamic behaviour of HRV (Tiberio et al., 2013). Related studies have used electrocardiogram-derived HRV through the interaction of participants in a VR environment (Novak et al., 2011a; Novak et al., 2011b; Novak et al., 2011c; Goljar et al., 2011). According to past research, HRV extracted from PPG can be used instead of HRV extracted from an electrocardiogram (Lin et al., 2014). Feature extraction began by detecting pulse wave systolic peaks and calculating HRV from time intervals between consecutive pulse wave systolic peaks (NN intervals). There are some common measures used to quantify the HRV signal: Mean of NN intervals (MNN), the standard deviation of NN intervals (SDNN), the number of intervals bigger than 50 ms (NN50), and the ratio of NN50 to total intervals (pNN50). Driven features were normalized to their baseline conditions' value (extracted from PPG data during the warm-up period).

Statistical analysis

VR-HRS has been developed based on two assumptions as follows: Increasing a person's motivation during exercise leads to adequate rehabilitation, and motivation can be controlled through the parameters of game scenarios in VR, such as the difficulty level. Accordingly, to evaluate the system's performance, we investigated the difficulty level of psychological states. We needed to address the following question: "Was the difference in difficulty level in the tests sufficient to cause a change in the scores of the questionnaires or psychophysiological indexes?"

To answer this question, we assessed the significance of differences in subjective (enjoyment, valence, and arousal) and psychophysiological objective measurements for four difficulty levels using the analysis of variance test. If the null hypothesis of this test (i.e. equality of means in different groups) was rejected, then at least the index average in one of the difficulty levels would differ from the other levels. Kendall's W coefficient was reported to show concordance of measurements between subjects. Also, we used multiple comparison tests to report the significant differences between each pair of difficulty levels (Hochberg & Tamhane, 2008). All the statistical analyses were executed using the MATLAB statistical toolbox.

3. Results

Table 1 shows the outcomes achieved from statistical analysis for the self-reported SAM test (arousal, valence, and dominance) in different difficulty conditions. The results demonstrate a significant difference (at least for one of the difficulty levels) except for the extension scenarios' valence dimension ($P<0.05$). We performed a multiple comparison test ($P<0.05$) to provide more information. The horizontal lines marked with a star in Figure 3 show the pairs of significantly different psychological measures. The results indicated that in the previous test, the significant change in valence in the deviation game was due to the higher quantity in the third level in comparison with the second and fourth levels, not due to the coherent increase or decrease of it. Also, we observed no noticeable changes in the valence extension condition, but the maximum mean value of valence was observed at difficulty level 3 in both scenarios. Arousal and dominance matched to maximum pleasure during the extension task were obtained at 7.10±1.86 and 6.40±1.35, respectively. A similar result was achieved for the deviation task scenario. Mean arousal was 7.35±1.46, and mean dominance was 6.45±1.57 in proper challenging

Table 1. Significant differences and effect sizes for the psychological dimensions between the difficulty levels

Psychological Dimensions	Extension		Ulnar-radial Deviation	
	P	Effect Size W	P	Effect Size W
Arousal	0.001**	0.146	0.000***	0.501
Dominance	0.000***	0.591	0.000***	0.335
Valence	0.407	0.000	0.002**	0.139

*Significant difference for P<0.05, **Significant difference for P<0.01, ***Significant difference for P<0.001.

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conditions. The paired comparison results clearly show an upward trend for arousal and a downward trend for dominance for increasing game difficulty (in both scenarios). Reported dominance for the over-challenging situation (difficulty level 4) significantly decreased compared to other levels. Arousal was lower in the effortless condition (difficulty level 1) than the amount reported in the other levels.

An analysis of psychophysiological feature variations between difficulty levels found a meaningful difference only in the SDNN measure (Table 2). Based on the comparison of HRV extracted measures of the four difficulty levels (Figure 4), SDNN exhibited decreases during the high difficulty level than the low difficulty level.

4. Discussion

This study introduced a smart hand rehabilitation system that focuses on neural impairment patients using serious games and VR technology. We exploited the inherent features of this technology to increase patient motivation and other capabilities, such as guided therapy, enrichment environment, and real-time performance feedback, to enhance the rehabilitation outcomes. Complications of these disorders have imposed a considerable expense, including hospitalization, long-term rehabilitation, and lifelong care on patients and healthcare systems in various countries (Foerch et al., 2008). Therefore, devising cost-benefit therapy strategies through minimizing human intervention becomes a matter of new technology solutions for smart rehabilitation. VR-based smart rehabilitation systems potentially reduce associated costs via increasing treatment speed, developing home-based therapy platforms, providing task-specific exercise, and prolonging training times (Levac & Sveistrup, 2014). These potentials were eliminated because current prices are still prohibitive for users (Burdea, 2002). We addressed this issue by using cost-efficient equipment for motion tracking units and psychophysiological signal recording instruments.

The cognitive load affects the cardiovascular system, and some physiological functions include modulating the sinoatrial node's firing, decreasing the heart's muscle fibre length, and increasing the heart's contraction force. Also, the electrocardiogram time series is the most common signal used for evaluating the relationship between the mental and cognitive state with heart activity (Valenza et al., 2012; Agrafioti et al., 2012; Scher et al., 1984). Here, we investigated the feasibility of using pulse oximetry and PPG signal for the goal mentioned above, due to its cost-effectiveness and ease of use. Although a significant difference was reported only in one of the PPG extracted features (SDNN), it is important to note that the observed change was repeated with a similar trend in

Table 2. Significant differences and effect sizes for the psychophysiological measures between the difficulty levels

Psychophysiological Measures	Extension		Ulnar-radial Deviation	
	P	Effect Size W	P	Effect Size W
MNN	0.930	0.032	0.988	0.037
SDNN	0.661	0.017	0.716	0.2
NN50	0.000***	0.607	0.000***	0.768
pNN50	0.535	0.01	0.948	0.034

***Significant difference for P<0.001.

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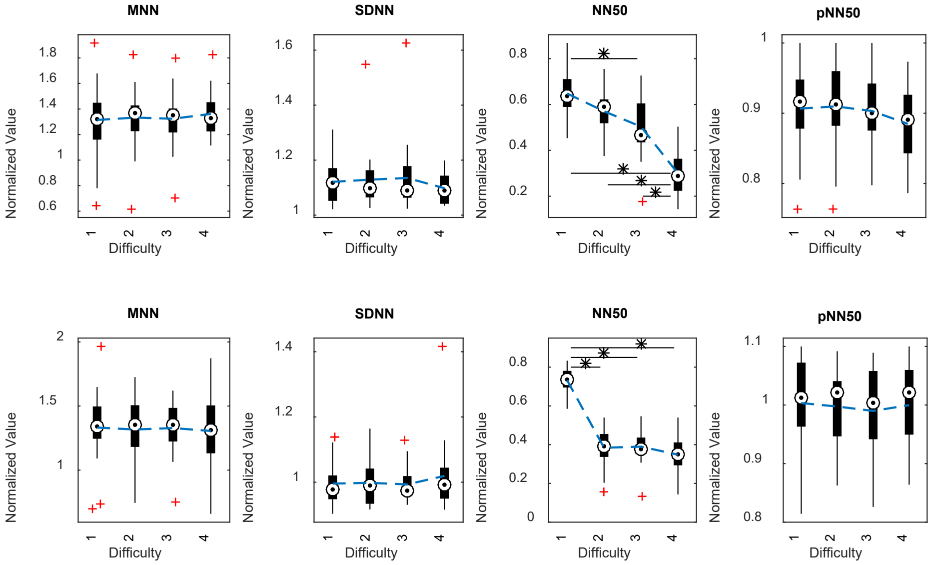

Figure 3. Changes in psychophysiological measures (MNN, SDNN, NN50, and pNN50) for the four levels of difficulty in the extension (first row) and deviation (second row) game scenarios

Note: Horizontal lines marked with a star show a significant difference between difficulty level pairs obtained by multiple comparison test (P<0.05).

both scenarios. Overall, this study strengthened the idea that the features extracted from the PPG signal are appropriate psychophysiological measurements to estimate psychological dimensions.

Data acquisition from motor behaviour is a vital component of a VR-based system. Rehabilitation motion tracking technologies can fall into three categories: Visual tracking, non-visual tracking (Su et al., 2003) three-dimensional electromagnetic sensors have been integrated into a data-glove to accurately model and capture the motion of the human hand. By modeling the movement of the human hand, this system has been shown to accurately measure the tremor evident in subjects with

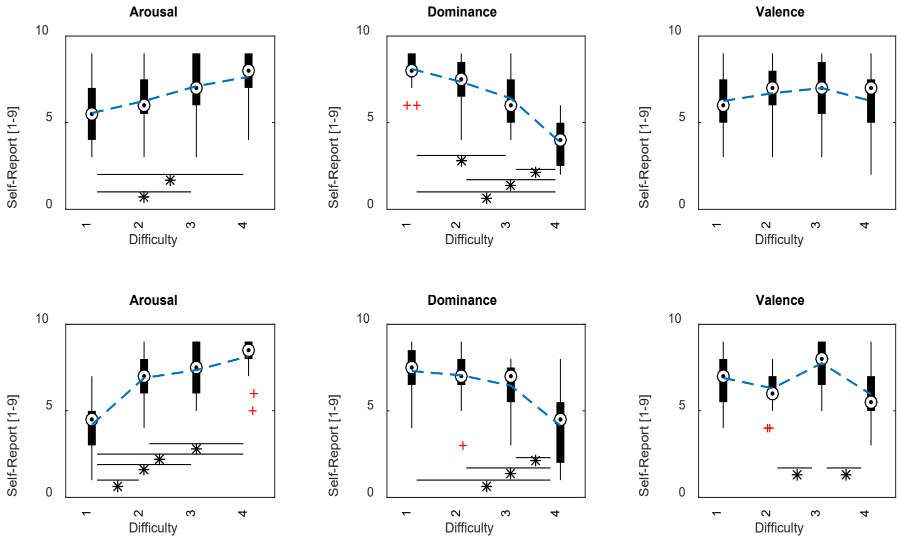

Figure 4. Changes on psychological dimensions (arousal, dominance, and valence) for the four levels of difficulty in the extension (first row) and deviation (second row) game scenarios

Note: Horizontal lines marked with a star show a significant difference between difficulty level pairs obtained by multiple comparison test (P<0.05).

Parkinson's disease (PD, and robot-aided tracking (Hogan et al., 1992). In our reviews, we concluded that Leap Motion (as a specialized visual tracker for the hand) is an acceptable option for our target application with low cost and reliable accuracy.

The results of the experimental phase indicate that the change in the difficulty significantly and monotonically changes the arousal and dominance (ascending and descending changes, respectively). This implies the proper design of the experiments so that the performance of the tasks arouses different emotional states in the participants. As expected, in more challenging situations, the person's arousal increases, and dominance decreases. Based on a closer inspection of Figure 3 and Table 1, we obtained a similarity between the statistical results and the overall psychological dimensions' changes. Accordingly, the self-reported SAM test measures are independent of scenarios and physical motion used to control the game. Furthermore, it means that these observations are not accidental and repeated in two individual experiments.

We observed that the peak mean valence (maximum pleasure) occurs at moderate levels of difficulty (level 3) in both scenarios. Having a more enjoyable experience in not too challenging nor too easy conditions is consistent with the basic idea of flow theory (Csikszentmihalyi, 1997). Accordingly, pleasure maximized when the task is not under-/over-challenged (avoid boredom and anxiety). These findings present a potential mechanism to develop automatic difficulty adjustment for the introduced VR-HRS.

5. Conclusion

Maintaining motivation is known to be essential to the success of rehabilitation. Within the framework of this study, a VR-based smart hand rehabilitation system was proposed to improve patients' comportment. Game scenarios are presented for wrist extension and radial-ulnar deviation exercises. The results of the experimental study demonstrated that the defined difficulty parameter (disappearance time of target objects in the game environment) is a good option for controlling the mental state of players.

Psychophysiological activity and perceived psychological states changed according to the task difficulty level in the games, so it seems that we could control these indices through the game parameter regulation. Subjective measures analysis shows that selecting the appropriate level of difficulty (corresponding to optimal challenge/skill ratio) maximizes users' satisfaction when interacting with the rehabilitation system. Apathy or boredom states occur when challenges are so low. It led to a meaningful decrease in arousal for this condition. On the other hand, the anxiety caused by experiencing very challenging tasks led to a reduction in the dominance perceived by the person compared to different levels.

The standard deviation of NN intervals extracted from the PPG signal is sensitive to changes in difficulty level. This feature is relevant for the objective quantification of patients' psychological and emotional state when they interact with a VR environment. There are many other methods for extracting information from the PPG signal. Appropriate psychophysiological indicators would be funded using more precise signal processing techniques.

One limitation regarding the present study's conclusion was that all of the experiences were performed on healthy subjects. The performance of the system on cases with disabilities should also be evaluated. Using machine-learning methods to estimate subjective psychological states from psychophysiological activities directly could be an interesting topic as a future topic of this study. This could allow closing feedback loop for dynamic difficulty adaptation of difficulty level in VR environments.

Ethical Considerations

Compliance with ethical guidelines

The ethical principles observed in the article, such as the informed consent of the participants, the confidentiality of information, the permission of the participants to cancel their participation in the research.

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Authors' contributions

All authors contributed equally to the conception and design of the study, data collection and analysis, interception of the results and drafting of the manuscript. Each author approved the final version of the manuscript for submission.

Conflict of interest

The authors declared no conflict of interest.

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