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Chapter · July 2020

DOI: 10.1007/978-3-030-49698-2_27

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Sampling Electrocardiography Confirmation for a Virtual Reality Pain Management tool

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Abstract. Previous research has shown that Virtual Reality (VR) technology may provide an alternative solution to pain management for clinical applications based on some psychological intervention strategies. Additional research has suggested that Electrocardiography (ECG) can be an objective measure of pain, with evidence showing that as pain increases, ECG signals should also increase. The aim of this study is to examine the effect of VR on naturally occurring pain when no pharmacological analgesics nor psychological intervention strategies are applied. The above statement will be validated via physiological responses, such as ECG and a correlation between subjective and objective measurements of pain will be made. The findings of the present study extend our understanding of the physiological and psychological effects of VR, providing useful insights into the relationship of VR and the levels of pain and discomfort caused by an exhaustive single limb muscle contraction. The main conclusion reached is that the use of VR can reduce physiological and psychological responses associated with negative sensations. Specifically, the results suggested that VR technology can significantly reduce ECG by 6 bmp, and perceived pain and exertion up to 50%, it can also significantly increase pain tolerance up to three minutes, without the use of any pharmacological analgesics and psychological intervention strategies.

Keywords: Virtual Reality, Electrocardiography, Pain Perception.

1 Introduction

In the treatment of some conditions, patients have to go through painful physical therapies as parts of the recovery process. For instance, patients with burn injuries have to deal with painful physical therapeutic processes. These processes are fundamental components of rehabilitation because they improve functional outcomes and minimize persistent disabilities; however, patients with burns usually neglect to participate fully in physical therapies due to the acute procedural pain [16, 43].

Pain has been defined as “an unpleasant sensory and emotional experience associated with actual or potential tissue damage” [40], which suggests that pain has both a nociceptive and subjective element to its perception. Therefore, whilst the sensory signal of pain for a given therapeutic process is unavoidable, the intensity or quality of pain that one consciously experiences may not always be the same.

Given the key role of pain perception in influencing people’s behaviour, it is therefore important to explore techniques which can offset pain perception during physical therapies, as this could result in an increased willingness to engage with the physical therapeutic processes for a sufficient period of time.

In recent years, computer technology and interactive video games such as Dance–Dance Revolution (DDR), Wii Sports, and Wii Fit offer new opportunities for promoting physical activity. Some research has shown that computer technology and interactive video games have increased energy expenditure and physical activity which produces positive health benefits [17, 19, 20, 25, 33, 48, 53]. Research has also looked into using such technologies in rehabilitation. For instance, some specialized robots have been developed which are responsible to assist patients to regain and improve functional abilities after a stroke [30, 51], or motion analysis of human movement which can assist clinicians and patients during physiotherapy through the provision of a detailed representation of movement related to a specific disability [56].

In the past few years, Virtual Reality (VR) has moved beyond research labs into a mainstream consumer electronic device, allowing users to experience a computer-simulated reality based on visual cues, enhanced with auditory and, in due course, tactile and olfactory interactions. VR provides the user with a complete illusion of different senses and creates an immersive experience [29]. Low-cost consumer-facing immersive VR systems have now become widely available (e.g., Google Cardboard, Gear VR, and Oculus Rift), providing a wide range of opportunities for healthcare applications. In the past few years, there have been emerging research looking into using VR and distraction strategy in pain management mostly in dealing with burn pain with promising results [35].

However, and despite the potential benefits of VR technology, there is a gap in the literature with regards to the positive outcomes of VR in physical pain when no psychological intervention strategies, nor pharmacological analgesics are used. This is even more surprising given the growing interest in VR and pain management in recent years.

Although positive results were found in using VR and psychological intervention strategies to manage chronic or experimental pain, little or nothing is known about the pure use of VR and its effect on reducing the naturally occurring pain experienced during strenuous exercise or physiotherapy when no psychological intervention strategy is in place. Such investigation will improve our knowledge about the pure impact of VR technology on the experience of pain. In addition to the above, most of the previous research on VR for pain management supported their results only via subjective measurements, such as pain scales. Therefore, there is a clear need for physiological responses, so as to validate the accuracy of VR on minimizing pain.

Finally, with few exceptions [31, 36, 37] the majority of the previous studies used high-cost immersive VR solutions. Therefore, further research needs to be conducted in order to examine the feasibility of low-cost affordable VR technologies. Using such affordable VR solutions will reduce the cost of equipment maintenance and allow personalized home-based use.

Given the key role of pain perception in influencing people's behaviour, it is therefore important to explore and validate though psychophysiological responses the VR technologies which can offset pain perception during physical training and therapies. With this study, we aim to determine if and how VR technology on its own (without the use of any psychological interventions and pharmacological analgesics) may moderate the experience of pain. This paper will, therefore, provide knowledge for academics and clinicians on the effectiveness of VR for pain management and guidelines for designers, which can turn out to be invaluable in creating virtual environments for reducing exercise pain.

1.1 Electrocardiography and Pain

The significance of pain as human experience can be inferred from the high percentage of people who experience pain, e.g. one out of four US adults experience continuous pain that lasts for a year or even longer [23].

Although the assessment of pain is often based on subjective self-report, research has shown that Electrocardiography (ECG) can be an important, valid and objective physiological signal for the assessment of clinical pain [39, 52]. In addition, there is a highly positive correlation between ECG reports and pain intensity with one shaping the other [5, 7, 8]. This means that as pain level rises, ECG rises accordingly [49]. As such, clinical research often uses ECG to validate self-report of pain [27]. In terms of exercise and physiotherapy, ECG allows recording physiological changes and correlations between exercise intensity [38]. Therefore, ECG is an important measurement to assess pain intensity during exercise and physiotherapy.

It is worth mentioning that, even though the normal ECG differs between people, there is a healthy range of Beats per Minute (bpm), which should be close to resting ECG. In addition, ECG recovery after exercise is generally fast among athletes but much lower among patients with chronic heart failure [24]. Therefore, we hypothesize that if pain perception could be offset during exercise, this could result in a possible decrease in the ECG rates. This decrease in ECG could mean a lower burden to the heart, since the ECG will remain closer to the resting one which will result in a willingness to either intensify exercise or continue the exercise for a longer period of time, without burdening the heart.

To investigate whether VR technology without the use of any specific psychological intervention strategies can have an effect on the experience of pain, we carried out a within-group study involving 20 participants, who were allocated both in the VR and a non-VR groups. The findings of the VR group were then analyzed in relation to the non-VR group and were validated via physiological responses, such as ECG. The findings were further corroborated through subjective scale self-reports. Correlation between the psychophysiological measurements of pain were also made. This was done to determine the effect of VR on naturally occurring pain when no pharmacological analgesics nor psychological intervention strategies are used.

2 METHOD

2.1 Ethical Considerations

The study was approved by the University of Kent, Research Ethics & Advisory Group (ref. Prop. 77_2016_17). All participants signed a consent form prior to the study and the study was performed in accordance with the Declaration of Helsinki.

2.2 Participants

Twenty healthy participants, equally selected from both genders (10 males and 10 females), with a mean age of 23 years (M= 23.20, SD = 7.54) participated in the study. All 20 participants performed both VR and non-VR intervention in a counterbalanced design. Participants' one-repetition maximum (1RM) for 180^o of dominant arm elbow flexion ranged from 4 to 25 kg with a mean of 12.38 kg (SD = 6.91). Approximately 2/3 of the participants reported engaging in no regular, structured resistance or aerobic exercise (no resistance = 70%, no aerobic = 70 % during the testing week). Participants who reported engaging in the regular structured exercise had a weekly mean workout time of 3.20 hours (SD = 5.06).

All participants were healthy, with normal vision, and no disability that could affect their performance in the exercise task. In addition, no participant reported taking any chronic medication or having any cardiovascular, mental, or brain condition that could affect their performance or pain perception.

2.3 Procedure

The experiment required each participant to pay two separate visits to the laboratory. The first session involved establishing each participant's 1RM (i.e. the heaviest weight they could lift) and carrying out the VR familiarization session. The second session was the main experimental sessions (VR and conventional non-VR). The VR and non-VR sessions were performed in a counterbalanced design, which means that half of the participants performed first the VR session and then rested for 10 minutes before moving to the non-VR session. The rest of the participants performed first the non-VR session and then, after resting for 10 minutes, moved to the non-VR session.

2.4 Instruments

During both experimental sessions, the following data were collected:

Electrocardiography (ECG): ECG was continuously measured with a telemetric device, which was a Polar digital ECG monitor and a Polar Wear-link chest strap (with 2 electrodes) (Polar Electro, N2965, Finland). ECG, was found to provide a measure of the psychological pain anticipation of exercise and thus it has been used in several previous studies to assess pain [e.g. 39, **52**].

Time to Exhaustion (TTE): TTE was measured based on the amount of time the participants spent holding the dumbbell. TTE has been previously used during continuous pain tasks [**13**, **46**] to assess the effect of exercise pain (EP), on exercise performance [**2**]. For health and safety reasons, the maximum experimental time was set up to 15.00 minutes.

Pain Intensity Rates (PIR): Participants were asked to verbally report their level of perceived pain every 60 seconds, using the 1-10 Cook Scale [**12**]. Participants were instructed to report their PIR based on the feeling of pain during exercise rather than on other non-exercise type pain (e.g. dental pain).

Rating of Perceived Exertion (RPE): Participants were asked to verbally report their rating of perceived exertion, using the 6-20 Borg Scale [**6**], every 60 seconds of the exercise task. Specifically, participants were asked to report how much effort they had to put to keep their arm in a 90º flexion, irrespective to feelings of discomfort.

Immersive Experience: A self-report 7-point Likert scale questionnaire completed after the exercise task in the VR group to assess the immersive experience. The questionnaire referred to several factors such as Presence and Hand Ownership and was based on the individual's impression of realistic experience. The questionnaire also evaluated the system's usability, via assessing whether the exercise task was performed with no difficulties. The questionnaire also examines whether the individual was familiar with the use of VR technology. Finally, the participants' attitudes towards VR training were examined by asking them whether they can see a future where VR will be used on a daily basis for training routines.

2.5 Data Analysis

Data analyses on Electrocardiography (ECG), Pain Intensity Ratings (PIR), and Ratings of Perceived Exertion (RPE) were carried out using ISO time-points (i.e. those time-based data points consistent across all participants). The shortest time to task failure (TTE) across participants and groups was 2 minutes, and so ISO time analysis was completed on minute 1 and minute 2 of the exercise task (ECG1, PIR1, RPE1 and ECG2, PIR2, RPE2). Participants' ECG was also recorded when they withdrew from the task (finalECG). The mean ECG across the exercise task for each participant were also calculated (meanECG).

Descriptive statistics were performed to identify the levels of Immersive Experience, usability and the users' attitudes toward VR exercise.

An analysis of paired sample t-test and an ANOVA with repeated measures followed by Bonferroni post hoc test was conducted to examine how VR affects ECG, PIR and RPE, based on ISO time points, measured at task failure and mean ECG. All statistical tests were carried out using the Statistical Package for the Social Sciences (SPSS) version 26. Data are reported as mean and SD, and statistical significance was accepted when $p < 0.05$.

2.6 Apparatus

The VR system was developed using Unity3D version 5 to work with Samsung Gear VR and Samsung Galaxy S6 phone. The 3D models (human upper body, the virtual room, and barbells) (Fig. 1) were created in Maya version 2016. The system was developed to allow the researcher to customize the gender of the human body, dominant hand, skin colours, colours of the t-shirt, and the weights of the barbells. In order to create a sense of embodiment, a Microsoft Band's gyroscope was used to animate the virtual arm, reflecting the movement of the participant's arm (rotation X and Y).

Through the Samsung Galaxy Gear HMD device, the participant was able to see the virtual body sitting on a chair in a neutral looking virtual room. The virtual room was void of any distracting visual information since different environmental factors might cause a degree of distraction. A table with a yoga mat on it was present in the virtual room, simulating the conditions of the actual environment (see Fig. 1).

Fig. 1. To the left: Human 3D model. To the right: Representation of the Actual Environment.

3 Study Results

3.1 Immersive Experience

Most of the participants were not familiar with the use of VR technology. VR technology was a new experience for most of them. Therefore, participants reported moderate to low levels of VR prior use during the VR session (M = 3.00, SD = 2.51).
Overall, the participants reported high rates of Immersion in VR. Based on their ratings, the VR application produced a high degree of Presence and Hand Ownership. In addition, most participants reported that the VR application motivated them positively. The specifics of the results are presented as follows:

During the VR exercise session, the participants reported high levels of presence (M = 5.67, SD = 0.94) and moderate to high levels of hand ownership (M = 4.40, SD =

1.80). In addition, during the VR exercise session, the participants reported high levels of usability, since they found it easy for them to lift the dumbbell and perform the exercise through the VR (M = 5.95, SD = 0.94). Furthermore, we also asked the participants if they can imagine their self to use the VR technology to exercise daily and all the participants (n= 20) responded positively to this query. They also reposed that VR can be a motivational technology for strenuous exercise training (M = 4.90, SD = 2.10).

3.2 Electrocardiography (ECG).

To investigate whether there was a difference in the participants' mean ECG (meanECG) between the VR and the conventional non-VR exercise, an analysis of paired sample t-test was conducted. The analysis revealed a significant difference between the ECG and the two sessions ($t(19) = 2.63$, $p < .05$), with the participants' ECG showing significant reduction during the VR exercise (M = 85.46, SD = 12.77) in comparison to the conventional non-VR exercise (M = 91.09, SD = 12.02) (see Fig. 2).

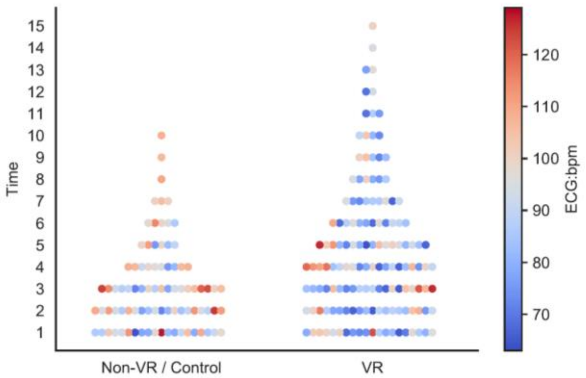

Fig. 2. Sina Plot of ECG rates during the Conventional non-VR and the VR session.

Additional analysis of an ANOVA with repeated measures followed by Bonferroni post hoc test was conducted to investigate whether there was a difference between the participants' ECG in the two sessions (VR and conventional non-VR) based on the ISO time. The analysis showed a significant difference for the ECG during the two sessions at the first – ECG1 – ($F(1,19) = 4.57$, $p <.05$) and second – ECG2 – ($F(1,19) = 15.31$, $p <.001$) minute. As can be seen in Table 1, the results were in line with the general meanECG, with the participants' ECG being significantly lower during the VR exercise in comparison to the conventional non-VR exercise. Interestingly, as time passed, the data revealed a growing trend for the ECG during the conventional non-VR exercise, in contrast to the VR exercise where the ECG data remained similar for both minutes.

Table 1. ECG: Effects for VR and Convectional non-VR exercise during ISO time.

	Intervention	Mean (bpm)	SD

ECG1	VR exercise	82.50	12.67
	non-VR exercise	87.60	14.06
ECG2	VR exercise	82.50	11.53
	non-VR exercise	90.25	12.24

The above trend was further supported by the finalECG, with the VR group showing significantly lower ($t(19) = 8.22$, $p < .05$) finalECG ($M = 88.2$, $SD = 14.08$) in comparison to the conventional non-VR finalECG ($M = 95.05$, $SD = 12.15$).

3.3 Time to Exhaustion (TTE).

During the VR exercise, the minimum time to exhaustion for a participant was 3.45 and the maximum 15.00 minutes, whereas during the conventional non-VR exercise the corresponding minutes were 2.33 and 10.29. therefore, important differences were reported in terms of Time to Exhaustion (TTE) between the VR and the conventional non-VR group ($t(19) = -6.54$, $p < .001$). The data indicated that, when the exercise was performed with the use of VR, it lasted significantly longer ($M = 7.08$, $SD = 3.08$) in comparison to conventional non-VR exercise ($M = 4.23$, $SD = 1.59$).

3.4 Pain Intensity

Additional analysis of an ANOVA with repeated measures followed by Bonferroni post hoc test was conducted to investigate whether there was a difference in the participants' PIR in the two sessions based on the ISO time. The analysis showed a remarkable difference for PIR in the two sessions at the first – PIR1 – ($F(1,19) = 28.36$, $p <.001$) and second – PIR2 – ($F(1,19) = 25.62$, $p <.001$) minute. Further analysis based on the means indicated that, in the conventional non-VR group, at each minute point the PIR ratings given from the participants were significantly; higher PIR1 ($M = 3.08$, $SD = 2.41$) and PIR2 ($M = 5.95$, $SD = 3.17$), in comparison to the VR group; PIR1 ($M = 1.48$, $SD = 1.83$) and PIR2 ($M = 3.80$, $SD = 3.02$) (see Fig. 3).

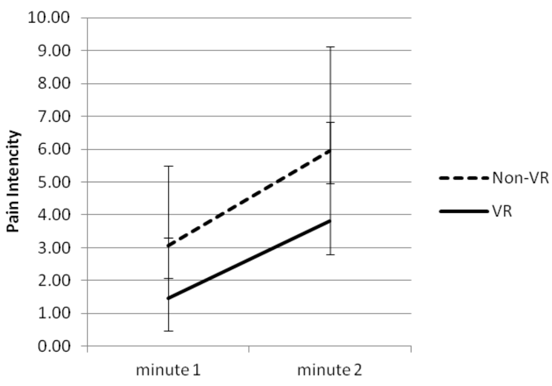

Fig. 3. Mean number of PIR for two sessions, for each ISO minute.

3.5 Rating of Perceived Exertion (RPE).

Additional analysis of an ANOVA with repeated measures followed by Bonferroni post hoc test was conducted to investigate whether there was a difference in the participants' ratings of perceived exertion (RPE) in the two sessions based on the ISO time. The analysis showed a significant difference for the RPE during the two sessions at the first – RPE1 – ($F(1,19) = 38.97$, $p < .001$) and second – RPE2 – ($F(1,19) = 25.77$, $p < .001$) minute. Further analysis based on the means indicated that exercising with the use of VR can decrease the participants' sensation of how hard they were exerting their arm in order to maintain the muscle contraction (RPE1 (M = 8.05, SD = 2.54) and RPE2 (M = 10.95, SD = 3.75) in comparison to the conventional non-VR group (RPE1 (M = 9.70, SD = 2.90) and RPE2 (M = 14.20, SD = 3.79) (see Fig. 4).

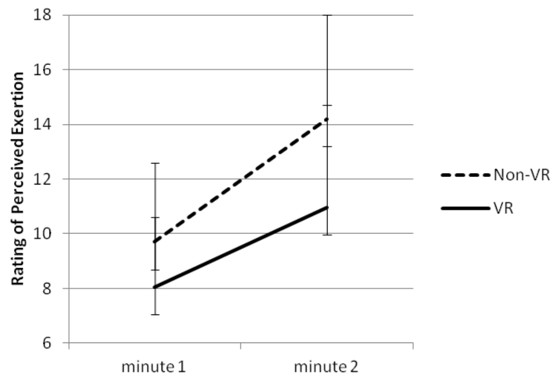

Fig. 4. Mean number of RPE for two sessions, for each ISO minute.

4 Discussion

The results show that VR technology can influence the perception of task difficulty, endurance performance and pain experienced during exercise when no pharmacological analgesics nor psychological intervention strategies are in place. Most importantly, exercising through the use of VR demonstrated a significant decrease in Electrocardiography (ECG), Pain Intensity (PIR) and Perceived Exertion (RPE) reports, and a significant increase in Time to Exhaustion (TTE).

As has been previously explained, ECG increases during exercise [24], but there is a healthy range of bmp, which should be close to resting ECG to be considered as healthy. In addition, ECG recovery after exercise is accelerated in athletes but reduced in patients with chronic heart failure [24]. Our findings suggest that the use of VR technology seems to have helped the individual to exercise for a longer period of time without burdening the heart since the ECG means remained closer to the resting one. This is the first time an application was found to help users to moderate the increase of ECG during exercise without the use of any pharmacological medication or psychological intervention strategies. This is an important finding, because not all pain signals propose a danger to the body, but the experience of it may lead to undesirable behaviour change of the subject. For example, the naturally occurring pain caused by vigorous exercise does not cause physical harm but may moderate exercise behaviour [38]. This conclusion is a useful starting point towards the identification of effective technologies for subsequent exercise improvement.

In addition to the above, the importance of these findings can be elaborated based on a possible application to individuals with heart disease who could benefit from engaging in exercise. A reduced ECG during exercise could reduce strain on the heart, and therefore exer-cise in VR could place these individuals at less risk.

The significantly lower ECG might be associated with an observation made in previous research studies, according to which the view of animated cartoons helped to reduce stress and anxiety in clinical environments [11, 28]. The virtual environment used in this study incorporated cartoonish features and representations of the virtual body, hand, and dumbbell, which might be responsible for the reduction of participants' perceived stress and anxiety, which is associated with ECG [47], which is however irrelevant to the personal levels of physical fitness [15]. On the contrary, psychological states, as well as emotional events and processes, can have a dramatic impact on ECG and may result in an increase without an accompanying increase in physical activity [4, 41]. To summarize, stress and anxiety can cause alterations in ECG [18] and their perceived level is an important factor which affects the fluctuations in ECG in response to painful stimuli [see 1]. We believe that the animated cartoon features in our VR encouraged stress reduction, which in turn contributed to the reduction of ECG.

As has been explained above, ECG and responses to painful stimuli increase and decrease in the same direction, which means that when ECG is rising, the pain responses are rising as well [5, 7, 8, 49]. Our findings are in line with the above statement since it was found that when ECG was reduced, the perceived pain and exertion were reduced as well. This effect can be explained by the correlation between ECG and stress. Previous research has shown that stress and anxiety can increase perceived pain [21] and that VR has the ability to decrease situational anxiety related to painful chemotherapy and burn wound care [21] treatments. As a result, the cartoonish representation of the virtual environment might influence the anxiety levels and act as analgesic factors to pain and exertion.

Furthermore, research in psychoanalysis suggests that, unconsciously, individuals recall memories from their childhood and that such memories can shape their mood [10, 42]. Another study has demonstrated that individuals usually regulate negative mood by retrieving positive memories from the past [44]. Therefore, the participants might associate the cartoonish VE with happy childhood memories [see 10, 34], which might, in turn, mitigate the negative emotional experience of pain. This is further supported by a study which demonstrated that viewing an animated cartoon during venepuncture can reduce the levels of perceived pain in comparison to standard treatments [55].

Another possible interpretation of the positive effect VR has on pain intensity and perceived exertion could be offered by Rubber Hand Illusion theory, according to which visual-proprioceptive information allows the individuals to perceive a fake hand as a part of their own body [9]. Research has shown that bodily self-consciousness is generated in the brain by sensory stimulation on a fake hand [50]. Therefore, the Rubber hand illusion theory explains why the user may have the illusive feeling that the fake hand is a part of the real body. Even though the fake hand was perceived as a real part of the body, the presentation of the hand via VR concealed visual stimuli that are perceived by the brain as signals of pain and exertion (e.g., veins swells, skin redness). This visual information might have minimized the perception of pain and exertion the individual felt. Furthermore, the level of interaction during sessions with immersive VR technology can increase participants' pain tolerance [54]. Having in mind that the virtual hand was imitating the real move and tremor, the participants might have felt that the interactivity levels were high, since the VR application produces natural moves, and therefore this might have had an effect on minimizing the perceived pain and exertion.

Finally, a positive relationship was found between VR technology and time to exhaustion (TTE), as it was found that participants using VR exercised for approximately three minutes longer compared to those involved in the conventional non-VR exercise. TTE has been considered to be an important, valid and objective physiological measurement for the assessment of pain. In the past, several studies have used the time for the assessment of pain during a continuous pain task [13, 46] and during a continuous exercise pain task [2].

The positive effect of VR on TTE might also be attributed to the interactive features incorporated by the virtual environment (e.g., hand and dumbbell were imitating the real move). It should be noted that additional interactive actions with the virtual world were not possible since the participant had to remain in a stable condition so as the bicep curl exercise could be performed correctly and no other muscles (e.g. back muscles) should contribute to the resistance exercise. Therefore, the resistance exercise performed in the virtual environment allowed the user to interact with the virtual environment in real-time and perform the exercise. This impacted on the levels of immersion the participants felt. Previous studies showed that the participants' level of interactivity and immersion into the virtual world could affect the perception of time [22, 32, 45]. A comparison between interactive and passive VR technology for individuals experiencing cold pressor pain revealed that the interactive condition was significantly more effective [14]. In addition, it was found that increased levels of immersion can reduce the level of pain reported by participants [22].

4.1 Design Guidelines

Drawing on the findings of this study, it can be claimed that the effectiveness of a virtual environment depends on several factors. Therefore, designers of VR for pain management can derive some guidelines and recommendations from the present study.

Although this study did not compare animated virtual environments to photorealistic ones, the positive findings should not be overlooked; animated virtual environments should be used by designers so that a reduced ECG, PIR and RPE and an increased TTE is achieved during resistance exercise.

In particular, it was found that when interactive virtual environment was void of distracting visual information, but enhanced with cartoonish elements, and incorporated animated elements that did not depict fatigue and pain (e.g. did not depict the swell of veins that normally appear on the limb during exercise), then participants had a reduced ECG, PIR and RPE, and an increased TTE during painful exercise.

Therefore, we suggest for designers of VR, not only to focus on the virtual presentation of material properties that are to be used in exercise and surround the user, but also on the proper design of the virtual human body and the part that will be involved in the performance of the exercise.

4.2 Conclusion, Implications and Future Directions

Given the continuous advances in the usability of VR technologies and accompanying interactive devices, it is now conceivable to use affordable VR technology and low-cost interactivity devices. Our study shows that VR can be used to reduce significantly the naturally occurred pain and effort associated with single limb exercise. Our participants had limited engagement in regular, structured resistance or aerobic exercise (only 30%) and generally low interest in exercise. However, positive attitudes were reported toward the VR exercise. Participants expressed their willingness to use the VR application to exercise on a daily basis. Therefore, an implication of this study is that VR can motivate positively individuals who are reluctant to exercise, and this could potentially result in an increased level of physical activity and thus a healthier lifestyle.

We should not overlook the fact that perceived pain and exertion have been considered to be an obstacle for athletes and professionals during exhaustive training. The results of the study are promising in this respect; perceived pain and exertion can be reduced and this can increase the duration of the exercise. This suggests that VR technologies can be used more widely by athletes and professionals to offset pain and exertion. In such a case, athletes and professionals will increase their durability during training and, by extension, improve their performance. In addition, VR exercise accompanies interactive devices, which have the potential to monitor the user's physiological signals and levels of performance during VR exercise.

The positive implications of this study may well be extended to patients suffering from heart disease. Our results suggest that VR technology can play a significant role in pain perception during endurance performance. In particular, it is shown that the positive outcomes of VR can help to offset the ECG increase. We found that VR can help the individual maintain ECG rates closer to the resting ones. Based on these findings, it can be inferred that VR technology can allow the individual to continue exercising for a longer period of time without burdening the heart. This calls for further research on individuals with heart disease, who could benefit from engaging in exercise but at the same time protected from the risk of an increased ECG that can cause heart failure.

The reported study may also have an implication on stroke patients with arm motor impairments, which need exercise and physiotherapy. Research has shown that a key factor for an effective exercise rehabilitation of stroke patients is the duration and intensity of the exercise performance [**26**]. The study demonstrated that VR can influence positively PIR and RPE, meaning that the user is able to continue exercising at high intensity for a longer period of time. This potentially results in patients being able to increase the duration and intensity of treatment to promote motor recovery after stroke.

Likewise, given the affordability and ease of use of mobile VR technology, one can imagine a scenario where such a VR intervention can be employed at home with minimal or no clinical supervision. A possible design idea would be to incorporate social interactions into the virtual environment since in many cases patients become homebound for a long period of time and hence lack social interactions. Therefore, in future VR exercise applications could allow patients to carry out daily exercise along with other people virtually.

Another aspect that calls for further investigation is the sustainability of VR in the long term. Although participants reported that they are willing to use the VR application on a regular basis for limb exercise, further research is needed to establish the sustainability of this motivation over a longer period of time. Previous studies, as well as this study, mostly cover short-term effects. Only one study [**3**] has compared the effect of VR over short- and long-term periods, which found that in the long run, VR is no better than standard interventions. Therefore, whether VR could have long-lasting beneficial effects on pain management remains to be established.

An area which needs to be investigated further relates to the observation that a virtual representation of the body part in pain (e.g., virtual hand) can reduce the perceived pain. Future studies could compare a digital–VR hand to a mixed relativity hand (virtual and augmented reality) in order to identify the most efficient way to represent affected body parts in VR. Moreover, future experiments could also examine whether the perceived immersion of the user is further improved by enhancing the sense of embodiment, via connecting the VR with portable, advanced and low-cost sensors (e.g., leap motion) which can track in higher precision the movement of user's hand and fingers. More precise sensing technologies may increase the sense of presence and hand ownership and this may potentially result in even higher levels of immersion.

The work done in this study provides a basis for future research related to pain management and VR. More importantly, it provides VR designers with innovative ideas to create engaging and effective virtual environments not only for healthy people engaging in regular exercise but also for patients who avoid participating fully in physical therapies due to procedural pain.

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