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A system for head-neck rehabilitation exercises based on serious gaming and virtual reality

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Abstract Acute and chronic neck pain are common medical conditions, and the treatment typically includes physical therapy involving daily exercises. Insufficient motivation of people afflicted with neck pain to adhere to the prescribed exercise regimen may delay their recovery. Accordingly, in this work, we propose a system that motivates the users to perform neck exercises by engaging them in a serious exergame within virtual reality (VR) environment. The system measures the users' neck movements via a few static and dynamic kinematic tests and a novel VR serious game, tailored to the neck range of motion of each individual user. The game is designed to make the users perform rehabilitative neck movements according to the prescribed exercise regimen while playing. The analysis of acquired data from VR hardware provides insight into flexibility of the neck during head movements and overall neck kinematics, which is valuable for assessment of pain-related stiffness, as well as for progress monitoring. In a user study performed with the proposed system and the Oculus Rift DK2 VR headset, we show that the users find exercising more interesting and engaging when using the proposed system, and that introducing visually rich VR environments makes the users more motivated to continue exercising.

Keywords Serious game · Virtual reality · Neck · Exercise

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1 Introduction

Many people occasionally experience neck pain or stiffness in the neck [11], e.g. after working at the computer for long periods of time [23], sleeping in a contorted position [27], or prolonged overhead work [36]. Neck pain can also occur due to poor posture [35] or various physical injuries, e.g. falls, car accidents, or some other physical traumas [45]. These conditions can cause inflammation or movement of muscles and ligaments of the neck outside their normal range. An additional cause of pain may be aging [6], due to the degeneration of cervical disks and narrowing of the space between the vertebrae, which add stress to the joints.

Neck pain disrupts many activities of daily living. For example, it is unpleasant and dangerous when a person is unable to turn to look over their shoulder when reversing a car. If symptoms persist for a longer period of time medical care is required. Depending on the source of pain, drugs like muscle relaxers and anti-inflammatory medication or pain relievers might be helpful [11, 19]. Another treatment option are neck exercises, which are viable both for relieving and preventing neck pain, as supported by substantial amount of research [11, 25, 31]. A typical neck exercise program consists of a combination of stretching [48] and strengthening [5] exercises, and possibly aerobic conditioning [9] as well.

A variety of factors can positively or negatively affect adherence of injured persons with the prescribed exercises [18], which can translate into impact on their health. For example, various forms of motivation enhancement to injured persons to perform the exercises, including e.g. positive feedback from therapists, have been shown to reduce pain levels and disability in cases of low back pain [3]. On the other hand, boredom has been shown to negatively influence adherence to exercise [22]; as neck exercises involve multiple repetitions [47], boredom is a significant factor to consider.

In this work, we propose a system that motivates users to perform neck exercises through immersion in a serious game in virtual reality (VR). One of the main challenges in designing a serious game for neck exercises is to induce required movements with adequate repetition and stretching, as proposed by domain experts in neck rehabilitation. If this is achieved, playing the game will result in gradual improvement in the range of neck movement. In the proposed serious game, the required movements are induced through a game task that requires the user to visually follow a moving target in the virtual environment. Both the game task and the VR experience itself make it appealing for the user to complete given missions in the game, keeping the user engaged and interested in exercising. The idea is to catch the attention of the user in such a way that she/he forgets that an exercise program is being performed, and focuses on the game task instead.

An advantage of the proposed concept of a serious game for neck exercising is that it inherently includes a personalized platform, monitoring individual user's achievements and providing control of the game task difficulty. Hence, exercises can be tailored according to the individual progress of each person, for example by always respecting the limits of her/his neck range of motion. Aside from its direct applications for rehabilitation purposes, such personalized approach is applicable in VR-based assessment of kinematic difficulties in the neck. An example application may be related to the assessment of whiplash injuries [13], which frequently occur in car collisions and represent a controversial health care topic [24].

The paper continues with an overview of related work in Section 2. Section 3 introduces our VR-based system, including the overall concept and design of system calibration, target positioning scenarios and serious game, description of applied development tools and elaboration of in-game performance measures. A few increasingly immersive game variants are described, which can improve user interest, enjoyment and game-playing experience. Section 4 describes the postprocessing tool developed for visualization and analysis of measurement results, i.e. time series obtained from executions of the VR-based system. Section 5 describes the conducted user study, while section 6 contains the paper's conclusions.

2 Related work

Serious games are an active research area and their applications in healthcare are numerous, including e.g. medical rehabilitation [40, 44], help establishing a diagnosis [21], instilling healthy habits [1], etc. In terms of rehabilitation, three recent examples include a game for rehabilitation after stroke [40], a therapeutic game for treating motor impairment [44], and a mobile game for rehabilitative wrist exercises [16]. These games assume the exercise sessions are carried out under the supervision of therapists within rehabilitation as a part of the hospital treatment, and after being discharged from the hospital the person regularly exercises at home for a much longer period. The idea is to reduce rehabilitation costs and to emphasize home activity. Tele-rehabilitation enables the therapist to distantly monitor the progress of patients by remote access to patient data via a web portal. A special challenge in the development of rehabilitation applications is to enable therapists to dynamically control the placement and behavior of the objects inserted into the virtual scene during the session [34], deeply involving the therapist in session control.

In terms of aiding the diagnosis of a disorder, a recent example is a serious game that helps test the eyesight of children through measuring their responses in an engaging and fun visual game [21]. An example of a serious game that helps instill healthy habits is a mobile game that motivates the users to climb steps instead of using escalators or elevators in real life through simulating them climbing high famous landmark buildings, e.g. the Empire State Building [1]. On a side note, with the advent of augmented reality games, similar positive health effects can also be observed for commercial games that are not designed exclusively with that purpose in mind [2], blurring the line between commercial entertainment-based and serious games.

The usefulness of virtual reality-based platforms for rehabilitation exercises has been demonstrated in numerous studies. For example, a detailed overview of a VR-based platform for upper limb motor rehabilitation is presented in [44], and an extensive exposition of post-stroke neurorehabilitation using VR-based gaming system is given in [7]. The idea of VR usage for rehabilitation originates from various VR simulators, such as flight or driving simulators, that are helpful for learning certain activities in virtual environment and transferring adopted skills to the real world. Virtual educational platforms have also shown many advantages for learning activities, as well as for assessment of learning outcomes [33]. A systematic survey of empirical evidence for various positive impacts of games in general, including learning and engagement, can be found in [12]. The findings revealed that playing computer games is linked to a range of positive perceptual, cognitive, behavioral, affective and motivational impacts and outcomes.

While papers concerned with VR-based neck rehabilitation have just recently started to be published [8], various research works have applied VR technology in the assessment of cervical spine kinematics, i.e. kinematics of the neck [13, 15, 29, 30, 37, 38, 42, 43]. Cervical range of motion testing is commonly used as a part of the assessment procedure for people who sustain whiplash injury [14, 26, 32, 43] to quantify their reductions in neck mobility, and VR technology with its typical devices like motion trackers and head-mounted displays offers potential for conducting a more comprehensive assessment of the cervical spine kinematics [15]. Accordingly, VR technology has been applied in diverse assessment scenarios with virtual scenes of varying complexity, including: (a) measurements of cervical range of motion and ability to return head to a natural position [43], as well as peak velocity and smoothness of movement [42], which need no virtual scenes at all; (b) tests involving a single static or dynamic virtual object, for assessment of ability to maintain fixed neck rotation aligned with the static object or to track the dynamic object in continuous or jumping motion [13, 29, 30]; and, (c) more complex and engaging VR serious games [37, 38].

Our system integrates common tests involving static and dynamic virtual objects with a novel serious game, all of which are adapted to the user's cervical range of motion. Our user study is focused on making the exercises more engaging, appealing and interesting for the patient, facilitating a better continuity of physical therapy. In this sense, our study complements the work by Chen and colleagues [8], which investigates specific issue of visual-proprioceptive mismatch in VR, in order to increase magnitude of neck rotation movement, i.e. to encourage patients with chronic musculoskeletal pain to perform therapeutic exercises. Some extensions of our proposed system can be envisaged toward more complex neck-and-body exercises, in which head motion tracking via VR headset is insufficient to capture complete body kinematics while exercising. In such cases, application of devices like Kinect or Leap Motion for posture tracking and state-of-the-art human pose estimation methods from depth sensors (e.g. [17]) would be required.

3 The proposed system

Our VR-based system for neck rehabilitation exercises consists of hardware components that support the virtual environment, and of software components that incorporate multiple VR scenarios and serious exergame, in which appropriate head-neck movements are executed.

The main hardware component is the Oculus Rift DK2 VR headset, paired with a personal computer which meets the requirements for Oculus usage. Since Oculus includes sensors for orientation and position tracking of the head, the idea of this work is to use these measurements to measure neck flexibility. Specifically, the headset includes accelerometer, gyroscope, and magnetometer with an update rate of 1000 Hz that enables precise head orientation tracking, which is crucial for our application. Positional tracking via external camera with near-infrared CMOS sensor ensures all head motion is tracked, and a built-in latency tester constantly measures system latency to optimize motion prediction and reduce perceived latency. Rendering of the virtual scene is performed in resolution 1920 × 1080 (960 × 1080 per eye) with the maximum refresh rate of 75 Hz and the overall field of view of 100°. Different images for the left and the right eye form stereo vision and hence provide better immersion in the virtual scene. Displays are based on 5.7″ Super AMOLED technology with low persistence, which reduces unwanted motion blur effects and therefore reduces simulator sickness. Integrated 3D audio headphones are also included in the headset. Accuracy of Oculus Rift has been evaluated in the specific context of cervical spine kinematics assessment, with average errors during maximum range-of-motion testing in the range ± 5° [46].

In order to explore the neck range of motion and general kinematics, it is necessary to set up tests suitable for the analysis of neck problems, which are reflected in the speed of movements, twitches, smoothness of motion and reaction time. The overall idea is that the user should track a defined target in the virtual space by changing her head orientation. Only head-neck motion is measured, rather than eye movements, so tracking the target requires the user to make appropriate head-neck kinematic actions.

The two main software components of our system that support measuring the range of motion and the overall kinematics of the neck are *System setup and calibration* and *Serious exergame* (Fig. 1).

3.1 System setup and calibration

During the execution of *System setup and calibration* the user is required to visually follow a target object in order to measure their baseline neck range of motion. Inspired with system identification approach to neck kinematics assessment [13], we define three scenarios of the visual target positioning: the first one is having a statically positioned target, the second one is having a leaping target and the third one is having a continuously moving target. Furthermore, these scenarios focus on specific head-neck motion patterns generally employed by humans when accomplishing real-life tasks. Specific situations can require the head to be still for some time (captured by the scenario of static positioning of the target), other may require the head to move abruptly, i.e. at relatively high velocity (captured by the scenario of leaping positioning of the target), and yet other may require the head to move smoothly (captured by the scenario of following a continuously moving target). All these scenarios require system calibration, in order to personalize the scenarios according to the neck range of motion of each participating individual; for safety reasons, it is desirable to have all exercises respect the range of motion of individuals with neck pain. Accordingly, the first step in our measurement procedure is system calibration, i.e. determination of the neck range of motion ground truth for each individual user.

Figure 2 presents four segments in polar space colored in red, green, blue and cyan, where horizontal axis corresponds to axial rotation of the neck (i.e. left and right rotation, or yaw angle), and vertical axis corresponds to extension/flexion of the neck (i.e. up and down rotation, or pitch angle), relative to the user's neutral head orientation corresponding to the center of the polar space. The extreme positions on these axes, denoted by x_{min}, x_{max}, y_{min} and y_{max}, are measured during system calibration using a simple procedure. After putting on the VR helmet, the user is asked to keep the head in a natural position looking straight ahead and the helmet's orientation tracker is programmatically reset by the researcher, thus denoting the

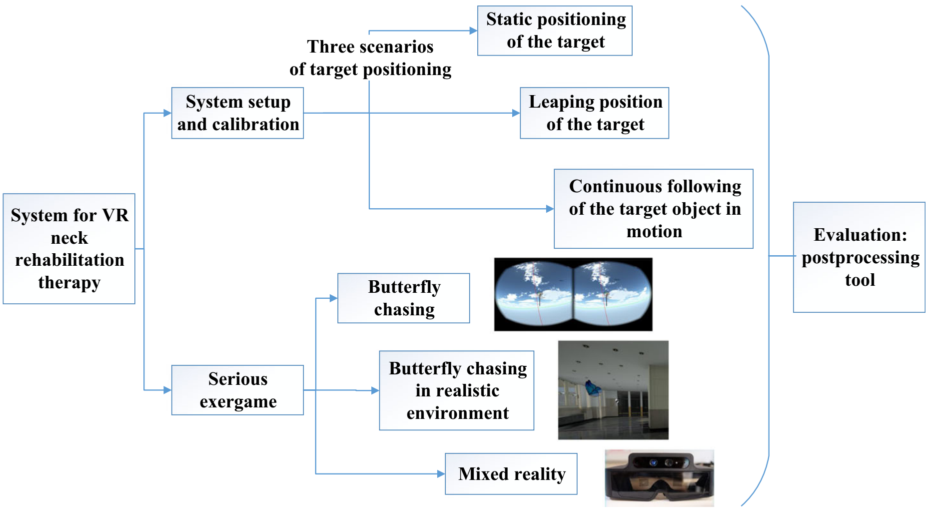


Fig. 1 System for VR neck pain rehabilitation exercises

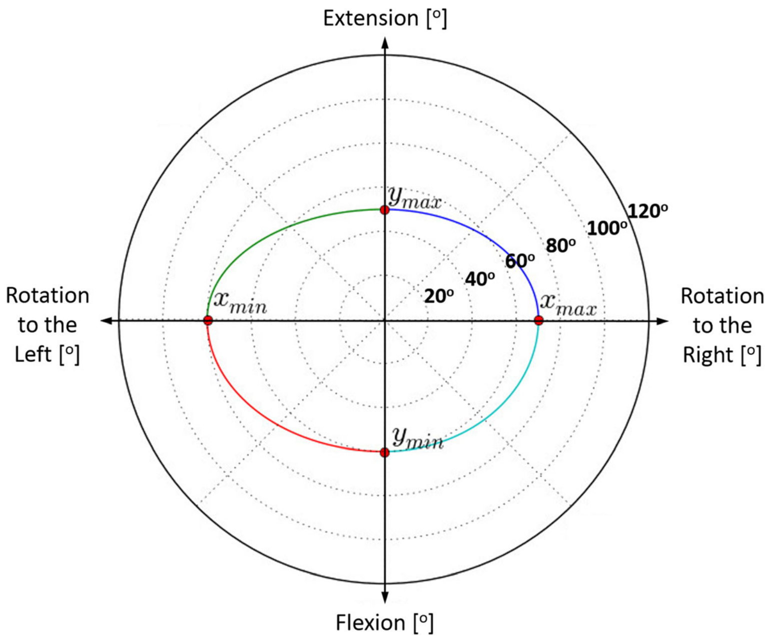


Fig. 2 System calibration in polar space

center of the polar space. Then, the user is asked to turn the head as far as possible to the left, right, down and up, while the system tracks and records the largest rotation in each direction as x_{min}, x_{max}, y_{min} and y_{max}, respectively. These extreme positions define an elliptical space in the presented polar space, which approximates real head movement limits quite well, as illustrated in Fig. 3. Such elliptical space is used for random positioning of the target in subsequent scenarios of target positioning.

The neck range of motion around the remaining axis of rotation (i.e. lateral bending toward the left and right shoulder, or roll angle) is also measured relative to user's neutral head orientation during the system calibration procedure. However, a healthy neck exhibits the most profound coupling of yaw, pitch and roll movements when roll is the primary motion executed by users [28]. Accordingly, when users must control their roll motion, they will have difficulties to also control the remaining angles. Therefore, the dynamic scenarios which are described in the following paragraphs, like leaping positioning of the target and tracking of the target in continuous motion, typically require users to control their yaw and pitch, but not roll, and the described elliptical space is used to maintain the position of the target within the users' yaw and pitch range of motion. If dynamic scenarios are designed to require users to control their roll angle, it is recommended that yaw and pitch are kept constant or zero, like in the user study in section 5.1.

Next, we define a workflow with three scenarios of target positioning. The first scenario is the static positioning of the target. In the static positioning of the target, the object is placed in the central position of the elliptic space and the user is required to keep the center of focus on the placed target object for several seconds. The difference between the angular position of the target object and the user's head orientation is measured. These initial measurements are used as the rest position because there should not be any tension in the initial rest position. However, small oscillations are always present in humans and might be affected by injuries to the neck; such changes in steady-state oscillations are captured by the static positioning measurements.

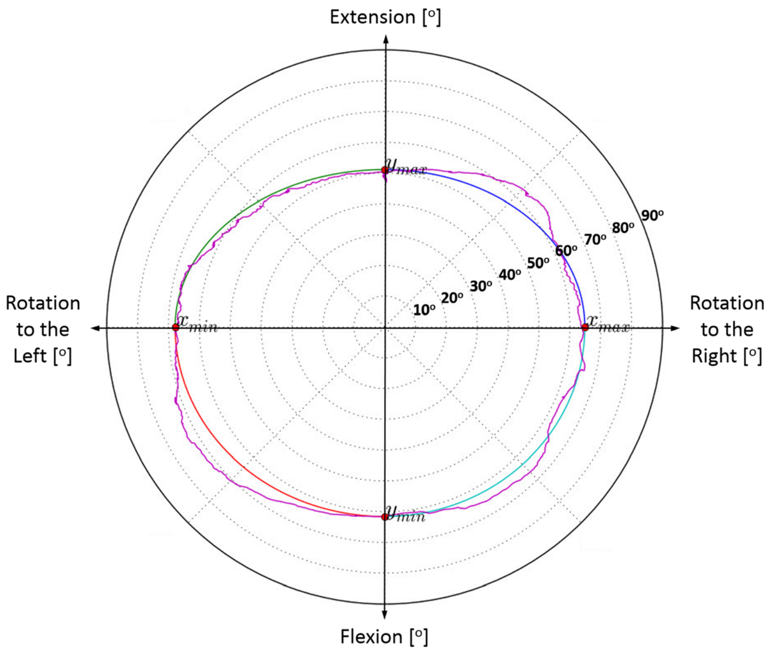


Fig. 3 Correspondence between elliptical space defined by system calibration (red, green, blue and cyan colors) and the limits of real head movements (purple color)

The second scenario is the leaping positioning of the target. In this scenario, a random sequence of positions of the target object is defined or a predefined sequence of positions is used, constrained by the limits of the user's neck movements that are represented by the described elliptic space. The user is required to follow the given positions of the target object and focus the view for a few seconds at each target position. Results from these leaping positioning scenarios are useful for several feature measurements that include response time, maximum speed, average speed, jerk index, and smoothness of movements.

The third scenario is the continuous following of the target object in motion. The object changes its position according to a smooth continuous curve. A result of this scenario is presented in Fig. 4. The blue line represents a continuous curve of target angular positions relative to the user's neutral head orientation and the red line represents the user's head trajectory while tracking the target object. The difference between these two lines represents the error of tracking. A greater deviation between the blue and the red curve or decreased speed might indicate positions that are painful and not reachable for the user.

Following the execution of the three scenarios, the participating user is engaged in a specifically designed VR serious game, which is described in the next section.

3.2 The serious exergame

The general idea of the serious exergame is to integrate different head-neck motion patterns that humans mostly use to accomplish real tasks in their lives, which are tested separately in the described target positioning scenarios. To include these motion

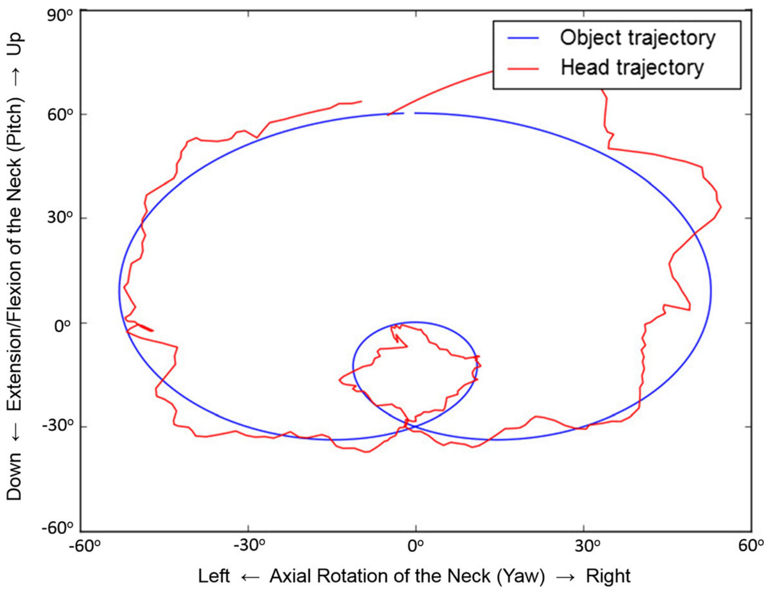


Fig. 4 Continuous following of target object trajectory

patterns in a single game, the main task of our proposed game is butterfly chasing, since chasing and catching of butterflies can be designed to require combinations of sudden high-speed head-neck movements and following of butterflies with smooth movements, including static positioning in special cases when specific butterfly does not move at all.

In the serious exergame we define two specific environments. The first environment is a classic virtual environment developed using the Unity game platform. The second environment is built in Unreal Engine, and it is a highly realistic environment with physically based rendering.

3.2.1 Classic virtual environment

For the first, classic VR environment of the serious exergame, we have chosen the Unity game development platform (Fig. 5). Unity is a software framework designed for creating video games. It handles essential tasks such as animation, rendering and physics. Unity is easy to use, well documented, and supported with plugins and assets needed for this project. It supports several VR devices, including Oculus Rift DK2 that is used in this work.

The base elements of the game scene are a butterfly and a butterfly net. The goal of the game is to catch and collect butterflies with the butterfly net. Butterfly positions are selected randomly from the person's neck range of motion baseline established during system calibration, as proposed by the rehabilitation domain expert. The butterfly trajectories are defined via Bezier curves.

The game parameters are adjusted in the parameter setup panel that is displayed before the execution of the system calibration, the target positioning scenarios and the game. This panel contains parameters for all the scenarios as well as the game. Dominant game parameters are

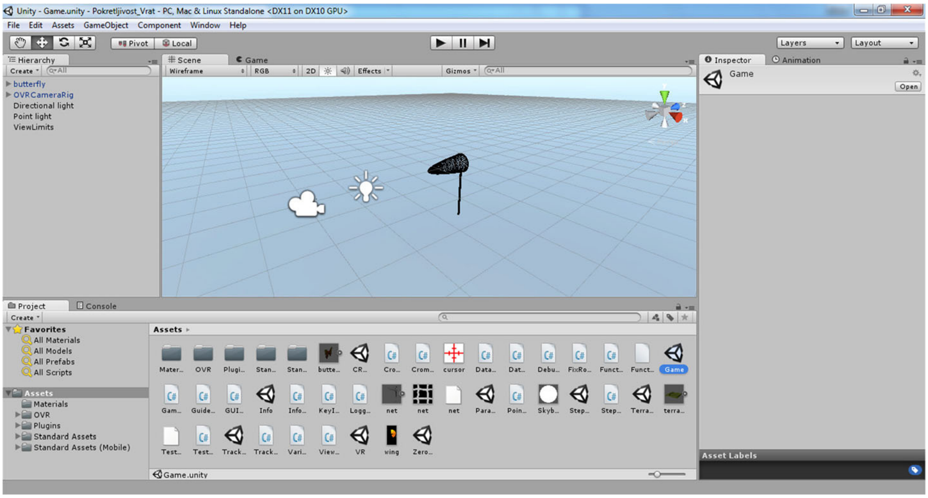


Fig. 5 Unity environment for serious game development

related to the number of butterflies and the time each butterfly stays visible before disappearance. One specific game parameter is not specified via the panel, but is instead computed from the system calibration; this is the user's neck range of motion, which constrains butterfly positions in the game. Figure 6 presents a screenshot from the exergame application, which shows the position of the butterfly net and crossing of the green and the red line, which indicates the orientation of the user's head in the neutral stance.

Game scoring depends on the number of "caught" butterflies. The user first needs to align the view orientation to the target butterfly sufficiently fast (in accordance with the rehabilitation plan), because otherwise the butterfly will disappear. Then, the user is required to track the moving butterfly as accurately as possible for a few seconds in order to catch it. Mathematical method for scoring the user's game performance is the same for classic and highly realistic VR environments, and is therefore described in section 3.3.

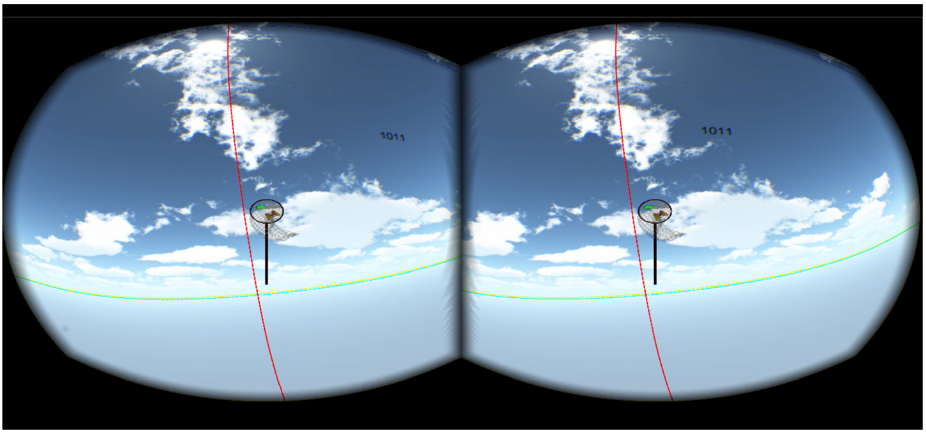


Fig. 6 Butterfly chasing

3.2.2 A highly realistic VR environment

One of the most important assumptions in usage of VR is the immersion of the person in the virtual scene. As one possibility for improving user immersion in the exergame, we propose building a virtual environment that closely resembles a real environment that the user knows. To investigate the possibilities of this approach, we build a 3D model of a hall in our faculty building (Fig. 7). Unreal engine UE4 is used for rendering this scene. UE4 supports physically based rendering and Oculus Rift DK2, which should improve the feeling of realism and thereby the immersion of the person in the virtual scene. Several blue butterflies are added into the scene, and they move following a B-spline curve with the appropriate orientation and wing flapping.

Besides tracking the orientation, the Oculus Rift DK2 enables tracking the position in space. For that purpose, a special sensor to track headset position is used. In our system, we currently do not use this feature, because we focus mainly on the changes in head orientation. Future work could include combined simultaneous changing of head position and orientation.

3.3 Scoring user performance

As the mechanics of the game is the same in all the described environments, we define two measures of success valid in each environment: the reach score and the tracking score. The reach score rewards the fast and accurate reorienting of the user's head to reach a newly shown butterfly, as defined by the formula:

$$P_{reach} = C\cdot\left(1-\frac{t_{\text{reach}}-t_{\text{init}}}{t_{\max}}\right), \quad t_{\text{reach}} < t_{\text{init}} + t_{\max} \tag{1}$$

Measure P_{reach} takes into account the difference between the response time of the user to reach a butterfly (t_{reach}) and the butterfly initialization time (t_{init}), in relation to a predefined empirical time ($t_{\max}$) after which the unreached butterfly disappears. Positive constant C

Fig. 7 Butterflies in the virtual 3D model of our faculty building

determines the maximum score that can be earned by theoretically ideal immediate reaching of the butterfly. The tracking score $P_{tracking}$ depends on the precision of butterfly tracking, which is defined by the angle θ_k between the vector to the butterfly and the view orientation of the user's head. The angle θ_k is measured with the frequency of 60 Hz during the tracking of each butterfly. The user should keep the angle θ_k below the threshold angle α; otherwise, tracking is considered incorrect, which affects the tracking score. Accordingly, $P_{tracking}$ is computed as:

$$P_{tracking} = \frac{100}{N} \sum_{k=1}^{N} (\theta_k < \alpha), \tag{2}$$

where N represents the number of measurements of θ_k obtained during the tracking of a single butterfly, and logical expression ($\theta_k < \alpha$) is evaluated as 1 if true and 0 otherwise. Defining the tracking score in this manner offers a simple interpretation of the tracking outcomes, since the score can be viewed as a percentage of measurements in which the butterfly is tracked correctly by the user. We believe that this simplicity of the measure is an advantage of the system, as it can be intuitively understood and interpreted by the therapist. Achieved cumulative game score,

$$\left\lfloor \sum_{i \in Butterflies} P^{i}_{reach} + P^{i}_{tracking} \right\rfloor, \tag{3}$$

is presented as a reward feedback to the user, but it also represents an evaluation measure of overall successfulness in the game.

4 Postprocessing tool for evaluation

To evaluate the individual performance of each user per each rehabilitation session, we have developed a tool for postprocessing the data collected during the session. A session involves the execution of the system calibration for a particular user, as well as the three target positioning scenarios and the butterfly exergame. After each session, the system generates a corresponding log file, which stores general information about the user and the rehabilitation session, as well as multiple time series with appropriate time stamps, including: the user's head orientation time series; the angular positions of targets in different target positioning scenarios; and the angular positions of all butterflies/flies in the game. From the archived log file, specific session can be loaded on demand in the postprocessing tool.

The postprocessing tool is illustrated in Fig. 8, with blue-colored annotations added to facilitate comprehension. The figure demonstrates characteristic patterns of target motion in static and leaping target positioning, as well as target tracking scenario. The figure also shows that the butterfly chasing game combines characteristics of leaping positioning and target tracking scenarios, i.e. requires the user to make both fast leaping and slower smooth tracking movements.

The postprocessing tool enables a detailed analysis of time series in time domain as well as in Fourier, frequency, domain. The beginning and the end of each sequence (i.e. specific target positioning test or the game) are denoted by vertical red lines in Fig. 8. The user head orientation is drawn in green, target/butterfly/fly position in yellow, and the difference between these two orientations (delta) is shown in red.

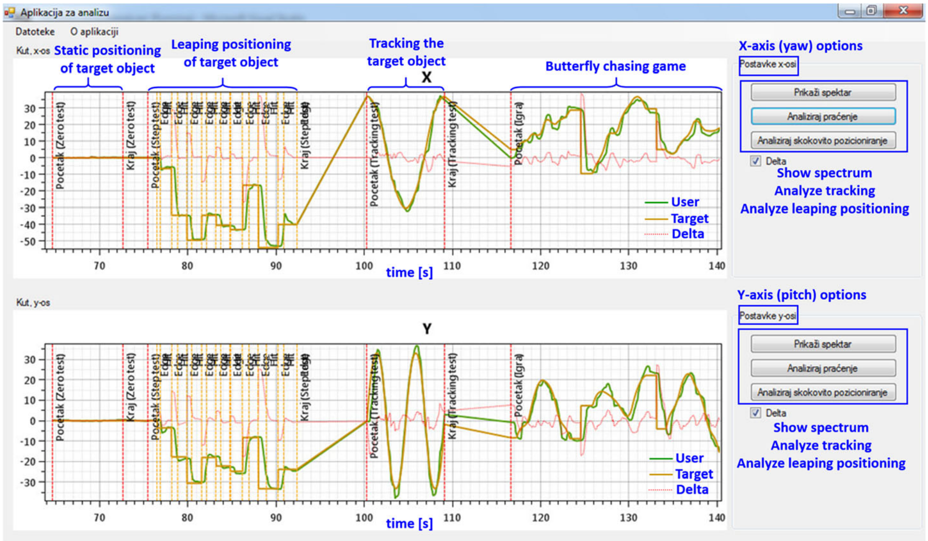


Fig. 8 Postprocessing tool

Using time-domain analysis, velocity and acceleration features, together with validated time-domain features of chronic neck pain, like e.g. jerk index [42], are calculated from the leaping-target scenario and the game. These situations elicit from the user the high-speed movements that are necessary for computation of the proposed features, when the user strives to reach the leaping target or butterflies/flies as quickly as possible. Velocity is computed as a discrete derivative of the angle time series, i.e. green lines in Fig. 8, for instance $v_k = \frac{1}{T} \cdot \left(yaw_{k+1} - yaw_k\right)$, $T = 1/60\,s$, for each sample k of the yaw time series. Acceleration is computed as a discrete derivative of velocity: $a_k = \frac{1}{T} \cdot \left(v_k - v_{k-1}\right)$, $T = 1/60\,s$, since it is necessary in the jerk index computation. Features like mean user's velocity and peak velocity for each leap of the target are calculated, as well as user's response times, i.e. times elapsed from each change of the target's position until the user reaches the new position of the target. By monitoring these and other imaginable time-domain features, in particular features of neck pain that have been validated in prior research works, it is possible to track the progress in the user's neck kinematics over time.

An illustration of frequency domain analysis provided by the postprocessing tool is shown in Fig. 9, using the data obtained from Fig. 8 for y-axis (pitch angle), in each of the three target positioning scenarios. Corresponding spectrograms have been computed via short-time fast Fourier transform using the sliding window 128 samples wide, which corresponds to approximately 2 s of contiguous data due to sampling frequency of 60 Hz. As in Fig. 8, text in the blue color represents annotations added to the tool screenshot to facilitate figure comprehension.

The left subfigure is obtained for static positioning of the target, the middle subfigure is obtained for the leaping positioning of the target and the right subfigure corresponds to the continuous tracking of the target position. In the left subfigure, there is no deliberate movement by the user, so the magnitudes in this spectrogram are much lower than in the middle and right subfigures, which have pronounced red color across the time axis and have larger range in log-magnitude scale. Vertical traces are also visible in the middle subfigure, which correspond to

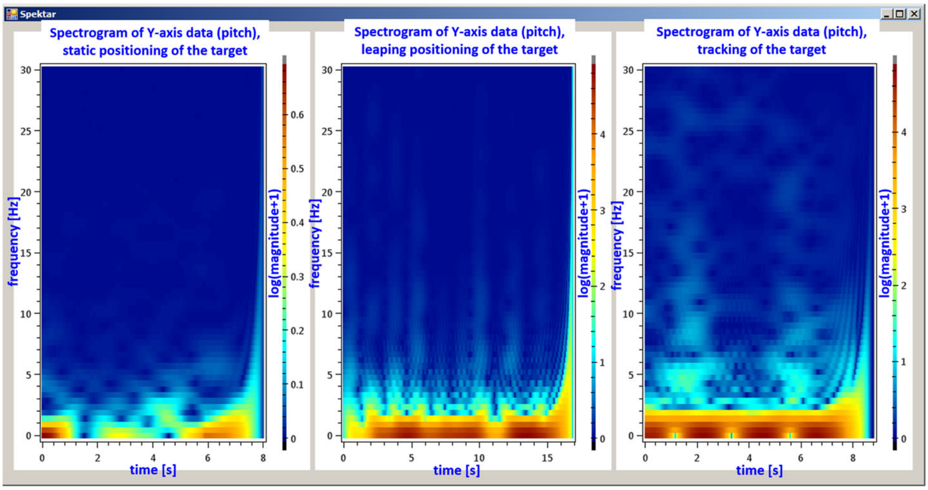


Fig. 9 Frequency domain representation provided for the three target positioning scenarios

the time periods shortly after target position was abruptly changed, which prompted the user to initiate fast head-neck movement to reach the target, temporarily increasing the magnitudes at higher frequencies. Computing the spectrogram in static positioning scenario, in which there is no deliberate motion being executed by the user but only miniscule head oscillations, is important in order to subtract this spectrogram from the spectrograms in other scenarios to reveal frequency content of the user's deliberate movements. Just like time-domain analysis of head-neck movements, illustrated frequency-domain analysis when conducted on healthy persons and patients with acute/chronic neck pain may lead to new findings important for assessment of neck injuries, as well as for therapy progress monitoring.

Further analysis in the context of future work on the postprocessing tool may be related to training of machine learning algorithms on the aforementioned features and psychological measures of the users' pain intensity and disability, in order to detect feature patterns that lead to most effective and efficient recovery.

5 Head-neck rehabilitation exercises: a user study

To alleviate neck pain through physical therapy, medical professionals commonly recommend a series of head-neck rehabilitation exercises that have been proven effective through continuous use in medical practice, as shown, for example, in [39, 47]. Since prior literature indicates that neck exercises help to reduce pain [4, 10, 20, 41], this user study accordingly does not focus on measuring and analyzing the medical effectiveness of these exercises. Rather, the goal is to implement these exercises in a virtual environment and show that the use of a virtual environment can make the exercises more engaging, appealing and interesting for the user, resulting in a better continuity of physical therapy. Furthermore, the VR devices used in the proposed system can automatically measure a number of parameters as the user performs an exercise, adding a degree of quantifiable evaluation to the qualitative evaluation performed by a medical professional. Through tuning the parameters of the VR environment, the medical professional can consistently and precisely guide the range of movements performed by the users to ensure compliance with the prescribed exercise regimen.

To evaluate the potential of the proposed system for measuring quantifiable parameters of neck motion, guiding the range of neck movements, as well as to objectively measure how engaging and immersive the system is to end users, we perform a comprehensive user study.

5.1 Overall study design

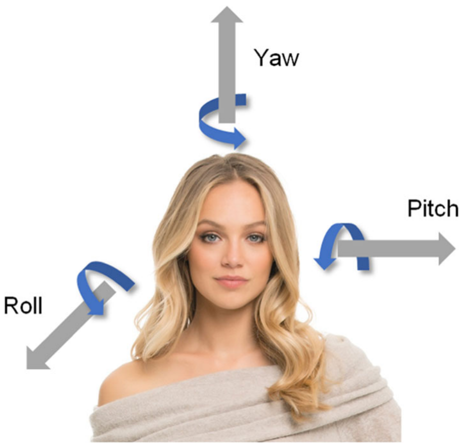
In the user study, we apply a neck pain exercise regimen prescribed by medical professionals from the Croatian Polyclinic for Rheumatic Diseases, Physical Medicine and Rehabilitation. Specifically, we implement the following three exercises in the virtual environment: (i) “Turn your head to the right and attempt to touch your right shoulder with your chin. Repeat the same motion to the left side.”; (ii) “Tilt your head right as if attempting to touch your shoulder with your ear. Hold, then return the head to its normal position. Repeat the same motion to the left side.”; (iii) “Holding the head in its normal position, turn your head downward as if trying to put your chin on your chest. Hold, then return to normal position. Repeat the same motion in the upward direction.”

In the context of computer graphics, these exercises represent three Euler angles in a coordinate system defined by the human head that performs yaw, roll and pitch. Yaw represents the head turning left-right and corresponds to the first exercise, which is therefore called yaw exercise. Likewise, roll represents the head rotating around the view axis and corresponds to the second exercise (roll exercise), and pitch represents the head nodding and corresponds to the third exercise (pitch exercise). An illustration of the three exercises is shown in Fig. 10.

The user performs the exercises by visually tracking a butterfly in the virtual environment. When the angular tracking error is below a predefined threshold angle α, as described in section 3.3, the butterfly emits a particle system that acts as a reward to the user, giving feedback information that the exercise is performed correctly.

The exercises are repeated in three scenarios: (i) a classic VR environment, where the butterfly is moving in an empty space containing some textures (Fig. 11), referred to as VR1 scenario; (ii) a highly realistic VR environment where the butterfly is moving in a VR model of our faculty building rendered in high detail (Fig. 12), referred to as VR2 scenario; (iii) without

Fig. 10 Head rotations in three main directions: yaw, pitch and roll



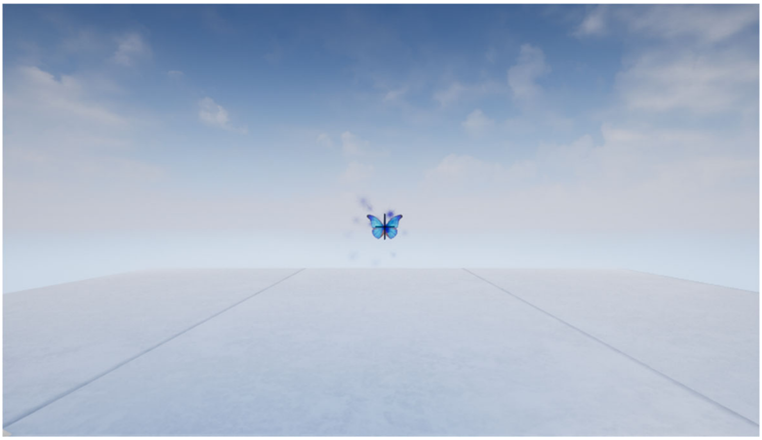


Fig. 11 A classic VR environment used in VR1 scenario

VR environment, i.e. the user repeating the required exercise motions while the VR headset is showing a blank screen, referred to as BLANK scenario. The position of the user's head is measured and recorded at 60 Hz and used to calculate the tracking score $P_{tracking}$, as described in section 3.3. In our user study only one butterfly is used, since a single butterfly in continuous motion is sufficient for implementation of the described exercises. As the butterfly's location is initially aligned with the user's normal viewing direction and there is only one butterfly, the reach score P_{reach} is not measured, because all users would get the maximum reach score. For the same reason, there is no use for the butterfly net described in section 3.2.1; instead of catching the butterfly with the net, the butterfly emits shiny particles as an indicator that the user is tracking it correctly. While there are leaping target-based gaming scenarios where the reach score P_{reach} and butterfly net can be used, the movement patterns in this user study were continuous, rather than sudden and jerky movements that might be unsafe without supervision by a medical professional.

Fig. 12 A highly realistic VR environment used in VR2 scenario

Aside from quantifying the tracking score $P_{tracking}$, we measure the minimum and maximum range of motion of the neck for all three exercises in each of the three scenarios. Furthermore, we perform a perceptual study in which we ask the users to qualitatively evaluate their experience of using the system.

A total of 30 users aged 18–50 participated in the study. According to the users' self-report, none of them had medically diagnosed acute or chronic neck issues, and three users reported that they generally experience some soreness/unpleasantness in the neck area without the need for medical intervention.

5.2 Quantitative evaluation methods and results

In the quantitative evaluation, we measure the mean tracking score of the 30 users who participated in the study, along with its standard deviation, depending on the angle α (see Eq. (2)). The tracking score is measured for each exercise (yaw, roll and pitch) in each of the two VR scenarios (VR1 - a classic VR environment, and VR2 - a highly realistic VR environment). We also compute the mean tracking error and its standard deviation for each exercise in these scenarios, using the corresponding tracking error time series; for example, yaw tracking error time series are:

$$E_{yaw} = \left(|yaw_k^{user} - yaw_k^{butterfly}|, \ \ k = 1, 2, \dots, N \right) \tag{4}$$

where N represents the number of measurements of the user's and butterfly's yaw angle during the first exercise. The results are summarized in Table 1.

We see that the tracking score depends on the selected threshold angle α. As expected, setting a smaller threshold results in smaller tracking score values.

In a physiotherapy session, the threshold α can be set by the therapist depending on the exercise and the required performance of the patient with respect to the goals of the session. The user receives instant feedback in the VR environment, as the butterfly emits a particle system as long as the tracking is correct. The system can also be configured to show the numerical score in the VR environment, serving as a further feedback and motivation to the user.

Table 1 Tracking score and tracking error means and standard deviations in the two VR scenarios (VR1 - a classic VR environment, VR2 - a highly realistic VR environment) for different threshold angles α

Scenario		Tracking score						Tracking error	
		α = 3°		α = 5°		α = 7°			
		Mean [%]	StDev [%]	Mean [%]	StDev [%]	Mean [%]	StDev [%]	Mean [°]	StDev [°]
VR1	roll	55.96	19.57	79.30	16.16	91.05	10.17	3.25	1.24
	pitch	70.64	10.86	88.42	8.87	97.35	5.03	2.30	0.62
	yaw	46.01	8.06	74.83	11.25	93.84	7.29	3.45	0.62
VR2	roll	57.01	14.94	80.43	11.96	91.51	8.57	3.20	1.10
	pitch	76.86	11.84	96.24	4.50	99.50	1.47	1.89	0.52
	yaw	55.59	11.44	84.06	11.12	95.80	6.07	3.01	0.71

Overall, the best tracking scores were obtained for the pitch exercise, regardless of the selected threshold α, which indicates that the pitch exercise was the easiest to perform correctly for our sample of users. The tracking scores in the highly realistic VR2 scenario seem to be somewhat better than in the classic VR1 scenario. The reasons for this are inconclusive; while it might be the case that the highly realistic environment is more motivating to the users, it is also possible that the users have performed better simply because the highly realistic VR environment was shown *after* the classic VR environment, so the users knew what they were required to do and their neck muscles were already warmed up.

Aside from measuring the tracking score, we also measured the users' range of motion for all three exercises (yaw, roll, pitch) in each of the three experimental scenarios, i.e. VR1, VR2 and BLANK scenario (Table 2). In the classic (VR1) scenario, the yaw range of the butterfly was set to [−90°, 90°], the pitch range to [−60°, 60°], and the roll range to [−30°, 30°]. In the highly realistic (VR2) scenario, we left the yaw and pitch ranges unchanged and modified the roll range to [−40°, 40°] to evaluate whether this modification will result in a change in user performance. In the BLANK scenario, we told the users to repeat the exercises moving their head as much as it felt comfortable.

We see that in the VR scenarios the users' range of motion in any direction, yaw, roll or pitch, corresponds with the set exercise ranges. Modification of the roll range of the butterfly from [−30°, 30°] in the VR1 scenario to [−40°, 40°] in the VR2 scenario is reflected in mean roll ranges achieved by the users which are very close to the set values. The same is true for the minimum pitch value. In terms of maximum pitch value, the mean value achieved by users is somewhat smaller than the set 60°, showing that angling the head in such a way is difficult. While the mean maximum pitch for the unguided, VR-free exercise in BLANK scenario is over 60°, which might seem contradictory, we note that the standard deviations of measurements in that scenario are much higher than in the two VR scenarios. In other words, while some users are able to reach angles higher than the set 60°, others reach angles smaller than 60° when asked to repeat the motion in an arbitrary manner not guided by the VR target. It is also interesting to analyze the obtained yaw ranges, where we see that the comfortable range obtained when users performed the exercise while shown a blank screen is approximately [−82°, 84°]. Our measurements show that by following a VR target that range is increased to approximately [−87°, 85°] and the standard deviation is much smaller, i.e. the users are guided to perform the exact required therapeutic motion with little variation among individuals, and the exercise motivates them to push a bit past their comfort region. This serves to illustrate that

Table 2 Means and standard deviations of users' range of motion, in all three directions of head rotation. Butterfly's range of motion for roll, pitch and yaw was ±30°, ±60°, ±90° respectively in VR1 scenario, and ±40°, ±60°, ±90° respectively in VR2 scenario (VR1 - a classic VR environment, VR2 - a highly realistic VR environment, BLANK - exercise without VR)

		Scenario VR1		Scenario VR2		Scenario BLANK	
		Mean [°]	StDev [°]	Mean [°]	StDev [°]	Mean [°]	StDev [°]
Roll	min	−30.35	3.35	−39.59	3.19	−43.72	12.25
	max	32.23	4.61	39.73	3.38	43.97	12.39
Pitch	min	−58.90	2.00	−59.17	2.54	−59.55	10.63
	max	54.36	1.61	56.17	0.85	62.08	9.77
Yaw	min	−85.05	2.49	−86.50	3.68	−81.74	10.11
	max	84.85	1.74	85.31	1.89	83.66	8.78

Table 3 Users' mean responses to the five questions in the qualitative evaluation study (VR1 - a classic VR environment, VR2 - a highly realistic VR environment, BLANK - exercise without VR)

	Scenario VR1	Scenario VR2	Scenario BLANK
Q1	3.53	4.00	1.97
Q2	3.53	4.31	N/A
Q3	2.94	2.63	3.69
Q4	3.34	3.78	2.25
Q5	4.47	4.63	3.78

our system could be used in a real physiotherapy session, enabling the therapist to precisely prescribe and monitor the exact motions needed for the therapy, in contrast to just demonstrating the exercises to the patients for practice at home, which the patients might then perform incorrectly. Furthermore, the therapist could set goals in individual exercises that would gradually improve neck range of motion, e.g. through starting with smaller ranges and working in small increments until full neck function is restored. The system is not limited to the three exercises prescribed here: complex motions with leaping and directional changes could easily be implemented through scripting the behavior of the target.

5.3 Qualitative evaluation methods and results

As a follow-up to quantitative evaluation where the users were asked to perform three exercises in three scenarios, we performed a perceptual study asking the users to evaluate their experiences with each of the scenarios. The users were asked a series of five questions with the answers recorded on a Likert scale of 1 to 5. The questions were as follows: (Q1) How fun was the activity? (1 – not fun at all, 5 – very much fun); (Q2) How realistic was the VR environment, if applicable? (1 – not realistic at all, 5 – highly realistic); (Q3) Did you feel like you were performing a physical exercise? (1 – not at all, 5 – totally); (Q4) Is it likely that you would perform the activity again? (1 – not likely at all, 5 – very likely); and (Q5) Is it likely that you would perform the activity again if it were medically necessary? (1 – not likely at all, 5 – very likely). The mean response scores are summarized in Table 3, and individual response distributions for each question are shown in Figs. 13, 14, 15, 16, 17.

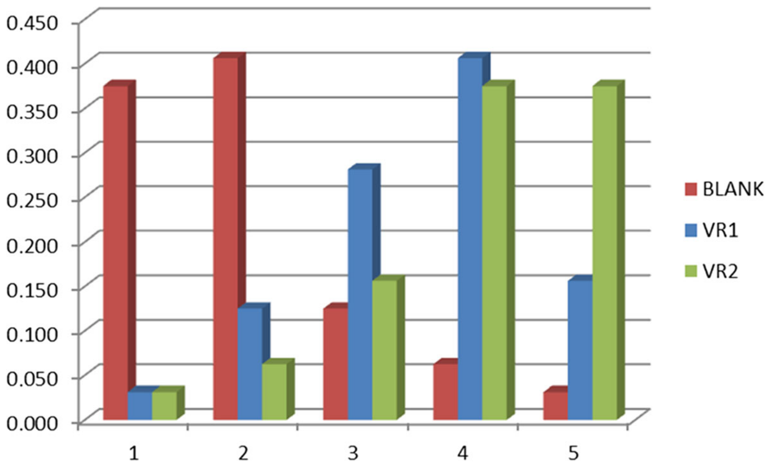


Fig. 13 Distribution of answers to question Q1: How fun was the activity? (1 – not fun at all, 5 – very much fun)

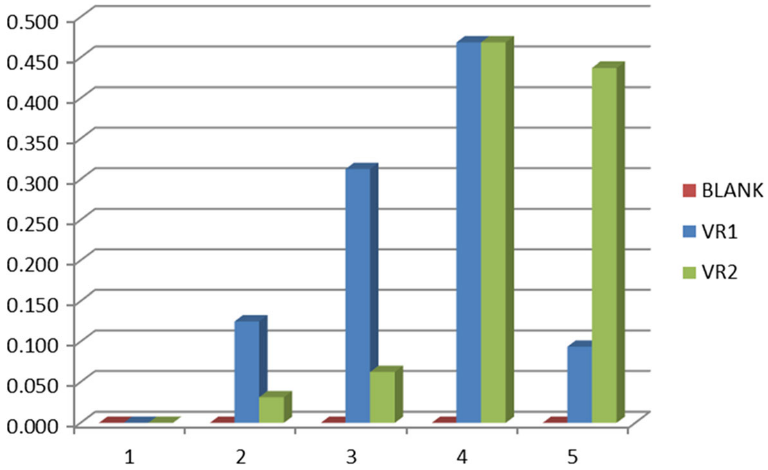


Fig. 14 Distribution of answers to question Q2: How realistic was the VR environment, if applicable? (1 – not realistic at all, 5 – highly realistic)

We see that the users perceive the VR exercises as more fun than exercising with the VR screen turned off (question Q1, where the perception of fun of the VR1 scenario was rated at 3.53, the VR2 scenario at 4.00 and the BLANK scenario at 1.97). The VR2 scenario with the highly realistic environment is perceived as more fun than the VR1 scenario with classic environment. Also, as expected, the users perceive the VR2 scenario as more realistic than the VR1 scenario (question Q2, where the realism of the VR1 scenario was rated at 3.53 and the realism of the VR2 scenario at 4.31). Exercising in the VR environment lowers the users' perception of being engaged in physical exercise, and this is especially the case when a highly realistic environment of VR2 scenario is used (question Q3, where the VR1 scenario was rated to be similar to physical exercise at 2.94, the VR2 scenario at 2.63 and the BLANK scenario at 3.69). The users are more likely to want to play the VR game again than to want to perform the

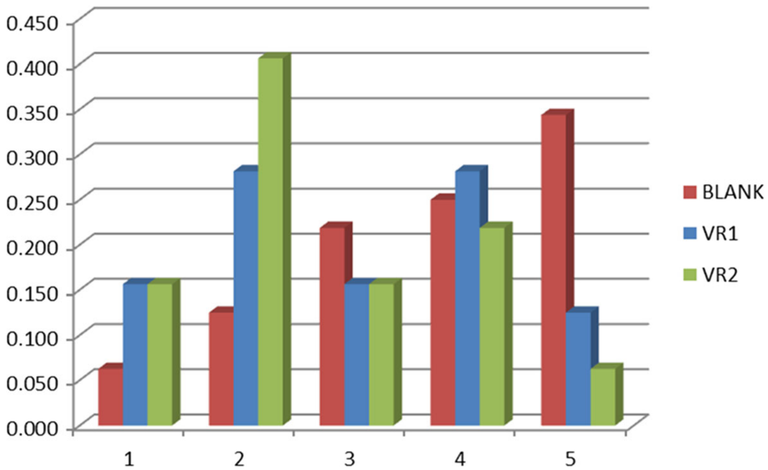


Fig. 15 Distribution of answers to question Q3: Did you feel like you were performing a physical exercise? (1 – not at all, 5 – totally)

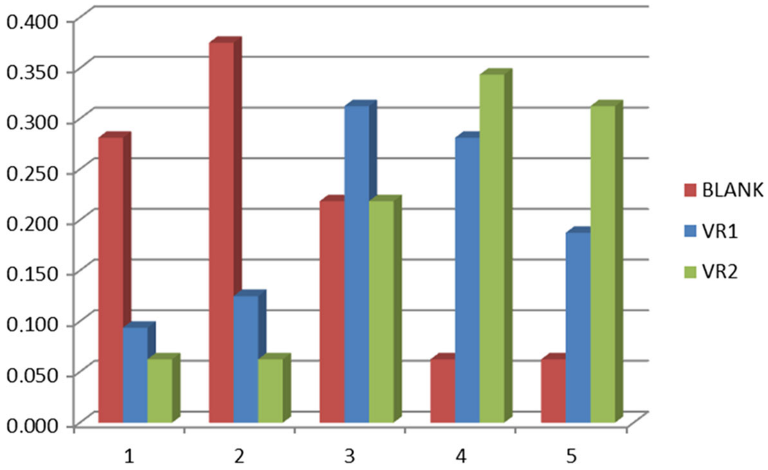


Fig. 16 Distribution of answers to question Q4: Is it likely that you would perform the activity again? (1 – not likely at all, 5 – very likely

neck exercises without VR (question Q4, where the likelihood of repeating the activity was rated at 3.34 for the VR1 scenario, at 3.78 for the VR2 scenario and at 2.25 for the BLANK scenario). Finally, if medically necessary to perform neck exercises, the users prefer to do them in a VR environment, and they prefer the highly realistic environment of VR2 scenario over the classic one of VR1 scenario (question Q5, where the likelihood of repeating the activity was rated at 4.47 for the VR1 scenario, at 4.63 for the VR2 scenario and at 3.78 for the BLANK scenario). This perceptual study shows that our system presents an engaging and motivating alternative to neck pain exercises, even if implemented in the form of a single butterfly tracking VR game as in our user study. More imaginative and complex VR games, e.g. with multiple butterflies as described in section 3.2.1, should further increase the users' motivation to perform these exercises correctly and according to schedule determined by the therapists.

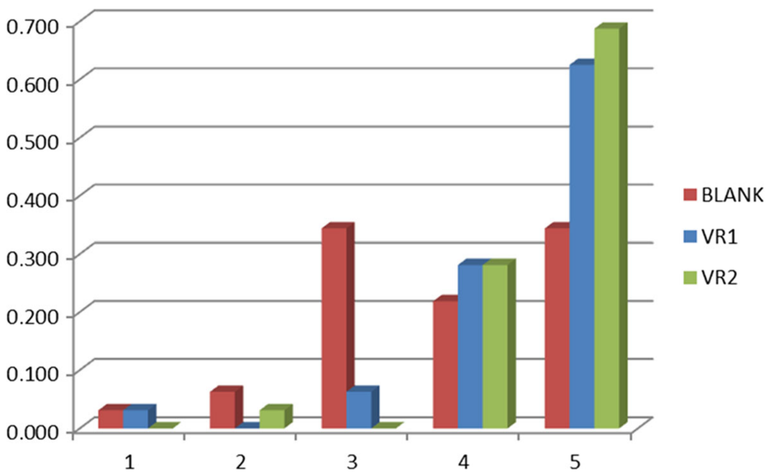


Fig. 17 Distribution of answers to question Q5: Is it likely that you would perform the activity again if it were medically necessary? (1 – not likely at all, 5 – very likely)

6 Conclusion

We have presented a system for neck exercises that utilizes VR and serious gaming to keep the user engaged in the exercise process. Simultaneously, the system gathers valuable information concerning the range of motion and overall kinematics of the user's neck that enables a domain expert to monitor the user's progress and adapt the exercise program accordingly. In the described study with asymptomatic users, the system has been tested in configurations without visual feedback to the users regarding the performed exercises (blank screen) and with two kinds of virtual environments: a classic VR environment and a highly realistic VR environment that closely resembles the real-world environment known to the users. It was found that the users perceived VR environments as more motivating than blank screen to perform simple neck rehabilitation exercises, which should therefore promote exercise adherence and facilitate recovery.

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