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Abstract:

Context: Chronic low back pain is a major cause of disability in the world. As most cases have no pathological cause, methods have traditionally been focused on graded exposure therapy and exercise. These methods however, are costly in terms of manpower, have unclear time spans, and are often associated with high patient attrition.

Objectives: With the advent of affordable high performance virtual reality system, we investigate the feasibility and acceptability of a virtual reality game for treatment of chronic low back pain.

Methods: We used graded activity, biofeedback, and gamification principles to create a virtual reality dodgeball game where patients have to pick up balls and hit enemies. We create a full body tracking solution such that we can tailor the game to the individual patients range of motion. The game is further created with feedback from an expert in pain rehabilitation.

Results: The game is tested with experts, patients, and a healthy sample. The experts were interviewed on feasibility and usability, patients on acceptability, and healthy participants on general usability. The findings showed that the game in a clinic setting was very feasible, and patients were high encouraged by the game, and moving more than baseline.

Conclusion: We found that the game could be used in a clinic setting, and patients are very willing to play as well as finding it fun, while not increasing or decreasing back pain, and provides suggestions for future improvements.

Virtual Reality Graded Exposure Therapy for Chronic Low Back Pain: A Pilot Study

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Medialogy Master's Thesis
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1 Introduction

Low back pain is among the leading causes of disability in the world, and alone in Denmark accounts for ten percent of primary care visits, 30% of physiotherapist visits, and over 4.5 billion Danish kroner lost in production. Current rehabilitation methods are focused around graded exposure therapy, and while these are effective, they suffer from high patient attrition and significant costs. With the advent of affordable, high performance virtual reality systems, research has increasingly been focused on using this new technology in rehabilitation. Indeed, virtual reality has already shown promising results in a variety of acute and chronic pain conditions. This report aims to create a virtual reality rehabilitation game for chronic low back pain patients, which employs graded activity, motivation, and gamification principles. This report seeks to investigate feasibility with experts in the field, as well as patients, both utilising the virtual reality platform, and full body kinematic feedback for this purpose.

2 Literature Review

This literature review will touch upon the issue of low back pain and explore the fear avoidance model of chronic low back pain. It will then go on to virtual reality in rehabilitation and continue with how body movement is captured in virtual reality, and how it has been used.

2.1 Chronic low back pain

According to Refshauge and Maher (2006), chronic low back pain (CLBP), is back pain which persists for more than three months. In a Danish context, according to the National Institute of Public Health (Flachs et al., 2015), low back patients account for ten percent of all visits to primary care, and 30% of all visits to physiotherapists. Low back pain is responsible for twenty percent of all sick leave days, and 4.836 billion Danish kroner in lost production. Despite the issue being a growing problem, clinical trials are currently unable to determine the tissue source of the pain in most cases (Hartvigsen et al., 2018), and term it non-specific CLBP (Refshauge and Maher, 2006). Henschke et al. (2009) studied 1,172 new presentations of acute pain, and only found direct pathological reasons for 0.9% of the participants. This has led research to increasingly focus on the psychological factors, such as depression, anxiety, and catastrophizing (Hartvigsen et al., 2018). Catastrophizing is the act of thinking about the worst possible outcome of movement, and thus avoiding that movement even if it may be beneficial. The fear-avoidance model, which describes how fear of pain and movement leads to avoidance, deconditioning and in turn more disability, is a well-established model regarding these factors, and is a strong indicator of whether a person will transition from acute pain to CLBP (Chou and Shekelle, 2010). Lee et al. (2015), found that self-efficacy, psychological distress, and fear explained a relationship between pain and disability, based on a systematic review of twelve studies. Springer et al. (2016) based a project on the Fear of Daily Activities Questionnaire by George et al. (2009), which is used to assess ten mandatory and two optional activities where a patient can input other activities to rate from zero to ten. Springer however used virtual avatars to create video clips which patients would rate, thereby establishing a fear hierarchy which is then used to plan the treatment of patients with CLBP.

Bailey et al. (2010) systematically reviewed seventeen studies, and found that the most promising and effective methods of overcoming fear-related pain is *acceptance and commitment therapy*, *graded in vivo exposure*, and *graded activity*. Acceptance and commitment therapy is the idea that patients are encouraged to take part in activities previously avoided due to the fear of pain, and instead acknowledging the pain as part of their present situation without attempting to control it. This method facilitates a shift in focus away from pain onto other values in the patients lives. Graded in vivo exposure works by arranging previously avoided activities in a hierarchy according to pain expectancy. Patients are then over multiple sessions exposed to more and more activities previously avoided, while providing ratings of expected pain and fear before and after each activity. This method seeks to reeducate patients about their fear such that avoided activities can be performed. Graded activity is similar. Instead patients are asked to assess their functional degrees of motion (45° right side lateral bending for ten minutes), and gradually approach this baseline tolerance by engaging in twenty percent movement, 40% movement and so on. This is typically coupled with positive reinforcement by therapists.

According to Foster et al. (2018), the common first line recommendation among western countries for treatment of low back pain is to remain active, and education. Emphasis is placed on self-management, physical, and psychological therapy (cognitive behavioural therapy). In line with the aforementioned, Stochkendahl et al. (2018), and Nijs et al. (2017) recommends interaction between the patient and the health care professional, reassurance, and persuasions to limit the patients fear of movement and illness. As no evidence exists for one exercise being better than another, it is often recommended that graded activity is used, where patients are more and more exposed to the avoided movement (Foster et al., 2018).

Furthermore, Nijs et al. (2017) highlights potential inefficiency in treating CLBP without the knowledge and understanding of the underlying pain and sets out to inform and update general practitioners about the current knowledge of pain with regarding the condition, and how they can utilise this in a clinical context.

Nijs et al. (2017) explains that the amygdala is the central target for exercises as it is the fear-memory centre and is associated with fear- and pain-memories and one's negative emotions. It also has a role when painful memories are created, connections between an experience and the emotion tied to it. Together with the hippocampus and anterior cingulate they are responsible for applying protective behaviours (guarding) or avoidance when encountering movements where painful memories are attached. Even the preparation or visualisation of a perceived dangerous motion, can provoke pain and alter the patient's strategies.

Nijs et al. (2017) also presents the cognition-targeted method, where a patient is asked to do an exercise 10 times regardless of what it induces. This approach needs to take the patient's individual pain into account, as it tries to rewire the idea of pain when doing exercises and daily activities. It also includes extensive discussions of the anticipated consequences and the perceptions before, during and after each exercise. In these discussions, and compassion focused therapy is often utilised.

Wertli et al. (2014) systematically reviewed 78 articles and found the recommendations for treatment of LBP is inconsistent and often touches on anecdotal beliefs of the general practitioners. In addition, an idea presented is to categorise patients into the different types of avoiders e.g. misinformed, learned pain, and affective avoiders, and adjusting their treatment accordingly. Their main finding shows that fear avoidance beliefs should be confronted or it may delay their recovery and chronicity.

While conventional graded activity has been found among the most effective methods

(Bailey et al., 2010; Hartvigsen et al., 2018), there are a number of limitations to this protocol. Firstly, the patient typically needs to be supervised by a team of professionals, and rely on multiple sessions for an indefinite timespan, increasing cost and decreasing transparency (Trost and Parsons, 2014). Furthermore, graded activity is typically associated with high drop-out rates (attrition). Reasons are unclear, but seem to point towards little motivation, that they are too psychological, body-fat, and poorer general health status (Bailey et al., 2010; Oleske et al., 2007).

2.2 Virtual reality in rehabilitation

Virtual reality in different clinical contexts has been found to be a capable tool when used for managing pain, rehabilitation cognitive assessment, clinical education, and improving motor functions and biomechanics when used as physical therapy. Further, the distraction-therapy which the technology facilitates has been found to outperform standard pharmacotherapy when dealing with treatment of pain and anxiety (Pourmand et al., 2017).

Tabak et al. (2017) along with experts in the field, created a game simulating daily living where CLPB patients had to pick fruits and vegetables in different heights, clean up their virtual apartment, and make soup. The players were then rewarded for doing the tasks. Tabak further found seven rehabilitation requirements and translated them into requirements for a virtual reality application. The virtual reality requirements are as follows:

- Familiar environment with activities of daily living.
- Distracting elements, and graded exposure to stressors.
- Graded exposure to amount and/or intensity of the stimuli.
- Graded activity (Same task with different difficulty levels).
- Relaxing environment.
- Provide in-game feedback and/or request input from user.
- Utilise biofeedback.

Jin et al. (2016) created a virtual reality "on-rails shooter" where the user would throw snowballs at different types of enemies, and where they were meant to remember a pattern of different figures throughout and recall them in order at the end for bonus points within the game. They found that their application could significantly reduce chronic pain sufferers' perception of pain intensity. Vilalta-Abella et al. (2015) developed a virtual environment for fibromyalgia, a disorder which causes widespread chronic pain in different musculoskeletal systems. They found that patients could modulate and visualise their perceived pain in a 3D human body. By watching the movement of a virtual character mirror, neurons activate as if that person was moving themselves, which in turn reduced their perceived pain.

Thomas et al. (2016) create a virtual dodgeball arena to treat CLBP using a 3D television, and optically reflective markers to capture kinematic data of users. They performed an experiment of pain and harm expectancy and lumbar spine flexion over two months with a treatment and control group. Thomas found that patients experiencing the game would move more, but found no change in pain expectancy, apart from it decreasing as patients in either group underwent more sessions. Jones et al. (2016) found that patients suffering from chronic pain, had a 33% decrease in pain shortly after being exposed to virtual reality, and 60% during exposure of a snowball game for a variety of chronic pain patients. Jones hypothesise this is due to the gate control theory of pain, where non-painful input can close "gates" which block painful sensations from reaching the central nervous system. Mahrer and Gold (2009) link this phenomena to the presence and distraction that virtual reality induces. According to Jerald (2015) presence is the sense of "being there", in this case the feeling of being present in virtual reality. Presence is the psychological state where all or most of the current experience is being generated and mediated by some technology. This is not to be confused with immersion, which is a characteristic of the technology. Immersion is something the system delivers, and as such pen and paper roleplaying can deliver immersion into a game, just as a 3D television can, to varying degrees.

Schönauer et al. (2011) developed their own motion capture system for motor rehabilitation. They derive through different requirements for input devices used in rehabilitation games, that the system should firstly track patients reliable and stable. Second, multiple degrees of freedom have to be recognized. Thirdly, the system has to provide real time feedback to foster "knowledge of performance". Finally, to foster "knowledge of results" the measured data should be comparable between patients and therapy sessions.

2.3 Related technology

Due to aforementioned requirements from Tabak et al. (2017) and Schönauer et al. (2011), it is relevant to look at technology which can be used as biofeedback in a virtual reality application.

2.3.1 Marker based motion capture

Marker based motion capture systems are classified as an outside-in system (Menache, 2011). Such a system is typically multiple (8-32) cameras in an array connected to a single computer, enclosing an area where the actor performs. The cameras record with a framerate of 60 frames per second, and up to 120 frames per second in scenarios with high velocity movement. The actors are outfitted with motion capture suits, which are full body suits with highly reflective spherical markers, being illuminated with LED's attached to the rim of the cameras. The markers can be as small as a couple of millimetres for facial motion capture, to a couple of centimetres for joint motion. The system is calibrated using a "wand", which is an object of a known size, outfitted with reflective markers. The wand is placed such that all cameras can see it. It is recommended to recalibrate often as a slight bump to any of the cameras will interfere with the tracking. After recording, image processing techniques (thresholding) are used to isolate the markers from noise in the recording. Afterwards, the 2D coordinate of each marker must be determined for every camera and tracked through time.

Another marker-based system is using trackers associated with virtual reality systems such as HTC Vive and Oculus Rift. The HTC Vive system (SteamVR Tracking version 1) works by having two devices (lighthouse base stations) setup to create a rectangle shape enclosing a play area. These base stations emit a fan of infrared light that sweeps the play area horisontally and vertically. The head-mounted display (HMD), and two controllers worn and used by the user, knows the timing of these sweeps (through synchronisation signals), and determine the position of the HMD and controllers based on when the infrared light hits several infrared photodiodes on the devices.

Soffel et al. (2016) found that the HTC Vive and its precise head tracking would be superior to other VR systems, when looking into postural stability in a VR scenario. In addition, they found that it could be used for rehabilitation in patients' homes. Borrego et al. (2018) compared the Oculus Rift and HTC Vive, by placing the HMD's on a mount at three different heights as well as outside of the recommend work area. The Oculus Rift proved to have less jitter and be more accurate though they state that both HMD's should be highlighted and put into context. Furthermore, they found both systems feasible for serious games and rehabilitation. Yang et al. (2017) recorded positional accuracy using a slider moving a HTC Vive tracker in front of the base stations, at three distances. Yang recorded angular accuracy by placing a tracker on a turntable and rotate it 5 degrees at a time on one axis at a time, at three distances. Yang found an average positional accuracy of 1.465 mm and an angular accuracy of 0.32 degrees. Sletten (2017) developed test cases for general movement, speed, and jitter over time, with a HTC Vive controller attached to a robot arm. Sletten found similar to Yang that the positional accuracy is within one mm.

2.3.2 Marker-less motion capture

Marker-less systems are classified as inside-out systems (Menache, 2011), because they employ sensors outfitted directly to the actor, without external equipment. The actor can wear a suit with a number of small sensors capable of capturing movement in it's own frame of reference. These are called micro electro-mechanical systems (MEMS) inertial sensors, which are either capable of capturing the angular velocity in three axis (gyroscope), acceleration in three axis (accelerometer), or measure the Earth's magnetic field in three axis (magnetometer). This information can also be combined (fused), to counteract noise and inaccuracies specific to each of the three sensors.

Hellmers et al. (2017) found these suits provide a high enough accuracy for gait analysis, while costing significantly less in comparison to optical marker-based systems. Rojas-Lertxundi et al. (2017) performed a similar study on jump analysis and found the recent development in IMU accuracy and decreasing price, makes them suitable. Nevertheless, they note IMU's are slower than optical based systems. However, according to Menache

(2011), one big drawback with IMU-based systems are they can be obtrusive to human motion, they apply constraints to the joints, and they do not measure global translations. Magnetometers are furthermore, sensitive to nearby metals, typically found in buildings made from reinforced concrete. Other technologies include the Windows Mixed Reality (WMR) platform by Microsoft. WMR works by having users wear a HMD where cameras on the front side point outwards and down to both track controllers with LED's and perform real time simultaneous localization and mapping (SLAM) using optical flow, where environmental features in the physical play area are tracked across frames to determine the position of the user (Aaron et al., 2017a), (Aaron et al., 2017b).

2.3.3 Pose estimation

In rehabilitation scenarios it is important to ensure body pose measurements are accurate if these are used to tailor the experience. Roth et al. (2016) developed an inverse kinematics system using only five markers (both hands, feet, and head), using the Optitrack marker-based motion capture system, feeding data into the Unity3D engine. They found system latency and task load was lower with fewer markers, suggesting users are more "comfortable". Hellmers et al. (2017) built a gait analysis algorithm that analyzed hip, knee flexion, and ankle flexion, with regards to the Joint Coordinate System. They used an IMU suit and validated measurements with video recordings and with regards to accuracy of gait recognition found mean precision at 0.86 and mean recall at 0.98.

Estimating the position and rotation of intermediate limbs between two markers, for example the leg, is commonly known as inverse kinematics. Inverse kinematics is the problem of finding the configuration of limbs with a known length, given the position of the end effector, e.g. a foot. A popular method to solve this problem (a solver) is FABRIK, by Aristidou and Lasenby (2011). FABRIK is an iterative algorithm that moves one joint at a time, and moves the next joint in the chain based the fixed distance between each, along a line from the previously moved joint. This solves the problem of having matrix computations at each step such as with the jacobian methods. It works backward and forward continuously until it has found a valid configuration of all joints that satisfy the root joint does not move, and the end effector is reaching the target within some heuristically defined error margin.

In order to use the measurement of a system, in this case a virtual reality tracking system, to accurately depict a person's movement, ground truth is needed, where data is compared and validated between systems. These comparisons have been done by placing sensors of objects with fixed and known movement (Shin et al., 2016), or comparing an optoelectronic system and a Microsoft Kinect (Gaukrodger et al., 2013). To ensure accuracy between the measured pose, and the real-world pose, a common method is comparing using video frames, and measuring the angles between joints photographically (Hellmers et al., 2017). Clark et al. (2012) compared the Microsoft Kinect with a full 3D motion capture system, with the purpose of using the Kinect in a healthcare environment. Their test consisted of having users perform three postural tests, and measuring flexion angle between joints with a Pearson correlation, ordinary least products, and Bland-Altman 95% limits agreement.

3 Design

3.1 Equipment for the tracking system

The chosen virtual reality system for this application is the HTC Vive. The Vive uses controllers worn in each hand, and a head-mounted display (HMD). In order to track more features of the human body apart from the head position and hand position, more tracking information is needed. This issue is solved by using the HTC Vive trackers which are rigidbody trackers that can be fastened with $\frac{1}{4}$-inch screws and tracks the absolute position and rotation of itself, inside the play area. To track the motion of the back, we have to track the feet and have trackers placed on the back, such that the rotation and position of the back always is in reference to the feet. To test how many trackers are needed to be secured on the back for reliable and accurate lower back measurements, a test was set up (see section 4.3). Inspiration for the position of the trackers on the human body was taking from the Unity's Humanoid Avatar (Unity Technologies, 2018), seen in figure 3.1.

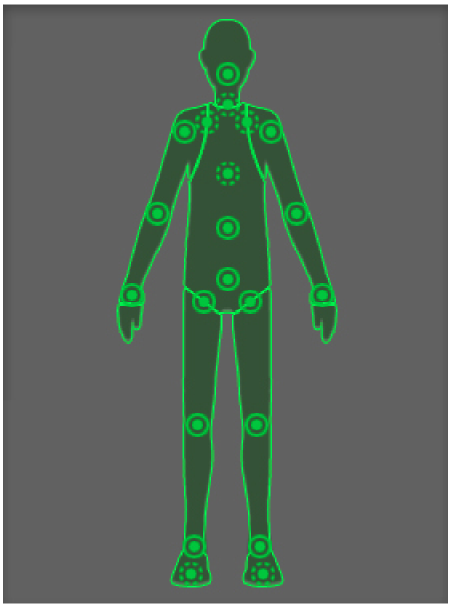


Figure 3.1: The Unity Game Engines humanoid avatar, used for animation purposes. Circles highlight joints of the body which can be affected by rotation and/or position.

Since the idea is that the user should be able to walk into a room with the device and play without help, the equipment should be something which one person has no problem taking on and securing themself.

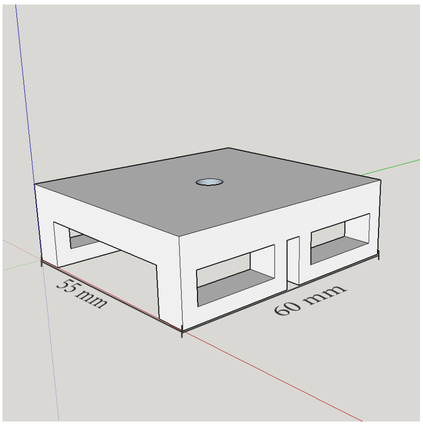
As seen in figure 3.1, there is a possibility of having multiple trackers on the back (hip, lower spine, upper spine, neck). With this in mind, a backpack was adapted and chosen as base for the trackers. The entire front of the backpack was removed, a waist belt was added for tightening, velcro along the spine, zippers on each side of the spine with a net in between. Small pieces of wood with $\frac{1}{4}$-inch bolts screwed in were fitted velcro on the back and placed in between the velcro on the backpack and the net. The adapted backpack can be seen in figure 3.2. The velcro allows for moving the trackers along the spine and accurately position them in alignment with the humanoid avatar in Unity.

Figure 3.2: The backpack finished on a person with a tracker on the lowest placement.

To track the position of the feet, a small mount was 3D printed with holes for elastic bands. Since the Vive trackers used to track the feet have standard $\frac{1}{4}$ screw threads, bolts originally made for cameras were fitted through the mount to secure the trackers, along with a small piece of foam in between the bolt and the mount to reduce small movement. The mount with tracker can be seen in figure 3.3.

3.2 Game design

The game design is based on Fæster et al. (2017), who created a dodgeball inspired game to encourage back movement. The player was placed on a virtual platform, set in an environment which promoted an illusion where if the player moved too far they would fall, as to reduce leg movement. The player's goal was to pick and throw balls, and hit enemies appearing (spawning) in a semi-circle in front of the player. This awarded points. Dodging, catching and blocking incoming balls from the enemy was also a possibility.



(a)

(b)

Figure 3.3: The 3D drawing of the mount (a), and the finished 3D printed mount with the tracker attached (b).

In the present version of the game, the player can use both hands, since a controller was not used to track the lower back as in Fæster et al. (2017), thus enabling the player to block, catch or throw with both hands. Additional features included a new environment to provide more depth cues, inducing relaxation, and that ball placement is defined by the players range of motion and height which is calibrated in the beginning of each session. Furthermore, the frame of the game was to create the distracting elements inline with literature (Tabak et al., 2017).

According to Schell (2008), the more production loops a game can go through the better potential it has. As such features were tested throughout the process. The tests were primarily internal and occasionally informal external tests. In addition most of the asset fidelity was kept low so that they are fast to produce and easy to take out without losing too much time which lowers the time between each iteration. Another reason for this agile approach is to counter "learned-helplessness" highlighted by Jerald (2015). Where the user of the system decides a certain task is impossible or cannot be done, resulting in them giving up due to a perceived absence of control over set system. In order to avoid this state Jerald (2015) recommends testing every aspect of the design often which is inline with the aforementioned strategy of production. As a side note he also highlights the importance of additional or extra feedback on interactions used within the game to avoid this state, this could e.g. be effects when killing enemies or vibrations when picking up a ball.

The chosen visual style for the game was a mix between keeping the graphical polygon count low to ensure performance and avoid the "uncanny valley". The uncanny valley is described by Jerald (2015) as the "descent into creepiness", where the reality of a character is approached but is not fully obtained, resulting in reactions going from empathy to revulsion as seen in figure 3.4.

Jerald (2015) continues to state that for presence, the replication of reality is unneces-

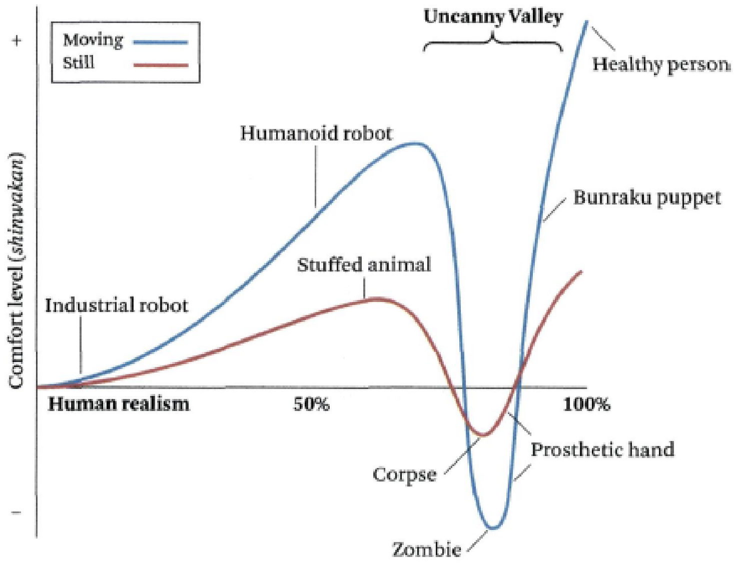


Figure 3.4: Comfort levels of representation fidelity, with moving and still objects.

sary. Instead he highlights that a responsive system, depth cues, and character motion are more effective as presence inducers. He also introduces a VR fidelity continuum, which includes: *representational*, *interaction* and *experiential*. The chosen representational fidelity for this project, ranging from very realistic (photorealism) to very abstract, is in the middle, being a cartoon feel. The interaction fidelity is normal (close to real world), however since the act of throwing a ball is tweaked to avoid player fatigue, it could be regarded as magical. Experiential fidelity for the present system is fairly high, since the amount of options for the player is very reduced, a low experiential fidelity would be a large open world with many options, where the intent of the creator can be lost.

The health meter (bar) is placed somewhat in alignment with Jerald (2015) who argues that placing objects in the head reference frame may result in a cluttered-up perception, instead it is suggested that it should be placed near waist height or the torso reference frame. This makes it easily accessible but not in the way. A bracelet is placed around the player's wrist, with a bar that showed their health points, which can be seen in figure 3.5. Though it has to be said that there is always the chance that the player will keep their hands up in front of them to e.g. block or catch an incoming balls and thereby adding to the clutter. Initially it was thought that a 3D hand would accompany the bracelet but it was more intuitive to communicate which physical controller button needed to be pressed when the actual controller is present in VR.

A tutorial was also created, in order to instruct, educate and inform the player about all basic aspects and rules of the game. It allows players to navigate back and forth between the steps within, ensuring they can retry anything which they were uncertain

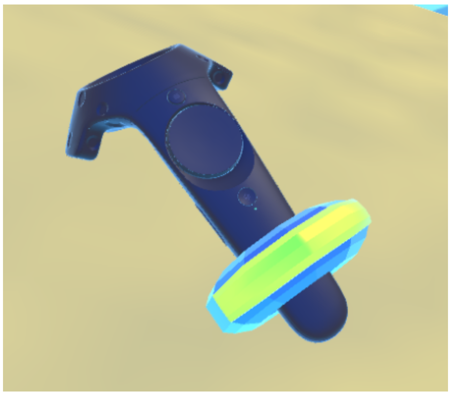


Figure 3.5: The health bar of the player within the game, placed at the base of the controller.

about. When each of the different interactions like dodging, throwing, and catching is introduced, the player is able to try each before moving on. Jerald (2015) points out how using more human sensory capabilities and motor skills increases understanding and learning. Hence the player is able to try each interaction, some with a small movie clip to showcase, however always accompanied by explanatory text. When a certain button was to be pressed, it would pulse with a green glow on the controller model, and in the case of the player having to touch a virtual push-down button, a semi-transparent controller model was shown hovering over the button.

In the stage where the player has to perform the six movements of their spine within their limits (lumbar calibration), a 3D model was animated to demonstrate the wanted movements from the player as seen in figure 3.6. Using all these different mediums of instruction is inspired by Jerald (2015) and their adaptation of the cone of experience, seen in figure 3.7. Jerald suggests embedding abstract information such as symbols, text and multimedia into a scene to increase the understanding compared to the real world.

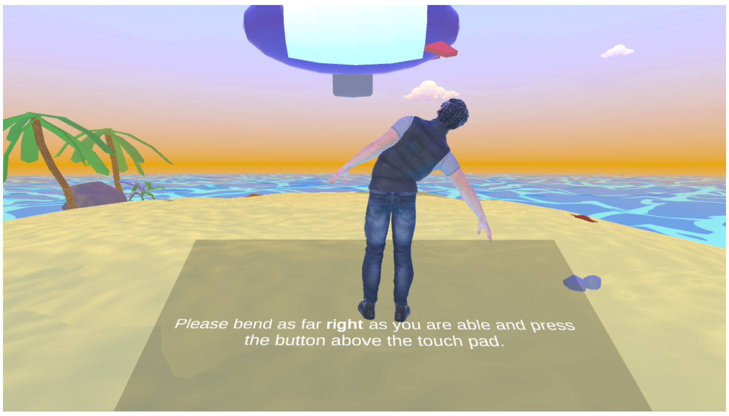


Figure 3.6: The avatar shown to exemplify what kind of movement is wanted during the lumbar calibration. Here it is right side bending.

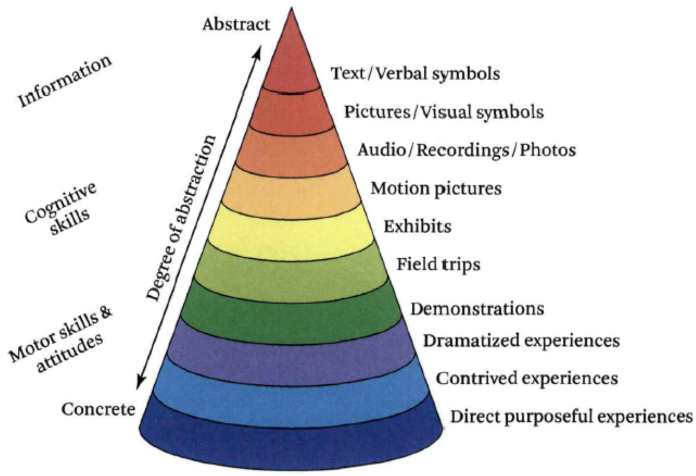


Figure 3.7: The cone of experience, and its different levels of abstractions. Adaptation of model found in Jerald (2015).

3.3 Prototype testing

A preliminary test of the game was performed with a physiotherapist who works at one of the national pain centers. He went through the aspects of the game, from account creation, tutorial, and gameplay. After the play session, the therapist was interviewed in a semi structured interview. Questions starting out broad, and then narrowing down, where enquiries were made if anything stood out. Questions consisted of what they thought about the experience, if they thought something was missing, if there was something which should have been changed if we were to have one of his patients to try it now, which data they would be interested in and how they would liked it to be presented. The setup can be seen in figure 3.8. During the session the facilitator or notetaker would assist if the person seemed to be stuck.

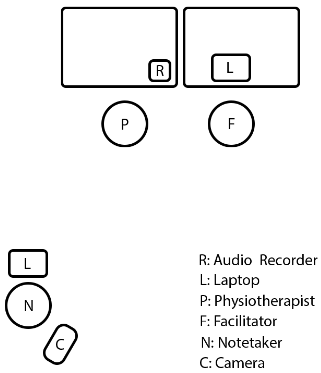


Figure 3.8: The setup for the first test.

3.3.1 Comments from semi-structured interview

The first remark is regarding the game's difficulty. The expert was both equally doubting and curious if it would fit for patients. A suggestion was to base some of the difficulty on their range of motion, as done with the balls. Later in the process it could be an idea to make change more dynamic. In this way, the system could automatically adapt if patients were able to kill an enemy on the side which required more movement than initially recorded, and then pushing this upper limit.

Another question was on reducing the different range of motions being utilised e.g. an option to reduce flexion in game play, by creating a mode where balls only spawn directly in front of the player at different heights. He could see the value within this but would also like an option where the player could play without restriction. In connection to this, language in the game which got the player to focus on limiting their body (like "Please reduce leg movement") should be reduced. His reasoning was that movements should be closer to what a person would do in their real life, and thus a very locked down, singular and specialised form of movement is not often done anywhere else, while complete motions have a bigger transferability to real life.

Another point made was that during his playthrough, he was able to skip through the tutorial in its entirety. He thought that making sure that a person had to do each task at least once before being able to move on would be an improvement.

He also highlighted the fact that he would want the patients to be more aware of their pain, as you may encounter a person with a very large range of motion, but it being extremely painful to do so. So, a rating of pain would be interesting to both him and the patient. He wanted it before and after both the tutorial and individual sessions. He also pointed out that if the application was meant for longer use over multiple sessions, then the quality of life may be an interesting measurement to investigate.

During gameplay the systems logs the user's degrees of motion. The expert thought this would be interesting, especially if the range of motion is preventing the patient from doing everyday tasks. The expert thought the data should not be shown as is, but rather the data should be presented in the game with a focus on the positive aspects and outcomes.

On the topic of the virtual environment being used, the expert had heard of an application where the environment was an ice town for burn patients. Following this, he suggested that since his patients often talk about warm holidays at the beach as their favourite place then maybe the environment within the application could reflect this.

His own experience was limited to the Samsung Gear VR system (mobile virtual reality system without positional tracking) before this, but he did think it might be confusing the first few times, as e.g. he had a hard time figuring out which controller buttons he had to press from time to time. Taking into account the typical energy level you can encounter with this target group should be a priority. An example was making lasagne, which had to be planned and done over multiple days, coupled with their window of concentration is often very small. So making text more understandable and present information in smaller bites may be favourable.

Finally, he thought that the model which shows you how to move during the lumbar calibration would be a good medium to show the evolution of their range of motion. However, in some cases this evolves very slowly, and could be demotivating. The expert instead suggested a comparison of the range of motion during calibration was compared with patients movement during play. To investigate and maybe show them that they moved more freely while playing.

Equipment

Throughout the tests of the equipment seen in figure 3.2, it was found that the need for multiple trackers on the back itself became somewhat irrelevant, as the addition of more trackers seemed redundant (see section 4.3). Through multiple observations of tests, the only tracker which remained was the lowest one (at the L1-L5 vertebrae). As the only crucial tracker placement was lowest, a belt version of the equipment may have been a better fit, with potentially less displacement and less intrusiveness.

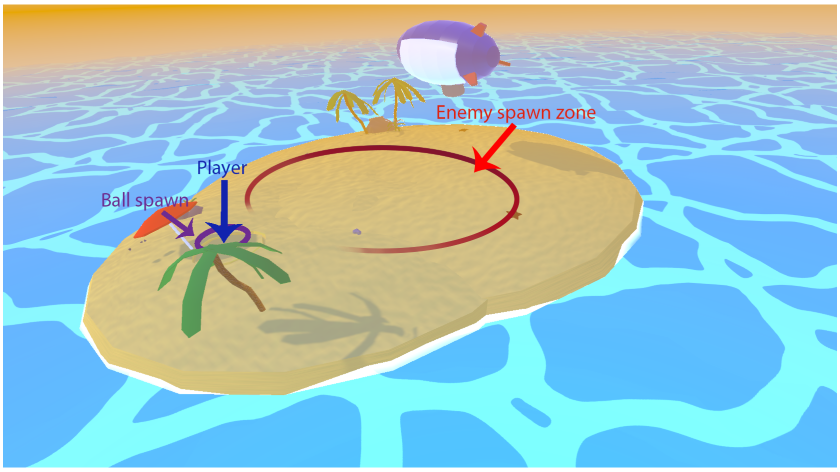
In-game feedback

It was reported that getting hit by the enemy was hard to notice, so a small vibration was added to each time a player was hit and lost life points.

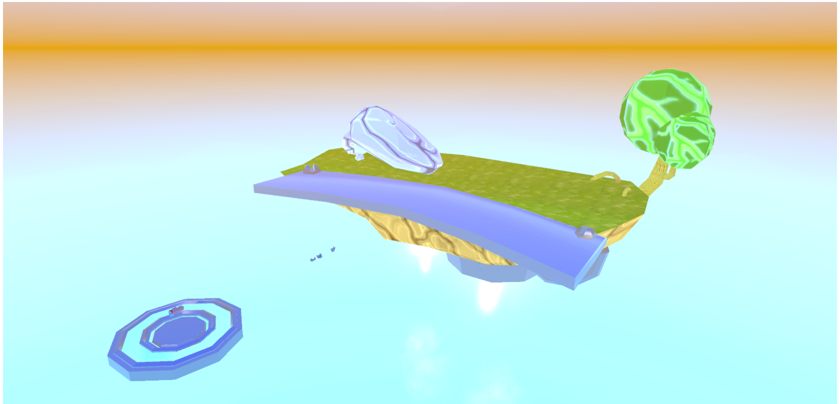
3.4 Environment

Following the aforementioned feedback, a new environment was needed. A tropical island was created, as seen in figure 3.9a, and replaces the old flying island and platform seen in figure 3.9b. In the new environment the player is not tricked in the same way to stand still, and the shadow of balls thrown can be seen all the way on the tropical beach hence more depth cues. The new environment is also more in line with the feedback from the expert who reported that it should be a more relaxing place for the patients. While the unique setting of a tropical island may potentially conflict with the requirements by Tabak et al. (2017) of activities of daily living in a familiar environment, it nonetheless fits perfectly for their other point of having a relaxing environment for the player. In line with Schell (2008) the dodgeballs were retextured to look like beach balls and some of the bouncy properties were altered to better fit the theme, which follows the lens of unification, which tries to unify the design towards a more singular goal.

Jerald (2015) includes guidelines to avoid negative effects on the player when in VR, one of which is the motion aftereffect, in which fatigued motion detection neurons makes one perceive motion as slowed down or stopped. If one looks away from the moving stimuli they may experience movement in the opposite direction. Following this, the rotational skybox was made static, and the water motion seen in figure 3.9a, as to limit this effect being present. This also counters a simulator sickness issue, where multiple things constantly moving can induce nausea.



(a)



(b)

Figure 3.9: The new tropical island (a), with a blimp and new water, and the old environment with the platform and the flying island (b).

3.5 Tutorial

As mentioned in the game design, the player was able to try each of the interactions which make up the game before they start playing, but with the feedback from the interview, checks were added to ensure that the player could not continue the tutorial unless certain activities had been performed. This means that when the player is asked to throw a ball, they have to hit an enemy before they are able to move on. The same applies for dodging, catching, and blocking. In addition, returning players have the option to skip the tutorial or take it again after they log in through the account system. Since there was a remark about the energy level of the target group, an option to change UI language between Danish and English was made, as it may make it easier for some to get through and understand.

3.6 Clinician user interface

The use case of the application is to be placed at clinics. It therefore makes sense to create a user interface for clinicians to create user profiles, and log sessions. In the beginning of the game the player is placed in a waiting area with a few balls, and text around them with the words “Please Wait”. At this stage, the idea is the clinician uses the user interface shown in figure 3.10, and either create a profile, or pick an existing profile, and create a new session. Upon selecting a profile, the clinician can view a list of previous sessions, as seen in figure 3.11. Creating a new session will load the island level for the player in virtual reality.

Figure 3.10: The overview page of the clinician UI.

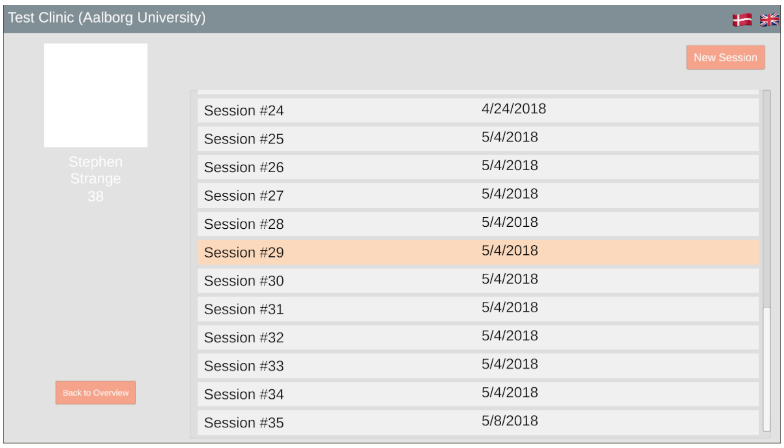


Figure 3.11: List of sessions, with the ability to create a new session for a user.

3.7 Motivation

In response to the feedback, and to improve the player's motivation, a system was created to award points if the user moved beyond their baseline movement from the calibration, during game play. Furthermore, this information was made available between each level, presented as green text, as seen in figure 3.12. This aligns with the requirements of Tabak et al. (2017) to provide in-game feedback to the user, and what was suggested by the expert during prototype testing, to only focus on whether the patient did something good, rather than how much. In the spirit of this, a comparison between sessions was also created, where players would be shown if they had more movement, less pain or both compared to their last session.

3.8 Difficulty adjustment

An important part of rehabilitation, found to be among the most effective methods, is graded activity as explained in section 2.1. Graded activity is where the activity progressively gets harder as to ease the patient into more and more movement. In relation to virtual reality games this is also recommended by Tabak et al. (2017), along with the expert interviewed in the prototype testing. To accommodate this, the game is structured in levels which describe how many enemies will appear (spawn), and which horisontal angle they will spawn, how often they will shoot (time between each shot), and how long the time between the enemies indicate (flash) they are about to shoot, and they actually shoot, and finally how many balls should appear around the player. These five parameters have baseline values for each level, which can be both individually tweaked, or tweaked globally using a difficulty slider. To increase difficulty the number of enemies are increased, while the other parameters are lowered. To decrease difficulty, the number of enemies, and the spawning angle is lowered, where the other parameters are increased. After the player has hit all enemies in a given level, the user is asked whether they would like to increase difficulty, decrease difficulty, or do another round on the same difficulty as they just completed. The prompt can be seen in figure 3.12.

Figure 3.12: Prompt for the user to choose difficulty for the next round.

3.9 Visual analog scale for pain severity

Based on feedback in the pilot test with a lower back pain specialist, and recommendations by Tabak et al. (2017), a visual analog scale was implemented seen in figure 3.13. It asks users to rate their pain on a horisontal visual analog scale (VAS) where the extremes are marked. Internally the values chosen are treated as between zero and 100. The user is prompted to rate their current level of pain after the tutorial, and again rate it after they have lost the game (end of session). The values are stored and associated with the account created, and it is thus possible to track change of pain severity over time for individual users across several sessions.

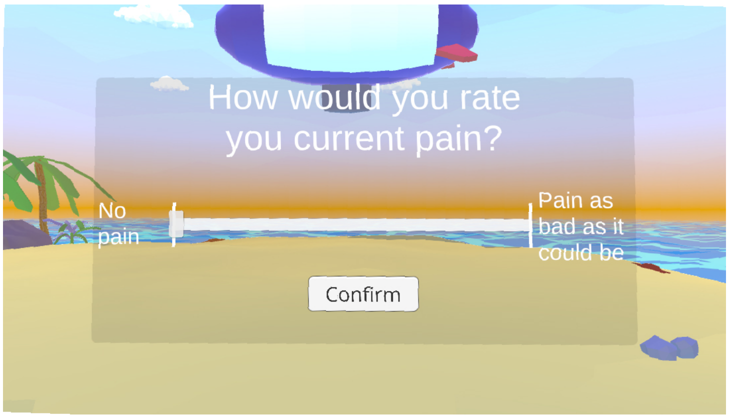


Figure 3.13: Visual Analog Scale for pain severity

4 Implementation

Within the implementation the various technical aspects of the project will be uncovered and explained.

4.1 Flowchart

The flowchart seen in figure 4.1 depicts the overall topics a player will go through from the moment the game is loaded with a profile selected, to playing the game. The flowchart highlights the four key modes of interaction taught to the player (dodging, throwing, catching, and blocking balls), as well as when those modes are introduced.

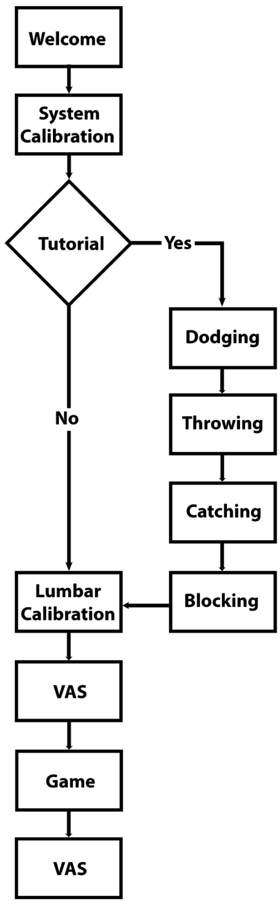


Figure 4.1: The flowchart of system to the point where the player has finished playing.

4.2 Technologies

Unity was the chosen game engine for this project due to familiarity with the system and its API. The Wwise audio middleware was chosen to handle sound effects and music due to its ease of implementation (by calling events), and the fact that it decouples sound development from the main game engine. Different royalty free assets were used in development of this game, as to maximise time spent on developing features. The external assets are as such:

- “Sign” by Xillute (2017) at Sketchfab (CC Attribution).
- “MCS Male” by Morph3D (2017).
- “Cubemap Extended” by Boxophobic (2018).

Autodesk Maya was used to create all internally produced 3D assets, while Adobe Photoshop was used for the various textures within the game. Music and audio was edited within Adobe Audition and the videos seen in the tutorial were edited in Adobe Premiere. External audio sources are provided with license, and are as follows:

- “Find a way” by lakeyinspired (2017a) at SoundCloud (CC-BY-SA)
- “That girl” by lakeyinspired (2017b) at SoundCloud (CC-BY-SA)
- “Watching the clouds” by lakeyinspired (2017c) at SoundCloud (CC-BY-SA)
- “Seagull on beach” by squashy555 (2016) at Freesound.org (CC Attribution)
- “Ambience, Seaside Waves, Close, A” by InspectorJ (2017) at Freesound.org (CC Attribution)
- “Hint” by dland (2015) at Freesound.org (CC Attribution)
- “Metal click” by mkoenig (2009) at Freesound.org (CC Attribution)

4.3 Analysis of accuracy

As mentioned in the literature review, it is necessary to ensure the measured position and rotation of joints are correct, especially if used in health-related applications. Thus, internal evaluation has been performed, where green crosses were placed on the clothes of an author (see figure 4.2), where the bones tracked by the equipment were located. The person, was then asked to perform flexion, extension, and lateral bending. Pictures were taken at the maxima of each movement, and the angle between the aforementioned crosses was calculated using image manipulation software. The angles were normalized such that when standing in a neutral standing position, the angle was zero, and negative or positive depending on the direction of movement. Along with pictures taken, the system logged the rotation of the spine in the same manner. In line with what Clark et al.

(2012) suggested, the data was compared with a Pearson correlation, for a total of two users. Pearson's r for all movements for participant 1 was $r = 0.91$ and for participant 2 $r = 0.92$. This indicates strong reliability in the measurements by the system, and was used to conclude that measurements are suitable for a health application.

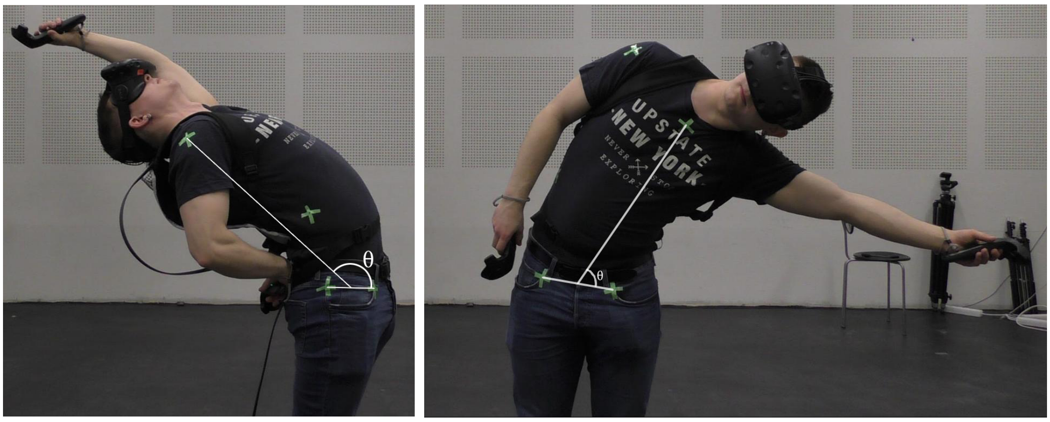


Figure 4.2: Body bone markers on a person for accuracy validation.

4.4 System calibration

The calibration phase of the system is a crucial element to properly understand how the user's movement correlate to degrees of motion. In the beginning of each session, the user is asked to straighten their back. This is done to set the height of the internal kinematic model. The kinematic model is a virtual representation of the user's body (avatar), and is used to derive motion of the body in the system. This means that when the user moves their body in the physical world, an avatar moves accordingly in the virtual world. Due to the uncanny valley explained in section 3.2, this avatar is hidden to the player.

The height of the avatar is set by taking the the y-position (y-up coordinate system) of the users' head in the virtual environment (the camera position, and HMD), and comparing it with the floor in the virtual environment. This leaves a slight error since the HMD is placed over the user's eyes, and not the top of their head. This error has, however, been found to be small enough to be negligible. Once the height is set, the system has to know which trackers are tracking which bodily bones. The user is asked to overlap his feet with two blue cubes on the floor in the VE, and overlap both controllers with two blue cubes on the left and right side of the user. This forms a t-pose. A nearest neighbour sort is then done to map each tracker to each tracked bone. This sort works by finding the nearest controller or tracker to each blue box, and associating that tracker with that blue box, which in turn is associated with a bone. The tracked bones are; Left hand, Right hand, Spine (lower), Left foot, Right foot and Neck. These can be seen in figure 4.3 which shows exactly where on the Unity Humanoid Avatar they are placed.

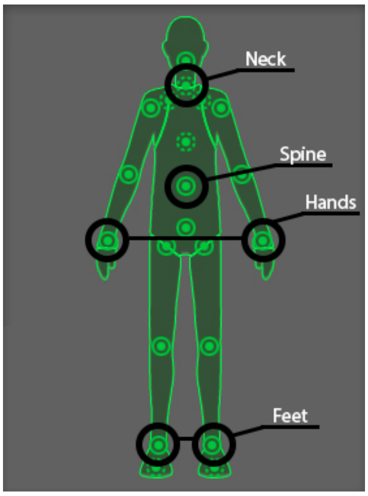


Figure 4.3: The different bones which are being tracked.

An important part of this calibration is to also record the positional and angular offset of the trackers, to the bone it is actually tracking. For example, the trackers for both feet are placed between the ankle and the toes on the upper side of the foot, but the tracked joint is actually the ankle.

Once each tracker is mapped to each tracked bone, and the positional and angular offsets are recorded, the system can start deriving kinematic data of the user.

4.5 Deriving kinematic data

Internally, we use Unity's Inverse Kinematics system to create an accurate representation of the user's body, an example of this model can be seen in figure 4.4. This allows for reading and recording the Euler angles of the joints of interest. In figure 4.5, a code example can be seen for how the position of a joint is set..

Figure 4.4: Example of the internal body model, used to derive motion of the spine.

```
if (spineMarker != null)
{
    animator.bodyPosition = spineMarker.position;
    animator.bodyRotation = spineMarker.rotation;
    animator.SetBoneLocalRotation(HumanBodyBones.Spine, Quaternion.Inverse(animator.bodyRotation * skeletonSpine.parent.rotation)
                                        * spineMarker.rotation * initialSkeletonSpineRotation);
}
```

Figure 4.5: Using Inverse Kinematics to set the position of the local rotation of the spine.

In figure 4.5, several variables are used to compute the rotation of the back. The "spineMarker" is the tracker positioned on the players back. This marker knows the positional and rotational offset between the bone and the tracker, and is recorded on system calibration. "skeletonSpine" is the object which is affected by the "SetBoneLocalRotation()" function, which rotates bones in the kinematic model. To transform the rotation of the "spineMarker" object to a local rotation with regards to the bone, we have to multiply its quaternion with the inverse of the parent of the "skeletonSpine". As the avatar itself also rotates, we have to multiply the "bodyRotation" onto the parent of "skeletonSpine". Finally, because the initial rotation of "skeletonSpine" is not the identity quaternion, we have to multiply the initial quaternion in the calibration pose, such that if the user is in the calibration pose, all components should equal to the identity quaternion. The spine is a special case, because Unity's Inverse Kinematics systems does not include IK goal handles for the spine. It does however have handles for the feet and hands, so setting the position and rotation of these joints, is as simple as setting them to their respective marker (akin to *spineMarker*) objects. An example of this can be seen in figure 4.6.

```
if (rightFoot != null)
{
    animator.SetIKPosition(AvatarIKGoal.RightFoot, rightFoot.position);
    animator.SetIKRotation(AvatarIKGoal.RightFoot, rightFoot.rotation);
}
```

Figure 4.6: Using the inverse kinematics system to set the position and rotation of the right foot.

In summary, we use the following body measurements for the internal avatar:

- Position and rotation of both controllers to set the position and rotation of the hands
- The rotation of the marker on the lower back is used to set the rotation of the lower back of the avatar, and position of the marker is used to set the absolute position and rotation of the avatar.
- The position and rotation of the markers on the feet is used to set the position and rotation of the feet of the avatar.
- The rotation of the HMD to set the neck rotation of the avatar.
- The y coordinate (in a Y-up coordinate system) of the HMD to initially set the height of the avatar.

4.6 Lumbar calibration

A recurring note from the expert interviewed during prototype testing, experts previously interviewed, and literature such as Thomas et al. (2016) and Tabak et al. (2017) is using kinematic/biofeedback to tailor and adjust the game to the individual patient. To tailor this game to the individual movement of the user, it is important to know how much the patient can move in the six degrees of freedom of the spine. This calibration phase is performed after the system is calibrated and the tutorial has been completed, as can be seen in figure 4.1. The game asks the user to perform the six motions of the spine, one at a time, to the best of their ability. When the user reaches this point, they press a button on their controller, until all movements are recorded. A recording is the angular rotation of the spine of the aforementioned avatar, for example, the user might be able to rotate 40° to the left and right. This information is used to make sure the balls that appear (spawn) in each level are within the movement of the user, so with regards to rotation, this can mean that the user never has to rotate their upper body more than 40 degrees to either side, to be able to pick up a ball. This information is also used to keep track of how the motion develops over time between sessions in the account system.

4.7 Account manager

To record the development of the user between sessions, and have information to show to the physiotherapist, an account manager was created to store user profiles, and their sessions. The manager uses Google Firebase, and more specifically their Realtime Database product, which essentially is a NoSQL database for JSON objects. The structure of this data can be seen in figure 4.7.

Whenever a user enters the game, the appropriate profile is selected in the clinician user interface. If the user has no profile a new profile can be created, which inputs name, age, and dominant hand. This is stored internally as an object of type “User”, which gets

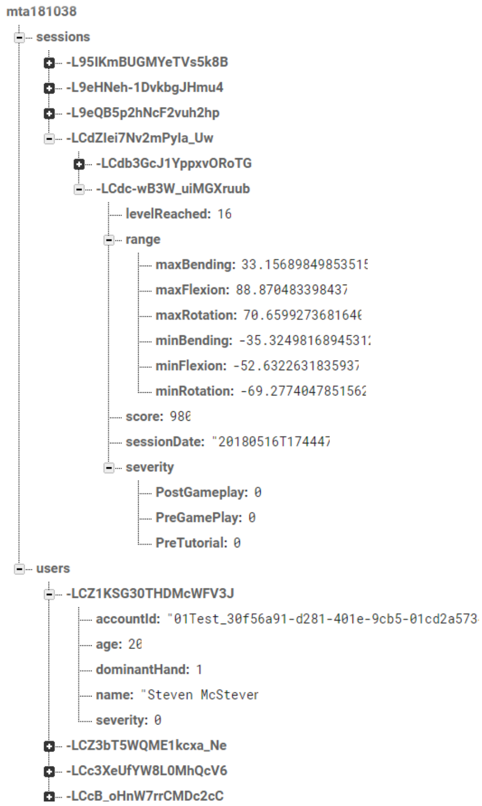


Figure 4.7: The structure of the account data in Google Firebase's Realtime Database.

deserialised or serialised to JSON when retrieved from and sent to Firebase. Further, session data contains range of motion, score, date of play, and the pain ratings from the visual analog scale. This, too, is stored internally as an object of type “Session”, and gets deserialised or serialised to JSON.

5 Evaluation

5.1 Participants

The evaluation of the VR application employs three different groups. A group of three low back pain experts, one being Ph.d fellow at the Department of Health Science and Technology at Aalborg University, and two pain professionals and physiotherapists working with chronic pain patients. Another group are two chronic low back pain patients with eleven and 25 years of illness. Finally, to assess usability and specific game design questions, a group of sixteen healthy students were recruited from a variety of graduate and undergraduate education programmes.

5.2 Procedure

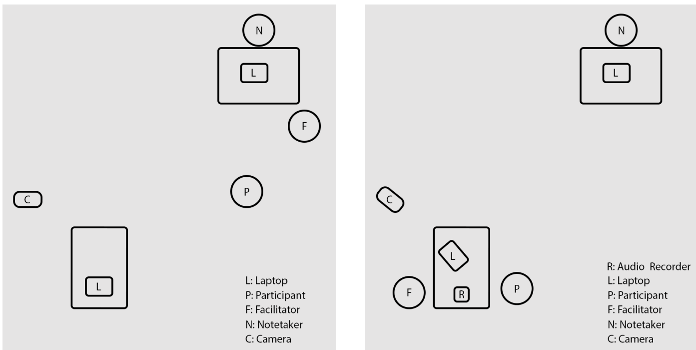
This evaluation procedure is three fold, however, the three procedures are largely identical. Upon arrival participants were given a welcome speech regarding who is facilitating the test, what participants are about to experience, and what to expect. They are asked to sign an informed consent answering whether data gathered can be used for the report, audio/visual production, and publication. Afterwards, participants are asked to rate their prior VR experience on a five point Likert scale, and elaborate what kind of experience it was. Participants were then instructed in how to put on and adjust the head-mounted display, the Vive trackers, and associated mounts, as well as how to secure the backpack. The controller was shortly introduced, as to familiarise the users with what buttons are available to them, what they are called, and how to actuate them. Participants would then start the game. Following the VR session, patients and healthy participants were asked to fill out the simplified Simulator Sickness Questionnaire (SSQ) by Kennedy et al. (1993), where severity is discarded, instead condensing into a multiple choice questionnaire. The questionnaire is used in order to assess if the system has a tendency to induce any of the negative related side effects of using VR. The setup can be see in figure 5.1.

Specific for the experts, they were asked to think-aloud while playing. Any comments made during the session were noted. To gain an insight into the overall usability of the system, experts were asked following the VR session, to fill out the System Usability Scale (SUS) questionnaire. Afterwards a semi-structured interview was performed and comments made during the VR session were discussed. The theme of the interview was feasibility, appropriateness, and perception of the game.

The patients were also asked to think-aloud. They were further asked about how long they've lived with CLBP, and when they last took pain medication for their pain.

Following the VR session, patients were asked to fill out the Game Experience Survey (GES) adapted in line with Thomas et al. (2016), which is used to assess game acceptability in health games. The questionnaire specifically asks about low back pain related issues, and related questions on game experience. In the semi-structured interview remarks made during the VR session were discussed, as well as specific questions answered such as: “What did you like most about the game?”, “What did you like least about the game?”, “What would make the game better?”, “What would make the game easier to learn?” and “Describe the game with three words”. This is in line with the procedure by Tabak et al. (2017)).

Specific for the healthy participants in the opportunistic sample, the idea was to detect obvious usability flaws, and determine which variation of the ball throwing game mechanic should be used. Healthy participants were asked to rate the overall feel of two versions of throwing a ball in the game, on two separate Likert scales items followed immediately after the VR session with either behaviour. The first behaviour (*throwing a*) applies force to balls thrown in the game the same way 75 gram ball would. Worth noting is, since there is no haptic feedback in terms of weight in virtual reality, it is difficult to determine how much force is required by users to actually throw a virtual ball. The second behaviour (*throwing b)* scaled the velocity vector applied when the player releases the trigger button by 1.5. This has the effect of speeding (boosting) the ball, and stretching it’s trajectory when the player throws a ball, thus, less physical force is needed to throw the ball further. Finally, usability was assessed with the aforementioned SUS questionnaire, with the purpose to compare with SUS score databases and to give an indication of when video footage should be analysed further if the score for a particular participant is low.



(a) (b)

Figure 5.1: The two different stages of the setup. First the camera is pointed toward the play space, and a laptop is available for the pre-test questionnaire (a). Next, the camera points toward the facilitator and a chair for the participant to answer interview questions are fill out the post-test questionnaire. Further an audio recorder is used (b).

5.3 Results

5.3.1 Experience with Virtual Reality

The three groups rated their previous general experience with virtual reality differently, as seen in figure 5.2. The experts had a mean of $m = 2.34$, patients: $m = 1$ and the healthy group: $m = 3.5$.

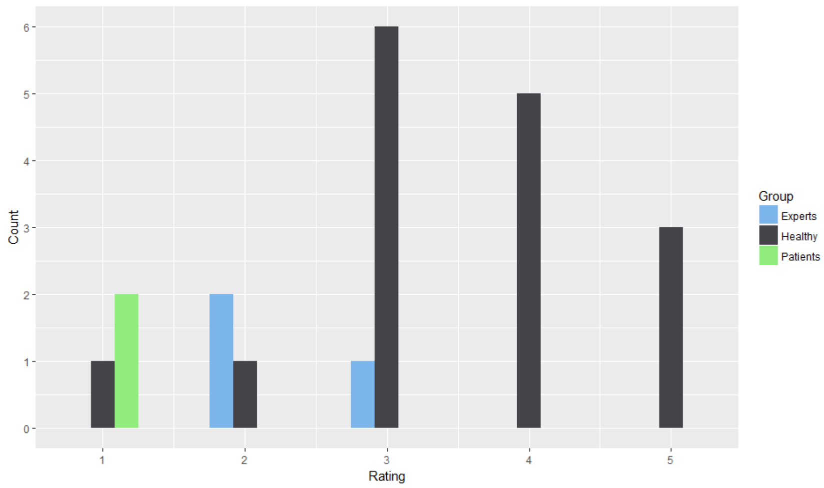


Figure 5.2: Histogram of the experience with virtual reality for the three tested groups.

5.3.2 Simulator Sickness Questionnaire (SSQ)

The SSQ was used on both the healthy sample and the patients. The results can be seen in figure 5.3. Eight out of sixteen participants reported sweating and nine participants reported feeling no discomfort of any kind. Three reporting fatigue, and one for each respectively; difficulty focusing, dizziness with eyes open/closed, eye strain general discomfort, and stomach awareness.

5.3.3 System Usability Scale (SUS)

The healthy participants and the experts filled out the system usability scale. The questionnaire results in scores ranging from zero to 100. On this scale, according to Bangor et al. (2009), scores greater than 50.9 is *OK* usability, 71.4 is *good*, 85.5 is *excellent*, and finally greater than 90.9 is the best imaginable usability. The minimum, mean, maximum, and standard deviation SUS score for both groups can be seen in table 5.1.

Table 5.1: SUS scores for the healthy sample and experts.

Group	n	Mean	Min	Max	Std. Dev.
Healthy participants	16	81.72	62.5	97.5	8.88
Experts	3	80.83	77.5	85	3.82

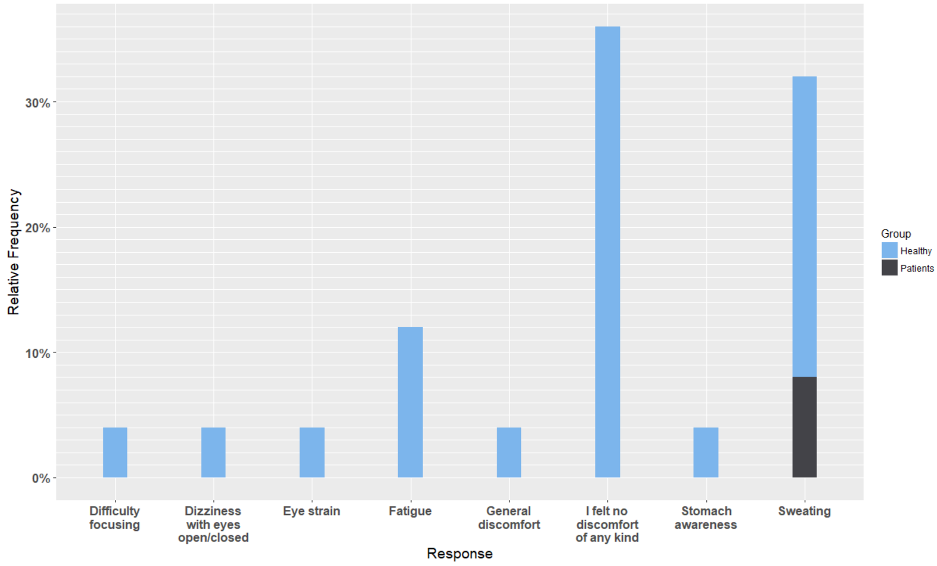


Figure 5.3: Histogram of percent options chosen in the simulator sickness questionnaire by all participants.

5.3.4 Game Experience Survery (GES)

Instead of completing the SUS, patients were asked to fill out the GES adapted by Thomas et al. (2016), which assesses game acceptability in health applications. Figure 5.4 shows the questions asked and the Likert scale option chosen by patient B (red) and patient T (blue). Where the answers overlap, the colours are tinted purple.

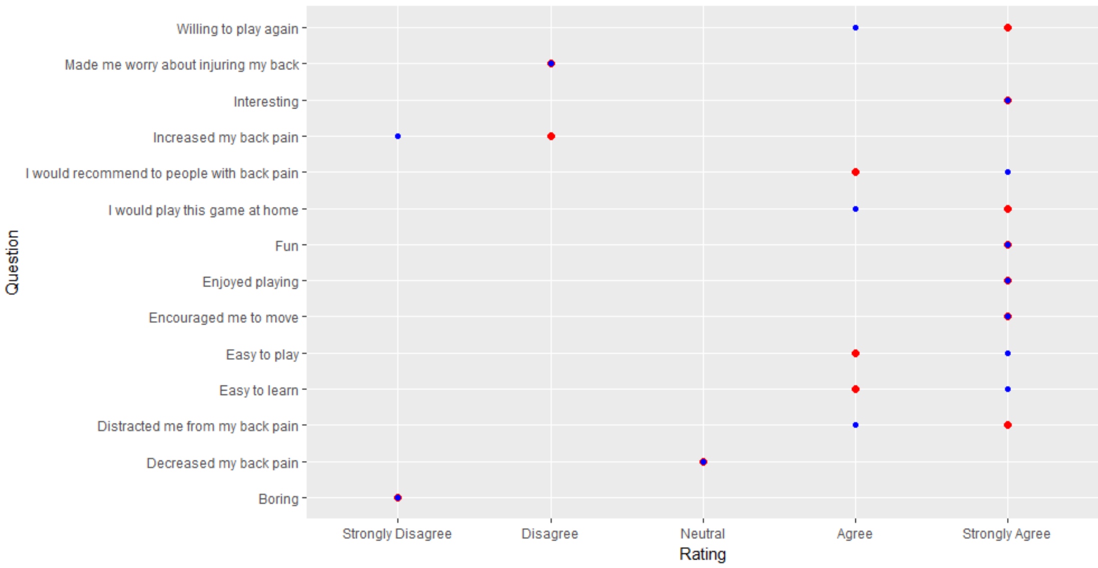


Figure 5.4: Answers to the GES by two patients in the evaluation.

Open ended questions to the Game Experience Survey

Patients were asked open ended questions in the semi structured interview, and asked to describe the game in three words. The responses are presented in table 5.2. Note that these answers are translated from Danish.

Table 5.2: Open ended responses to the questions in the Game Experience Survey.

Question	Patient T	Patient B
What did you like most about the game?	"That you were forced to move, you could not just slack, and that they were calibrated so they knew they would not be given a task which was impossible."	"Liked the environment and the happy colors."
What did you like least about the game?	"That there was someone looking at me."	"Trackers on the feet were sometimes tightening on my feet"
What would make the game better?	"Nothing, you make a lot of movement and good kind of movement."	"You could create different levels with different difficulties, potentially adapted for the individual patient. It could also be something the physiotherapist decides."
What would make the game easier to learn?	"That the text would appear in front of my head, as it was sometimes hidden behind some balls."	"There could be an indicator that shows what button you should press. Also some way to inform the player about the two cubes that you had to place you hand in."
Describe the game with three words.	Interesting, fun, and sweaty.	Fun, pretty, and moving.

5.3.5 Ball Behaviour

Healthy participants were asked to rate their overall experience with throwing the ball using two variations of ball behaviour, explained in greater detail in the procedure. The relative difference between ratings of *throwing b* and *throwing a* can be seen in figure

5.5. *Throwing A* had a mean rating of 2.94 and $SD = 0.85$. *Throwing B* had a mean

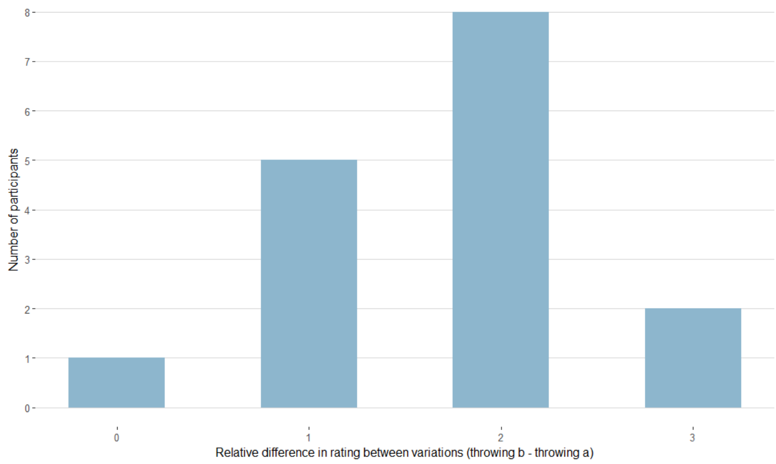


Figure 5.5: The relative difference between the ratings of individual users of throwing b and throwing a. E.g. this shows two users rated throwing b three levels higher than throwing a.

rating of 4.63 and $SD = 0.5$. Evident from figure 5.5, there is a preference towards *throwing b*, with a majority of users selecting 5 then 4. Using the ratings as interval data, a test of normality was performed with the Shapiro-Wilk test which yielded $p = 0.019$ for *Throwing A* and $p = 2.566 * 10^{-5}$ for *Throwing B*. With the alpha-level chosen at 0.05 we reject the null hypothesis that the data comes from a normal distribution. A Wilcoxon signed rank test revealed significant difference $w = 120$ and *p-value:* $5.54 * 10^{-4}$. Further, a sign test was performed where data from each user is given a sign depending on whether participants rate one over the other. This corresponds to 16 users rating *Throwing B* higher than *Throwing A*, and one tie. This allows us to perform a binomial test, which reveals significant effect as well, $p = 0.0005$. From the results of the Wilcoxon signed rank test and binomial test, there is evidence that *Throwing B* is preferred to a statistically significant degree.

5.4 Discussion

The system usability scale revealed mean scores of 81.72 and 80.83 (healthy participants and experts). According to Bangor et al. (2009) this would correspond to *good* usability (71.4 - 85.5). One expert highlighted that the usability of a system when trying it for the first time, will be different compared to when returning. Experts agree that the first time is a new situation, and once they have tried it once, they know what to do in the next sessions. These comments are mostly related to the tutorial phase of the game, which introduce the various elements of the game (game mechanics). Further, the tutorial instructs users in how to calibrate the system, and how to move such that the system can tailor game parameters to the individual. Two experts specifically mention the amount of text, and things users have to remember as maybe being too much, as CLBP patients tend to also have lower cognitive efficacy due to their disability. Patients described some of the user interface interactions as confusing at times, as methods varied between having to point with their controller on a button, place their controller inside a virtual cylinder (virtual push-down button), or press on either the trigger button or menu button on the controller. Similar effect was reported by healthy participants whom albeit have more mean experience with virtual reality. With respect to the game experience survey, the two patients recruited for the study found the game fun, easy to play, easy to learn, and felt encouraged to move. This theme continues into the semi structured interviews where patients mentioned they could feel they were moving, and patient B specifically mentioned it was more engaging than doing the traditional exercises at home. The same patient highlights that after 20 sessions the same game and environment might not be as engaging. Patient T specifically mentioned that they stopped following a workout program provided by a physiotherapist, because of perceived awkwardness of the context where the exercise were done (in a room with other "gym goers"). In regard to the game, the patient mentioned that their movements were much more natural, because they had to go pick up the balls, and in that sense the experience was distracting. Furthermore, the patient did not think about pain in their lower back, and thus increased their movement. The patient specifically mentioned that they could not just be inactive, and that was a big plus. With regard to the game environment, the experts believed that the more relaxing an environment can be, the more effect it has on patients. This was confirmed by patient B who enjoyed the *happy* colours, calm environment, and calm music. Patient B believed they got more happy in the environment, and spent time just looking at the props, and interacting with them.

One consideration in regard to the two patients was that both were in favour of a challenging experience, one explaining that they preferred that they were forced to move and another explaining that even though the amount of different interactions were a bit overwhelming they liked it. This could mean that the game and experience is fitting, or that the two patients were very capable both in their mental and physical capacity. In continuation, one of the patients reported that they preferred that you had to invest and use your whole body when throwing balls, which stands in contrast with the findings of the healthy participants who preferred the easier ball behaviour variation, where the trajectory is stretched. This indicates that further testing with patients would be required as to fine tune which behaviour balls should have when throwing.

With respect to simulator sickness, a large amount of participants reported sweating. This is however explained by the nature of the game, which requires people to move, and this fact was continuously highlighted verbally by the participants. Similarly a minority noted fatigue, which they reported as an association of the exercises. Two participants reported the remaining symptoms which may be related to the head-mounted display not being placed appropriately. Furthermore, since both patients were barefooted, the plastic mounts for the feet trackers were mentioned as slightly uncomfortable, but not enough to warrant an end to the test.

On the topic of feasibility, the results from the aforementioned GES clearly demonstrates that patients found the game engaging and fun, and preferable to traditional exercises, which was also explicitly said within the interviews. Experts thought the application was feasible, and envisioned it installed in clinics where patients could book or be assigned time slots to come and exercise for themselves or with limited supervision. Experts state that patients typically only spend five to ten minutes a day doing exercises, and they would like patients to do more for effective rehabilitation. In contrast, the game is thought to elicit this kind of required exercise. However, because patients could perform their exercises at home without any equipment just before they go to bed, patients and experts thought that it may have be too much to daily put on the equipment to play the game. This argument was countered by two experts who stated that for many patients, it feels pointless to show up at the clinic and perform the exercises they do at home, with some supervision, which is what is being done today. As mentioned previously, if the system was the reason the patients would come to the clinic, then the experts believed it would make more sense for patients as opposed to the current procedure. Concerns with regard to how structured the exercise is was raised. Specifically in regard to what kind of movement the patients would be doing, as the current iteration may have focused more on upper body rotation rather than flexion and bending. Though this is not intentional, it is worth noting it was a conscious choice to not unintentionally overly challenge patients in this pilot study, which as a result may have caused more rotational movement than flexion and bending. Similarly a suggestion was put forth were the experts could tune in and choose where balls would come from, and where they would spawn around the user, so that the physiotherapist would be in more control of the experience. Continuously patients and experts stated, without being probed about it, that the experience distracts them from pain. This indicates that patients may actively engage more in movements previously avoided by fear-avoidance beliefs, which is backed up by willingness to play again in the GES. To increase the willingness to play overtime, it may be beneficial to introduce other kinds of environments and additional game mechanics. Furthermore, one patient suggested creating tasks that focus on agility exercises. These adaptations and changes, over time, could also serve to counter the novelty effect virtual reality can have, where, because the technology is new, most kinds of virtual reality will be interesting to new users.

As mentioned by Tabak et al. (2017) it is important for applications like this one to make patients aware of their body and provide feedback on bodily responses. In this regard, the game implemented motivational elements between levels that told players they moved more than in the calibration, as well as the game would log lower back rotations 30 times a second. The game further enquired about current level of pain on a visual analog scale at the beginning and end of the game. Experts believed this data could provide insight into how the patients moved, if presented in such a way that it explains the patients collective movement. Experts would want to be able to attach notes to this data, and easily see progress overtime. It was stressed that it may not be beneficial for patients to see this data as increase in range of motion is very small from time to time, and could instead serve as demotivating.

6 Conclusion and future perspective

This project set out to develop a virtual reality game for rehabilitation of chronic low back pain, which could challenge users to move more, and reliably track and log the user's lower back movement without inducing fear-avoidance behaviour. The game tailored various game parameters to the individual's baseline movement, and required players to play a dodgeball like game where balls were thrown at them, and they in turn had to throw balls at enemies. This game was developed with feedback from experts in the field of pain rehabilitation, and tested with regards to feasibility, acceptability, and usability with three pain experts, two chronic low back pain patients and sixteen healthy individuals. The game was found by experts to be highly feasible and applicable as a supplement in clinic settings for current chronic low back patients. The patients indicated high acceptability in health applications, and was very willing to play the game again, as well as it being fun and easy to learn. Preliminary data analysis also showed both patients moved more than baseline, and reported no increase in back pain. Conversely there was no decrease in back pain after the session. The healthy participants and the experts reported good usability, with room to improve with regards to interaction schemes. These findings are highly encouraging and suggest that there is value to the game and its use case.

As with all studies, this study has some limitations. First, the number of patients being limited, and thus results can only be taken as a suggestion and indication. Moreover, the novelty effect of virtual reality may play into effect, which is based on the idea that most people will be impressed and engaged when using new and different technology, in this case virtual reality. This may bias the data, as experts and patients alike reported low to no previous experience with virtual reality.

In the future there are numerous things that would be changed. The first part, the introduction to the game (in game tutorial), was theorised by experts to be too comprehensive for the efficacy of CLBP patients. This could result in worse experience or even attrition. To solve this issue the language of the introduction would have to be simplified, as well text being read aloud, and further elements that highlight what the player has to do at all times. An example of this is the way catching a ball is explained, where all patients, experts, and a number of healthy participants tried to cradle the balls thrown at them, rather than overlapping the controller and pulling the trigger button to catch it. Furthermore, the system calibration element, where the system determines which trackers should be associated with which bones, would have to be changed. A common problem was when users were asked to make a t-pose and press a button on their controller. Often what happened instead was players placed their feet in the virtual blue boxes below them, and then simply pressed a button on their controller, or stood paralysed waiting for something to happen. This could be solved by breaking the calibration down into discrete steps, where the user first has to place their right foot inside something, then their left foot, and so forth. Similar problems were observed in the lumbar calibration stage, where the users were asked to perform six motions of the spine to calibrate the games parameters to fit the functional movement capabilities of the user. The user would for example have to perform right side lateral bending to the best of their ability, and then press a button on their controller. What would often happen is users would fiddle with the controller, trying to find the button, resulting in participants standing in a bending position for a longer time than desired. This could be solved by the user not having to press any button, and the system itself would recognise when the user starts and stops bending, and automatically advance to the next required movement. A user interface was created with the purpose that clinicians could create profiles for each patient containing personal information, as well as a log of previous sessions. Encouraging feedback was received with regard to this, but for future work, this user interface would have to be expanded to show general movement for each session, data about acceleration of movement, as well as the possibility for therapists to fine tune and customise game parameters for the patients.

The equipment used for this game was an adapted backpack for trackers on the back, and two plastic mounts to be strapped around the feet with trackers screwed on top of them. For future work the backpack could be reduced to a single belt, which could be less intrusive and more secure in terms of tracking quality. Moreover, both patients and a number of healthy participants, and expert users were barefooted during the testing session. This resulted in the plastic mounts being attached directly on the skin, causing slight discomfort due to the sharp edges of the plastic. This could either be changed by wrapping the mounts in light foam, or asking users to wear sports shoes.

A patient raised concerns about the longevity of the game, and it's ability to keep people interested over time. The suggestion was to create more levels, and other things to do within the game. To counteract this issue, one could, after the patient has completed enough sessions, the therapist enables it, or have shown enough movement, add smaller mini tasks. A mini task could be e.g. bouncing the ball off the ground and hit an enemy, creating targets at difficult to reach positions, in quick succession or in a certain order. New enemies could be created with different behaviours e.g. moving, feigning shots, and new projectiles. These projectiles could be unblockable, uncatchable or both. One way of increasing engagement could be to add more layers of satisfaction (juice) to all aspects of the core game play, adding particle effects on blocking, catching, throwing and killing an enemy etc. Anything within the game could offer additional feedback to the user. Another aspect which could be looked into is the high-score display, since it was consistently reported almost invisible, though some of the participants saw it, they paid it little to no attention. One of the patients highlighted that if they had noticed it during the game, they would have increased their efforts. Because the scoring system is an important element of motivation, it should be more present in the game, and one could consider Schell's (2008) lens of endogenous value. That is, the designer has to consider the player's feelings about scoring among others. This means that the designer has to think about what is valuable to the player within the game, how they can make it more valuable and what is the relationship between player's motivation and this value.

For some this could be solved with simply showing their personal high score. In other games the score could translate into a currency which they are than able to purchase different things with. In the context of a clinic this currency could be used to purchase certain desired activities or provisions such as a massage, coffee or a snack. Another suggestion for a future version is to keep testing and adjusting the throwing of balls as healthy participants and patients feedback was inconsistent. Hence a middle ground can be found from additional tests. Alternatively it could be made changeable from the therapists UI. Furthermore, the health bar was reported as barely noticeable. Healthy participants, experts and patients alike did not feel like the indication of lost health points was clear. However, since the game vibrated both controllers when losing health and catching a ball, there was little difference. Such a vibration could be moved to e.g. the belt mentioned above. A small vibrator could be inserted and triggered whenever a player lost health points. Furthermore, due to an error within the system the health bar was often shown on the dominant hand, rather than the non-dominant hand. This could mean the health bar was more hidden than intended. Future iterations should resolve this issue by testing where it should be placed.

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