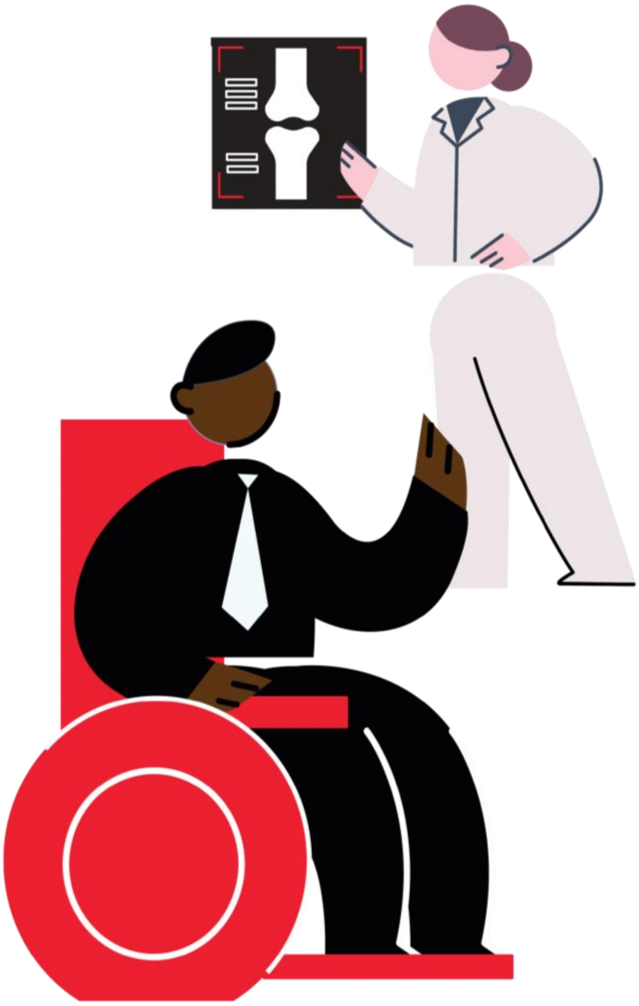

Virtual Reality and chronic low back pain – Co-design of an intervention and preliminary usability

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1. Executive Summary

In 2019, Medibank commissioned a multidisciplinary team from Swinburne University of Technology to undertake a project to explore the potential of Virtual Reality (VR), and other emerging reality technologies such as Augmented Reality and Mixed Reality as an emerging treatment technique for remote rehabilitation of chronic pain. Under consultation between all parties, Chronic Low Back Pain (CBLP) was chosen as the exemplar for this project, as it is one of the most prevalent causes of chronic pain with an equally high burden of disease, and a condition that is continually increasing in the community. CLBP is a persistent issue, and one which requires people with the condition to continue to manage their physical condition even when not in pain. Further, gold standard management requires repeated movement even when not experiencing an acute episode of pain, but evidence has demonstrated that this often does not occur. In 2019 virtual reality approaches had promising evidence for the management of acute pain, but not necessarily for chronic pain.

The multidisciplinary team consisted of people from several professions, including physiotherapy, anatomy, choreography and dance, exercise physiology, occupational therapy, design, engineering, astrophysics, and technical VR developers. This team was engaged to undertake a co-design process for developing VR experiences that had the potential to be translated into clinical practice, and was tasked with analysing data as such. They also undertook a systematic literature review of chronic pain and virtual/augmented and mixed reality and a review of headsets and hardware on the market. The procedure involved co-designing VR experiences over several iterations, followed by a feasibility study.

The co-design element consisted of clinicians, researchers, and end users with low back pain working with a technical development team with expertise in designing VR experiences targeted towards addressing desired movements. This also involved developing or modifying experiences and then collecting data to affirm whether the movements were satisfactory. This was progressing to the satisfaction of both Medibank partners and the research team until the 3rd co-design process in February 2020, when Victoria went into multiple extended lockdowns due to the COVID-19 pandemic, halting all non-essential face-to-face experiences for a 2-year period. During that period, the team worked on the systematic review, in addition to restarting the data collection no less than 6 times, only to be halted each time.

In 2022, data collection on the final iterative co-design process and VR experience development, feasibility and clinical studies recommenced and were completed in early 2023, and presented to Medibank colleagues in May and September 2023. We have created 5 bespoke VR experiences to address different exercises and muscle groups for rehabilitation exercises to address CLBP. These experiences have demonstrated that not only is this possible, but the utility both from a clinician and an end user’s perspective is excellent and shows promise as an evidence-based treatment.

Since the original literature review undertaken in 2019, an explosion of reports on VR and chronic pain have been published; thus, the systematic review search has had two significant modifications. According to the latest literature, VR shows great promise in addressing chronic as well as acute pain, however most VR approaches are based on existing experiences applied to chronic pain rather than being developed for the purpose of addressing an issue. The solution co-designed and collaboratively developed for the purposes of this project is unique in this space.

With an excellent product in terms of quality, clinical feasibility and end user utility established, we propose to register the Intellectual Property (IP) of the VR experiences, and to take them forward as a product. To establish the VR as a product will require further development, both from a commercialisation perspective, establishing proof of concept, and also from a clinical perspective. The data we have collected and established is sufficient basis for a clinical trial and/or basis for a grant that would include health economic assessment. We would then translate the product into clinical practice. Finally, the ideal would be to synchronise the VR technology with other monitoring technologies and telehealth procedures, so that remote monitoring and rehabilitation in an evidence-based manner can be established.

2. Introduction

In August 2016, the Australian Institute of Health and Welfare issued a report that outlined the impact of chronic low back pain (CLBP) on individuals and the community, and in 2017-2018 identified that low back pain was one of the leading causes of disease burden in Australia. Historical figures demonstrated that in Australia, CLBP and associated conditions contributed to approximately 1.8% of total health expenditure (between 2008 – 2009) and increased to 3.6% by 2011. Unfortunately, in the latest report by the AIHW this was largely unchanged, with back pain and problems accounting for 4.2% of Australia's disease burden (1) . The most common symptom is pain, however individuals who suffer from CLBP have been reported to have poorer quality of life, experience poor health, and have high levels of psychological distress compared to people without CLBP (1). In 2018 it was estimated that 3.24 million people (approx. 12% of the population) suffered from chronic LBP (including people with arthritis). It is predicted that by 2050 this number will increase to 5.34 million people or approximately 17% of the population (2).

> *"The costs of chronic pain are expected to increase from $139.3 billion in 2018 to $215.6 billion by 2050 in real 2017-18 dollars" (Deloitte Access Economics, 2019, p. 8)*

Chronic back pain, specifically low back pain, is now considered a global priority (3, 4) as it has become the leading cause of disability worldwide (5, 6). In 2020, the North American Spine Society published an evidence based clinical guideline for both diagnosis and treatment of low back pain (7), which demonstrated the difficulty with evidence for treatment of LBP. In a recent review, Urits et al (2019) purported that a multidisciplinary, multimodal interventional approach was required (8).

This project was commissioned by Medibank to determine the feasibility of Virtual or other reality technologies in addressing chronic pain. Thus, LBP was targeted initially as it is a high prevalence condition, that is difficult to treat, is costly at every level with costs increasing and, further, that it provides a model for management of other chronic pain conditions.

Virtual reality is an emerging technology, which has applications in areas such as sports, entertainment, gaming, and simulation. However, elements of VR, particularly simulation and engagement also has great potential as a treatment modality (9). For many years, VR has been used in acute pain as a distraction, but the effectiveness varies by patient characteristics, and has been found to be effective in acute pain management in about two thirds of patients (10). At the time of the project's inception, there was a gap in chronic pain management, however, there has been an explosion of literature in this area over the past 3 years. Much of the evidence for VR as a treatment for chronic pain is promising.

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In summary, LBP is considered one of the highest prevalence and costly conditions, with poor outcomes (3). This project will involve using existing Reality technologies (e.g., virtual reality – VR; augmented reality – AR; and mixed reality – MR), together with the latest chronic back pain management techniques and the psychological profiles of users to:

1. Determine whether VR technology is effective in delivering evidence-based techniques for treating and managing LBP.
2. Determine the psychological and health profile for whom these techniques are and are not effective.
3. Develop a bespoke program to trial.
4. Conduct an up to data systematic literature review. To provide the evidence base underpinning the project. The review includes grey and online literature as well as peer-reviewed publications.

2.1 Project aims (PA)

The aims of the project include:

1. Develop and evaluate Virtual, Augmented or Mixed reality technology as a complementary intervention for managing chronic pain (PA1).
2. Evaluate different hardware for utility with different abilities and tolerances (PA2).
3. Undertake a systematic literature review to examine current state of evidence in reality-based technologies (PA2).
4. Determine the feasibility of Virtual, Augmented, or Mixed technology as an effective form of rehabilitation for Low Back Pain (LBP) (PA3).
5. Examine if VR (or other reality technology) can be used to augment and/or deliver other therapies for pain management (PA4).

3. Systematic Literature Review Summary (PA1) PA1

Background

Technologies such as virtual reality, augmented reality and mixed reality are being innovatively explored as adjuncts to chronic pain treatment. Potential outcomes of this combined application include management of chronic pain and improvements in movement and function.

Objectives

This review synthesised literature on the use of virtual reality, augmented reality and mixed reality for treatment of chronic pain.

Data sources

Quantitative, qualitative studies and mixed-method studies were included, containing the following types of studies: interviews, focus groups, surveys, case studies, cohort studies, randomised control trials, quasi-experimental, mixed methods, intervention studies, and case studies. Excluded from criteria were review papers (systematic or narrative), opinions, letters, commentaries, book chapters and editorials. In addition, any non-human studies were excluded as well as papers focusing on technical specifications of equipment or theoretical papers; for example the study must include the technology and collect data (mixed methods, qualitative or quantitative) with participants.

Study eligibility criteria, participants and interventions

Studies had to be using fully immersive VR/AR technologies that were developed post 2007 in an adult population aged between 18 to 65 years. While a maximum age of 65 was stated in our Prospero protocol, research including participants within and above 65 years old were included as few adult studies restricted maximum age. Interventions that include the use of virtual, augmented and/or mixed reality as a rehabilitation tool for addressing chronic pain were included in this review.

Study appraisal and synthesis methods

The review was performed according to the 2020 Preferred Reporting in Systematic Reviews and Meta-Analysis (PRISMA) guidelines (11). Articles were independently screened using web-based software RAYYAN (12) by 4 reviewers to independently screen articles by title and abstract. Full text was reviewed by one reviewer with a second review divided by 5 others. Disagreements between reviewers throughout this process were resolved through discussion and a third reviewer. The quality of research was assessed by 3 researchers independently using the McGill Mixed Methods Appraisal Tool (MMAT). Discrepancies between reviewers were resolved through discussion. Clinical trial papers were also assessed for risk-of-bias using the revised Cochrane tool RoB2 for randomised trials (RoB 2, (13)).

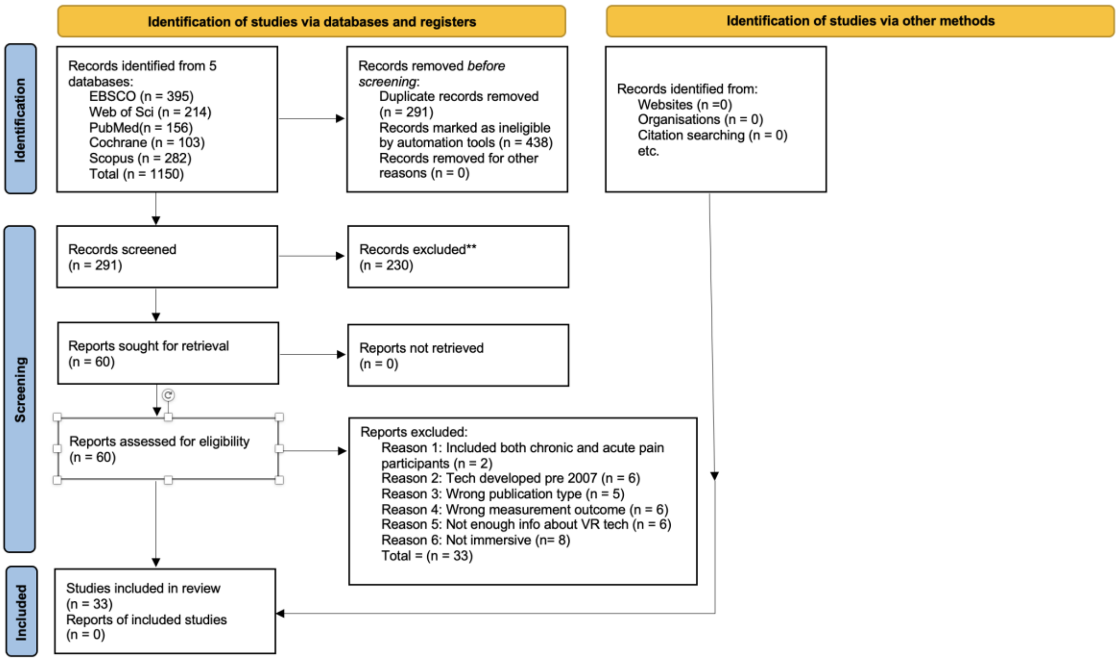

Figure 1: PRISMA 2020 flow diagram.

Results

The initial data base search identified 1150 studies, of which 33 were selected for inclusion in the final analysis. The Cochrane risk of bias assessment applied to 5 clinical trial studies showed that measurement of the outcome and the randomisation process had low risk of bias while some concerns of bias was present due to missing outcomes and deviations from the intended interventions. Only one study registered high risk for selectively reporting results.

Immersive technologies were shown to help reduce chronic pain during and immediately after use, however whether there are any long-term sustained effects requires further investigation. Significant improvement when compared to baseline was found across numerous pain related outcomes associated with function and psychological well-being. A reduction in pharmaceuticals being taken by participants was also reported post interventions.

Conclusions

A broad range of functional outcome variables were shown to improve after receiving VR intervention. Importantly, these findings indicated that VR does have an analgesic affect for people experiencing chronic pain, however longer-term effects have not been proven.

Implications of key findings

Based on these finding VR technologies could be used within a person's pain management plan as a complementary intervention tool for patients experiencing chronic pain.

Trial Registration

PROSPERO International Prospective Register of Systematic reviews number: CRD42019123827 https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=123827

Note: A publication for this systematic review is currently being generated and will be shared with partners in draft form.

4. Evaluating different hardware for utility with different abilities and tolerances (PA2)

4.1 Introduction

At the commencement of the project in 2020, there was no available information as to the quality and utility of different headsets for virtual, augmented or mixed reality headsets. At the time, most headsets were tethered, although wireless ones were being produced. An evaluation was undertaken to determine which headsets may be suitable for remote delivery of VR given requirements of portability and a balance between price and graphic quality and performance. To determine this, online research determining the most popular headsets currently available on the market, followed by an analysis of them in terms of advantages/disadvantages, and a comparison between them in terms of hardware (graphic quality, performance, capabilities), portability, user experience, and price was conducted. Investigation was restricted to headsets that provided a fully immersive 3D experience.

4.2 Results

In 2020, the VR headsets providing a fully immersive 3D experience on the market were: HTC Vive Pro,HTC Vive, Oculus Quest, Oculus Rift S, HP Mixed Reality, Lenovo Mirage Solo, Oculus Go, Valve Index [11][16][17]. In 2023, there is one generation further than the ones here, however most of the principles still apply.

4.2.1 Hardware-Based comparison

The evaluation of VR headsets in terms of performance and capabilities is made up of several parameters. These parameters included: field of view, resolution, refresh rate, and storage. VR headsets can be either PC-Empowered (in case the headset needs to be tethered to a computer to run the experience), or Standalone VR (in case the headset can run the experience independently). The performance of PC-Empowered VR headsets is highly dependent on the computer specifications; for example, a powerful computer will lead to a better VR experience. If the VR headset is Standalone VR, additional parameters should be considered, such as processor size and speed, RAM, integrated graphics and internal storage. Stand-alone headsets have the advantage of portability as no wires are necessary during the experience, but they are limited by these hardware parameters in terms of performance.

In the table 1, the headsets with best graphics quality are the Vive Pro and Valve Index (resolution per eye). The Valve Index has a bigger field of view (or field of vision) than other headsets, determining the extension of the virtual experience seen by the user, while the other headsets have an average field of view, which is usually sufficient to provide an enjoyable immersive experience. Vive Pro, Vive, HP Mixed Reality and Oculus Rift S have a good refresh rate – a parameter linked to the number of times the display updates the VR experience each second. This determines how reactive the VR experience is, with best refresh rates in the Valve Index, and worst refresh rates for Lenovo Mirage Solo, Oculus Go and Oculus Quest.

PARAMETER	Vive Pro[1]	Vive (std.) [2]	Oculus Quest [7,4]	Oculus Rift S [5,7]	HP [9] Mixed Reality	Lenovo Mirage Solo [10]	Oculus GO [15]	Valve Index [12, 14]
Resolution Per Eye	1400 x 1600	1080 x 1200	1440 x 1600	1280 x 1440	1440 x 1440	1280 x 1440	1280 x 1440	1440 x 1600
Field of View	110°	110°	110°	110°	95°	110°	101°	130°
Refresh Rate	90 Hz	90 Hz	72 Hz	80 Hz	90 Hz	75 Hz	72 Hz	120 Hz
Processor	N/A	N/A	Qualcomm Kryo 280 Gold	N/A	N/A	Qualcomm Snapdragon 835	Qualcomm Snapdragon 821	N/A
RAM	N/A	N/A	4 GB	N/A	N/A	4 GB	3 GB	N/A
Integrated Graphics	N/A	N/A	Adreno 540	N/A	N/A	Adreno 540	Adreno 530	N/A
Integrated Audio	Yes	No	Yes	Yes	No	No	Yes	Yes
Internal Storage	N/A	N/A	64 – 128 GB	N/A	N/A	32 – 64 GB + SD card	32 – 64 GB	N/A
Special Requirements	Enviro space, BS, Comp	Enviro space BS Comp	N/A	Comp	Comp	N/A	N/A	BS

Table 1: Hardware based comparisons of headsets – 2020.

Enviro space = Environment space, BS = Base Stations, Comp = Computers

4.2.2 Portability and user experience-based comparison

The portability and user-based experience of VR headsets were compared. Headsets can be either PC Powered where the user is tethered by power cords which can restrict movement range and can add extra complexity with regards to where it can be used or VR headsets that are standalone. The best headsets in terms of portability are the Oculus Quest, Oculus Go and Valve Index (see Table 2). When assessing the user experience several metrics were used, including the weight of the headset, the possibility to adjust eye relief, and ergonomics of the headset (e.g., adjustability of the display through strips).

As shown in table 3, Valve Index and Lenovo Mirage solo are the heaviest headsets, while the Oculus Quest, Oculus Rift S and Vive Pro are the best in terms of ergonomics. HP Mixed Reality and Lenovo do not present the possibility to adjust eye relief, leading to a higher chance of users experiencing ocular discomfort during the VR experience.

PARAM ETERS	Vive Pro	Vive (std.)	Oculus Quest	Oculus Rift S	HP Mixed Reality	Lenovo Mirage	Oculus Go	Valve Index
Headse t	Tethere d/Wirel ess	Tethere d	Wireles s	Tethere d	Tethere d	Wireles s	Wireles s	Wireles s
Require s a comput er	Yes	Yes	Option al	Yes	Yes	No	No	No
Wireles s Control lers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2: Portability based comparison.

PARAMETE R	Vive Pro	Vive (std.)	Oculu s Quest	Oculus Rift S	HP Mixed Reality	Lenov o Mirag e Solo	Oculu s Go	Valve Index
Features	Optimised Ergonomic s	Adjustabl e straps	-	-	-	-	-	-
Adjustable Eye Relief	Yes	Yes	-	Yes	No	No	Yes	Yes
Weight	555g	468g	571g	470g	528g	645g	468g	809g

Table 3: User experience-based comparison

4.2.3 Price-Based Comparison

The Oculus Quest and Oculus Rift S provided a good trade-off between quality and price. The most expensive headsets are: Vive Pro, Vive, and Valve Index, while the cheapest headset was the Oculus Go. For each of the tethered headsets, the cost of a computer with the required specifications needs to be considered for operation. Table 4 illustrates the cost of the various systems.

INCLUDED	Vive Pro	Vive (std.)	Oculus Quest	Oculus Rift S	HP Mixed Reality	Lenovo Mirage	Oculus Go	Valve Index
Headset	$900	_	$649	$649	$399	$399	$239-319	$999
Headset + controllers	–	–	$799	_	_	–	–	–
Headset + controllers + base stations	$1,899	$989	_	_	_	–	_	_

Table 4: Cost of headsets and included kit in AUD.

4.3 Findings

The headset with the most features was the Oculus Quest, which had portability, performance and graphic quality, and affordability. In 2023, this has been superseded by the Oculus Meta Quest 2 (formerly Oculus Quest 2) as a stand-alone VR headset, which does not need any additional hardware and is priced at around $500 AUD.

Of the headsets reviewed in 2020, the Oculus Rift S was similar in terms of performance, quality and price, however it is not as portable as it needs to be wired to a computer to run the experience. While the HTC Vive Pro and Valve Index were better performing headsets than the Oculus Quest, they had disadvantages in portability and price; and this is consistent in their later offerings. See Table 5 for a comparative summary of the headsets we investigated. Following consideration of these factors we choose the Oculus Quest for our study.

What is clear however is that competing headsets are different and inconsistent in terms of quality, maintenance, durability, and price point. Importantly, our comparisons were undertaken before the Facebook change to Meta and the Meta takeover of VR headsets.

In the future, if this were to be scaled, the data ownership, protection and ethics would need to be protected and an agreement made to ensure data protection for health-based studies. Cybersecurity measures such as blockchain would need to be implemented for any health or personal data that was collected and monitored.

Tech	Vive Pro	Vive (std.)	Oculus Quest	Oculus Rift-S	HP Mixed Reality	Lenovo Mirage	Oculus Go	Valve Index
Resolution/ Graphics	* * *	*	* * *	*	* *	* *	* *	* * *
Field of View	* * *	* *	* *	* *	*	* *	*	* * *
Refresh Rate	*	* *	*	*	* *	*	* *	* * *
Wearability	* *	* * *	* *	* * *	* *	* *	* *	*
Portability	*	*	* * *	*	* *	* *	* * *	* *

Table 5: Summary of VR headset comparisons

1. Stars are comparative indicator. *= poor, ** = middle, *** = good

5. Co-design and evaluation of virtual reality technology as an intervention for managing chronic pain (PA3)

Co-design is a participatory approach that involves designers, researchers, and individuals from diverse backgrounds collaborating in the design process (14, 15). To be more precise, co-design is described as a design-driven process that employs creative and participatory principles and tools to involve a wide range of people and knowledge in addressing public problem-solving (16). What sets co-design apart from other participatory approaches is its emphasis on creativity and active involvement of participants in the creative process (14) (15). This connection between co-design and the establishment and strengthening of relationships (17) (18) suggests that the collaborative creative aspect of co-design has the potential to enhance participants' feelings of connection and engagement.

Co-design principles are being applied in healthcare settings (19) to accomplish a variety of objectives, including enhancing patient experience (17) (20) and identifying priority health issues (21). This sense of enhancing participants feelings of engagement and connection is an important part of co-design in health. That is, the more an end-user is engaged in the process, the more likely they are to feel empowered over their own health and manage their conditions. In chronic conditions such as low back pain, this is an important consideration.

Self-management is key to successful management of low back pain (22), and co-design with end users of health services has been found to increase their participation and engagement.

There is not a definitive right or wrong method for co-design; however, the most effective co-design processes are those customised to the specific audience involved and the desired outcomes. For this project, we used the previous version of the UK Design council's 'Double Diamond' (23) approach to engage in design thinking when conducting research and delivering design sprint workshops. The Double Diamond process (see figure 2) is a well-established method used together by designers with non-designers in public, private and non-profit organisations (23). There are four phases: Discovery, where one understands and explores all aspects of an issue; Define, using insights and information gathered in the discovery to define the challenge in a different way; Develop, giving answers to the clearly defined problem, and; Deliver, testing different solutions and prototypes. It is important to note that traditionally this process is not linear but iterative; however, for the sake of time constraints within these design sprints, participants were asked to complete the phases linearly.

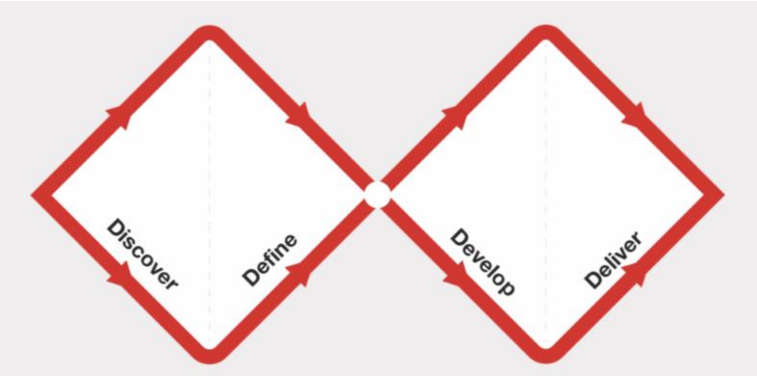

Figure 2: UK Design Council's Double Diamond Pictorial Representation

This approach facilitated effective engagement between developers, health professionals, researchers, and participants in the co-design process. Specifically, the 'Discover' and 'Define' phases necessitated the inclusion of individuals with lived experiences in crucial decision-making points within the problem-solving process. The act of empathising with end-users is essential for the successful development of data, research findings, and other project deliverables. It is vital that the co-design process emphasises the collaboration with people who have lived experiences, rather than designing solely for them. The Double Diamond framework provides a higher-level structure for problem-solving, wherein flexibility, adaptability, co-design, and empathy stand as pivotal elements contributing to project success. Users were further engaged in the development of the VR technology by changing the programs following feedback. In the delivery phase, the co-designed VR modules were delivered, with multiple end-users engaged to test the feasibility of the intervention going forward.

5.1 Rationale of data collected

In the first four sessions, the double diamond approach of discover, define, develop and deliver was used to create 5 VR games. The VR games were co-designed with the input from participants, clinical advisers, researchers, and the technology development team. Development of the games were also informed by objective measures including heart rate (HR), EMG and motion capture. The HR was recorded to help establish if the VR activities would be safe for people who are at high risk of cardiac events. The EMG sensors were placed on muscle groups predominantly around the torso to see if the VR games activated muscle groups central to strengthening when addressing CLBP. Motion Capture (MoCap) was utilised to capture their movements when undertaking the experiences, giving objective evidence of degree and quality of movement. Participants wore a MoCap suit with markers over pre-determined bony landmarks. Range of Motion (RoM) was captured in and out of the MoCap suit to ensure that the measurements were valid. Percentage of time spent performing trunk movements and the was calculated to gauge the level of therapeutic benefit expected to be gained through playing the VR games. Detailed information on participants with CLBP was collected so the sample could be sufficiently described. Quantitative information about functions associated with and impacted by the presence of CLBP was collected via a series of pen and paper questions and physical measurements. Height and weight measures were taken to calculate an individuals' BMI and a RoM assessment designed to assess a person's joint flexibility and were taken to understand the extent that CLPB was impacting a person's movements within the lower back regions. The methods used in each of the co-design sessions are summarised in Table 6. Further detail on all measures used can be found in Appendix A.

5.2 Testing and Feasibility of the final VR experience

At the completion of the co-design/co-production process, two further sessions (session 5 and 6) were undertaken to explore the feasibility of the VR games. A naive group of participants with CLPB were recruited for session 5 to experience the final VR games to verify its usability and safety. Then, for session 6, 3 participants without CLBP were videoed performing all VR games so movements could be independently assessed by 2 clinicians as to the movements and muscles activated during each game. The methods used in these last two sessions are summarised in Table 6.

5.3 Outcome measurement tools

There were three main categories of measurement: Questionnaires about health and low back pain, physical measurements, and interview questions with participants. The measurements and their administration are summarised in Table 6 below.

Questionnaires

- Screening tools: To identify those individuals with a known disease, and/or signs or symptoms of disease, who may be at a higher risk of an adverse event due to physical activity/exercise. An adverse event refers to an unexpected event that occurs as a consequence of a physical activity/exercise session, resulting in an adverse outcome the ESSA PSS was utilised. The motion sickness susceptibility tool (MSSQ-Short) was also taken. This questionnaire is designed to find out how susceptible to motion sickness a person is, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy, nauseated, or actually vomiting.
- Pain and Back Pain: 4 pain surveys were undertaken in the first session and repeated at session 5, although the numbers were rationalised following participant feedback – combined into 2 (Oswestry LBPDQ, and Brief Pain Inventory) on the advice of clinical specialists as to the best outcome tool; considered the gold standard.
- Health – general – The Short Form (12) Health Survey Version 2 (SF-12v2) is a 12-item questionnaire which evaluates the individual health status over eight domains including vitality, physical functioning, bodily pain, general health perceptions, physical role functioning, emotional role functioning, social role functioning, and mental health. Taking only two to three minutes to complete, the SF-12v2 is a practical, reliable and valid measure of physical and mental health.
- Mental Health/Anxiety: 3 tools were used in the initial protocol and again, the information was repetitive and thus only the Generalised Anxiety Disorder (GAD-7) was repeated.

Physical assessments: All physical assessments were undertaken by two people, one an exercise scientist or Exercise Physiologist and the other a physiotherapist, to ensure reliability, consistency and credibility.

- Height and Weight:
  - Standard height measurement was taken with the participant on two occasions in the initial session for reliability. Body mass (weight) was recorded three times, also for consistency.
- Range of Motion Assessment:
  - Knowledge of surface anatomy and proficiency in the use of a goniometer were required to ensure measurements were conducted accurately and with clinically reliable results. Thus, the two assessors had pre-training and reliability ascertained prior to the results
  - Rane of motion for each movement was analysed and recorded twice per session
  - Measurements were repeated if the difference between tow measurement was more than 5°
  - RoM was taken with the Motion Capture suit off, then repeated with the MoCap suit on.

- 3D Motion Capture (MoCap)
    - Data was collected at the Embodied Movement Design (EMD) studio space.
    - Participants were fitted with heart rate sensor and EMG and then asked to don a motion capture suit which was one size smaller than their usual clothing style to ensure fit, worn over bathers or underwear.
    - Markers were then placed on the body of the participant as per protocol.
    - Participants performed a T-pose so that markers are mapped to software
    - VR experience begins.
- Heart Rate:
    - The Polar H7 heart rate sensor, which has two parts – a chest strap and the connector (PolarH7,m Polar Electro, Kemple, Finland) was utilised to monitor heart rate as a risk factor during the experience and experiments. The heart rate sensor is worn around the chest, just below chest muscles. Data was subsequently downloaded and saved into an Excel file.
- Surface EMG
    - All users were trained by a technical staff member prior to using the machine, which was a Laptop with MR3 software, Noraxon Ultimum device receiver and wireless EMG devices.
    - Following RoM without the MoCap suit, the participant was prepared, and EMG electrodes fitted to the person using predefined protocol, with the MoCap suit fitted afterwards.
    - The electrodes are connected and recorded when actions have been completed. These are then saved and a new recording created for each movement.
    - Data was then exported to the appropriate database and visually inspected by technician.

It is noted that the sEMG data was visually inspected at the time of data collection but not analysed. As such, upon examination by an expert at time of data analysis, it was found that there was too much noise from the MoCap suit for the data to be useful and was therefore rejected from final analysis.

Interviews

- At the end of each co-design session (1-4), interviews were conducted with participants around their experiences:
    - Cyber sickness
    - How the experience felt, what they liked/didn’t like
    - Usability – performance, error rate, utility, satisfaction, and error tolerance
- At the end of session 5, interviews were conducted, but the questions were about the experience, feasibility of doing this in one’s own home, manageability, likelihood of undertaking this experience at home.

	Co-Design Double Diamond Phase				Test Phase	
	Population 1				2	3
Measures	Sess 1	Sess 2	Sess 3	Sess 4	Sess 5	Sess 6
Questionnaires						
Adult Pre-Exercise Screening System (APSS)	*				*	*
Motion Sickness Susceptibility	*				*	*
Questionnaire Short Form						
Oswestry Low Back Pain Disability Questionnaire	*				*	
Pain Catastrophising scale (PCS)	*					
Connor Davidson Resilience scale (CD-RISC)	*					
Generalised Anxiety Disorder-7 (GAD-7)	*				*	
SF-12 Health Survey	*				*	
Brief Pain Inventory	*				*	
Pain Self Efficacy Questionnaire	*					
Hospital Anxiety and depression scale (HADS)	*					
Physical assessments						
Height and Weight	*	*	*	*	*	
Range of Motion Assessment	*	*	*	*		
3D Motion Capture (MoCap)	*	*	*	*		
Heart Rate	*	*	*	*	*	
Surface Electromyography (sEMG)	*	*	*	*	*	
Interview questions						
7 short answer questions	*	*	*		*	*

Table 6 Summary of methods used for delivery and discovery, develop at sessions 1-5 and to evaluate effectiveness/feasibility at times 5 and 6

Sess =session,

1. Participants entering the co-design sessions after session 1 would have completed all questionaries as part of that session

5.4 Co-design of VR as an effective form of rehab for low back pain (PA4)

5.4.1 Overview

With the input from participants, clinical advisers, researchers, and the technology development team, a collaborative co-design VR of experiences occurred over 4 iterative sessions.

5.4.2 Procedure

The co-design phase of this project included 4 iterative sessions of VR evaluation and subsequent development. This section gives a summary overview of the procedure. A more comprehensive explanation of the methodologies applied as part of the procedure is provided in Appendix B.

Across the co-design sessions a total of 8 participants with chronic CLBP (age: M=35, SD=12.33) and 4 controls with no pain (age: M=32, SD=4.32) were recruited. Inclusion criteria for CLBP participants required individuals to have recurrent low back pain for a period of greater than 3 months and be aged between 18 and 65 years. For safety reasons, individuals with CLBP were screened over the phone and were excluded from the study if they did not meet our safety criteria. All participants were reimbursed with a $50 gift card per session for their time and travel. Control participants were only required to report the absence of chronic pain and pass the two screening questionnaires.

On arrival, all participants read through the participant information statement and provided their signed informed consent to participate. The CLBP participants' first task was to fill out a demographic questionnaire and a series of standardised pen and paper questionaries measuring different elements of chronic pain and mental health (see table 11 and 12). This took the participants 20-30 minutes to complete.

Height, weight and RoM was measured by a member of the team qualified in the area of physiology using standardised measurement protocols. The RoM measurements were conducted twice; without the MoCap suit and then again with the participant wearing the MoCap suit. After the first set of RoM measurements were completed we attached the EMG and HR sensors. The sensors being applied included a PolarH7 HR monitor and 8 electromyography (EMG) wireless sensors to the participants torso (see figure 3).

The participants proceeded to the VR specialist on the team who explained the VR safety instructions. Participants were shown how to wear and adjust the Oculus headset for comfort. Depending on the session participants partook in 2 to 5 VR experiences that each went for 5mins or less. After the VR experiences the participants were asked a set of questions on what they thought about their experiences, how it made them feel and if they would use this technology in the future.

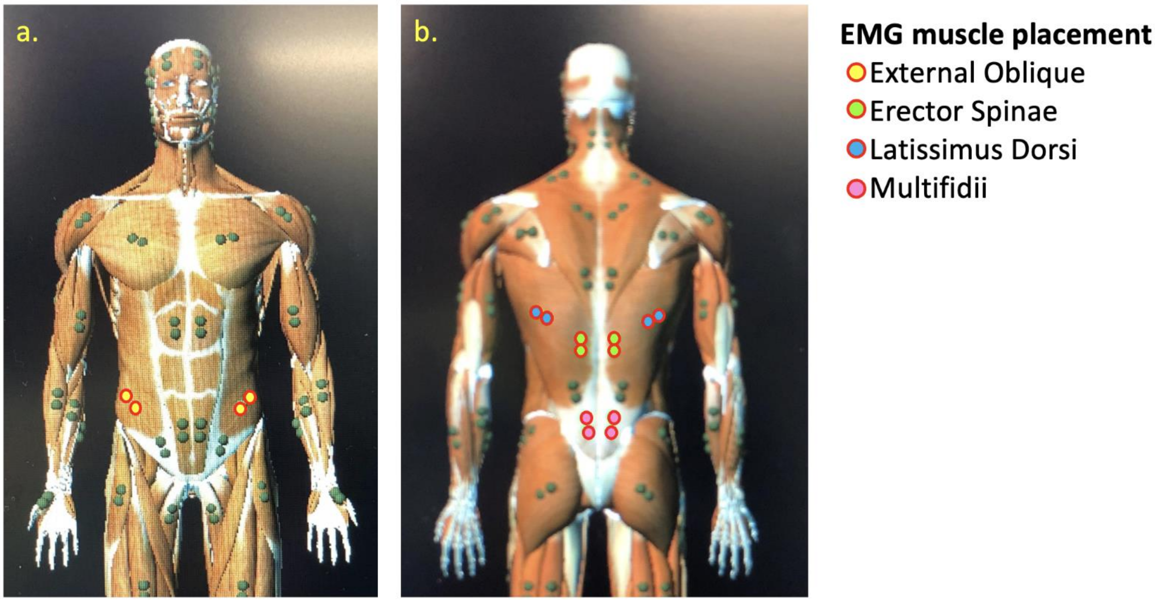

Figure 3: Placement of the EMG sensors on the front (image a.) and the back (image b.) of the body

5.5 Data analysis

5.5.1 MoCap

All data was filtered with a low-pass, 4th order Butterworth filter within Visual3D v5.01.9. Trunk range of motion (ROM) was calculated about each axis of rotation defined by the motion of the pelvis relative to the thorax in accordance with the International Society of Biomechanics (ISB) recommendations using a ZYX Cardan sequence. Whereby lateral flexion was defined about the X-axis, trunk rotation about the Y-axis and flexion/extension about the Z-axis (Figure 5).

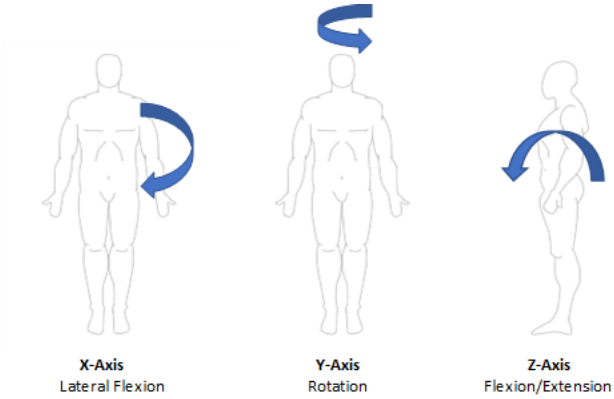

Figure 4: Trunk motion relative to each axis of rotation

During each participant's VR experience the maximum and minimum trunk angle about each axis was extracted and expressed as the RoM. Analysis of the RoM enabled comparative analysis accounting for inter- and intra-session variability in MoCap data. Due to the small data set, subsequent analysis was conducted via descriptive statistics. summary of the numbers included in the MoCap analyses for each VR experience is provided in table 7.

	Session 1		Session 2		Session 3		Session 4	
	CLBP	without-CLBP	CLBP	without-CLBP	CLBP	without-CLBP	CLBP	without-CLBP
Neural Poise	7	2						
River Crossing	7	2						
River Raft – Seated			3	2				
River Raft – Standing			3	2				
River Raft					1	3		3
Zen Garden					2	3	1	3
Planetarium					2	3	1	3
Treasure Hunt							1	2
Gyration Station							1	2

Table 7: Participant n included in the MoCap analyses for each VR experience.

5.5.2 Heart Rate

Heart rate data was processed to exclude any erroneous values, namely signal dropout (any period of time when the reading recorded equated to zero) or signal contamination (any sequential period of 100ms or more where the interpolated signal equated to zero). Resting HR (RHR) was defined as the average HR during the resting HR recording and maximum heart rate (MHR) was calculated via the Karvonen formula. Percentage of mean heart rate reserve (HRR) (MHR – RHR) was expressed as a percentage of the processed trial length and used to define exercise intensity zones (Table 8) in accordance with ACSM recommendations (REF). For any session where RHR was unable to be extracted from a reading the average RHR from the participant's previous sessions was used.

Intensity	Percentage HRR
Very light	< 30%
Light	30 - 39%
Moderate	40 - 59%
Vigorous	60 - 89%

Table 8: Different levels of exercise intensity zones for percentage heart rate reserve

5.5.3 sEMG

The root mean square (RMS) of each sEMG signal was calculated over a period of 20ms, from which a baseline was extracted from the initial 25ms of each recording. Defining the baseline per trial was chosen to account for between trial influences that may have affected readings (e.g., electrodes being reapplied). For each muscle, muscle activity was defined as any duration where the RMS signal exceeded three standard deviations above the baseline mean reading and was expressed relative to the total trial duration (based on the sEMG trial length).

5.6 Results

5.6.1 Participants

For the co-design phase of sessions 1 through to 4, participants were asked to come in for multiple sessions of the design and testing phase (see table 9). Displayed in the following tables are the participants demographics (table 10) and results from the mental health questionnaires (table 11) and pain related questionnaires (table 12).

	Group	Session 1	Session 2	Session 3	Session 4
P01	CLBP	*	*		*
P02	CLBP	*	*	*	
P03	CLBP	*	*	*	
P04	CLBP	*			
P05	without- CLBP	*	*		
P06	without- CLBP	*	*	*	*
P07	CLBP		*		
P08	CLBP	*		*	
P09	CLBP	*			
P10	CLBP	*		*	
P11	without- CLBP			*	*
P12	Without- CLBP			*	*

Table 9 Summary of participants involved in each of the co-design sessions.

ID	Group	Gender	Age	BMI	MSSQ	Resting HR
P01	CLBP	M	25	Healthy	15	77
P02	CLBP	M	46	Obese class I	12	98
P03	CLBP	F	56	Obese class II	25	83
P04	CLBP	M	27	Healthy	70	74
P05	without-CLBP	F	38	Overweight	-	71
P06	without- CLBP	M	30	Obese class II	-	76
P07	CLBP	F	28	Obese class II	97	91
P08	CLBP	M	22	Overweight		88
P09	CLBP	F	34	Obese class I	0	85
P10	CLBP	M	46	Healthy	30	69
P11	without-CLBP	M	28	Healthy		80
P12	without-CLBP	F	32	Healthy		79

Table 10: Participant demographic information

M = male, F = female, - = missing data, Age = reported in years, BMI = Body Mass Index, MSSQ= Motion Sickness Susceptibility Questionnaire

ID	Health	Anxiety		Depression	Diagnoses	Meds
	SF-12	(GAD-7)	(HADS)	(HADS)		
P01	22	Severe	Abnormal	BL abnormal		
P02	57	Minimal	Normal	normal		
P03	40	Mild	Normal	normal	schizophrenia	Clozapine
P04	37	Moderate	BL abnormal	Normal	depression	
P07	33	Severe	Abnormal	normal		
P08	27	Moderate	BL abnormal	normal		
P09	-	-	-	-		
P10	56	Minimal	normal	normal		

Table 11: CLBP participant health information

BL = Borderline, - = missing data, SF-12 = Short Form (12) Health Survey, HAD = Hospital Anxiety and Depression Scale, GAD-7 = General anxiety disorder

ID	Back Pain (ODI)	Catastro-phise (PCS)	Resilience (CD-RISC)	Physical Health (SF-12)	Self-Efficacy (PSEQ)	Severity (BPI)	Interference (BPI)	Treatment
P01	Moderate	Severe	60 (Q1)	33	Moderate	5	6.5	Norspan
P02	Minimal	Mild	81 (Q2)	46	Minimal	2	0.86	Panadene, walking, stretching
P03	Moderate	High	65 (Q1)	41	Mild	4.75	4	Panadeine forte
P04	Moderate	Mild	56 (Q1)	41	Minimal	4	3.57	Physiothera py Ibuprofen
P07	Minimal	Mild	50 (Q1)	46	Minimal	5.75	0.29	
P08	Minimal	Mild	82 (Q2)	44	Mild	4.75	3.83	Warm water bag
P09	-	-	-	-	-	-	-	-
P10	Minimal		82 (Q2)	49	Minimal	1.25	1	Stretching and resting

Table 12: Pain related information of participants with CLBP

ODL = Oswestry Disability Index, PCS = Pain Catastrophising Scale, CD-RISC = Connor Davidson Resilience Scale, SF-12 = Short Form (12) Health Survey, PSEQ = Pain Self-Efficacy Questionnaire, BPI = Brief Pain Inventory Q1 = first quartile, Q2 = second quartile, Q3 = third quartile, Q4 = fourth quartile, - = missing data

5.7 Session 1

5.7.1 Overview

Participants completed the full list of questionnaires which provided the project team with a comprehensive understanding of their CLPB and associated functions which are used throughout their participation in this project. Participants' RoM was measured in and out of the MoCap suit to assess how much the suit will restrict a person's movements when playing the VR games. In session one, two existing VR experiences developed by the CTMT dev team were utilised to measure lumbar movement in games that (a) should include some lumbar movement but (b) were not specifically designed for this purpose. Game on - Neural Poise is a free flow creative experience often used by dancers which encourages people to freely move around a space to create patterns. Game 2 - River Crossing is a problem-solving game, which requires bending and stretching to reach objects located in different heights on the ground.

5.7.2 VR experiences

Neural Poise

In Neural Poise participants found themselves in a black space with a blue square that they could move around via the handheld controller within the VR environment (Figure 8). This was a free from creative experience where participants could direct swirling pattens of light by moving the hand controller. The patterns were affected by the speed and direction that the participant moved the hand controller. Participants were given 5 minutes to explore the experience and the movement was recorded and analysed.

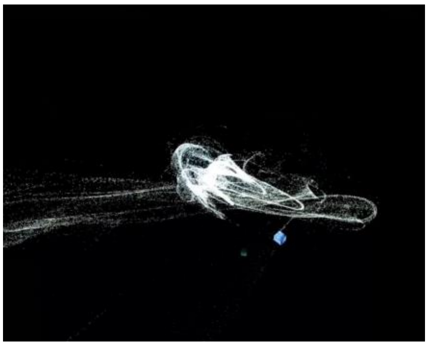

Figure 5: Image of a pattern created during the Neural Poise experience. The blue square provided feedback as to where the participants hand was in space.

River Crossing

River Crossing was an adapted classic children's strategy puzzle. This type of puzzle requires participants to carry items from one riverbank across to the other side in the fewest trips possible. To achieve this the person must navigate restrictions that are placed on which items can be transported together or left together. In our VR experience participants were required to transport a goat, a wolf and a basket of cabbages across the river without the wolf eating the goat or the goat eating the cabbages (see figure 7).

Figure 6: Screenshots from River Crossing. Left image shows the participants VR hand selecting the wolf to place in the boat. Right image shows the goat and bucket of cabbages.

5.7.3 Results

RoM in and out of MoCap suit

Joint RoM) of the shoulder and hip joints and throughout the cervical, thoracic, and lumbar spine were measured and the difference between range in and out of MoCap suit. Differences of 2±SD were deemed as outliers resulting in a sample of 213 measurements. Across all joints measured, wearing a MoCap suit resulted in a reduced range of motion of 1 ± 8°. Specific to the trunk RoM, this was observed to reduce by 2 ± 5° when wearing the MoCap suit. This was deemed to be acceptable.

MoCap Data

Both VR experiences were found to elicit trunk RoM about each axis of motion. Neither experience was sensitive to isolating motion about a single joint axis, with the predominant RoM being trunk rotation (neural poise: 27.67 ± 17.45°; river crossing: 25.67 ± 10.28°) followed by flexion/extension (neural poise: 24.29 ± 19.75°; river crossing: 21.99 ± 18.02°).

Across both VR experiences, CLBP participants were observed to elicit higher degrees of RoM compared to those without-CLBP (Figure 10), with greater variability noted about each axis, particularly for flexion/extension (neural poise: CLBP: mean: 28.76°, CI 95%: 10- 48; without-CLBP: mean: 9°, CI 95%: -11-28; river crossing: CLBP: mean: 26°, CI 95%: 8 - 43; without-CLBP: mean: 9°, CI 95%: -18-36. The implication of this is that those with CLBP were moving other joints, rather than isolating movements around their lower spine, whereas those without CLBP were able to attain the targeted movements uniformly.

	Lateral Flexion	Rotation	Flexion/Extension
Neural Poise	20 ± 12	28 ± 17	24 ± 20
River Crossing	18 ± 7	26 ± 10	22 ± 18

Table 13: Trunk RoM (mean ± SD) during each VR Experience

Heart rate

Mean heart rate reserve (HRR) response for all VR experiences (Neural Poise, River Crossing) during session 1 indicated exercise of very light intensity (<30%HRR) activity, apart from one participant who recorded <4% of light intensity (30-39%HRR) activity during River Crossing.

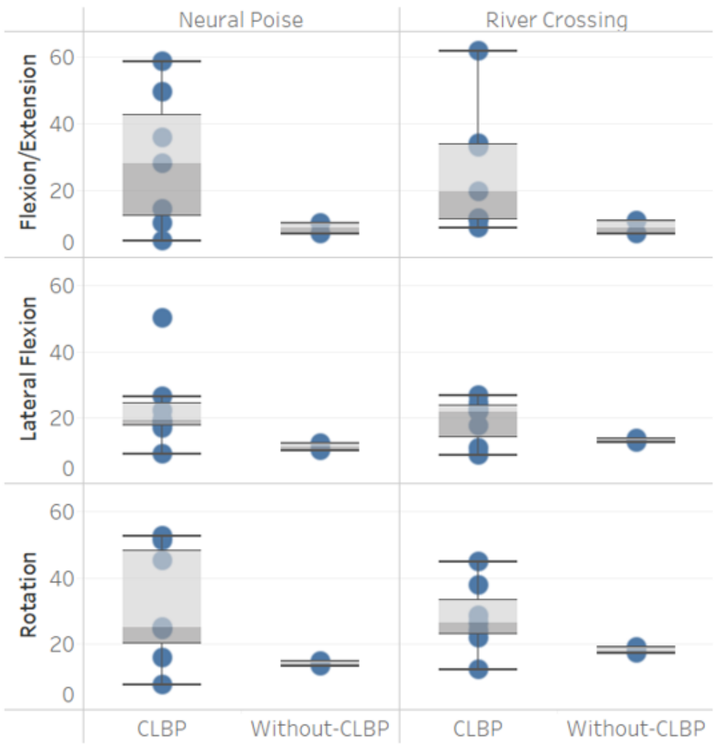

Figure 7: RoM during each VR experience according to condition and group

sEMG

Following expert advice on the integrity of the sEMG data, all data from the session were excluded from further analysis due to excessive noise impacting the integrity of the recorded signal. The MoCap suit was observed to impart movement artefact and compromise the skin-electrode interface resulting in signal contamination that could not be removed using post-processing techniques. All sEMG data from sessions 1-4 were reviewed post session 4, and excluded.

Interview

Participants reported enjoying the experience, typically describing it as fun. Neural Poise was described to be either boring or relaxing but also caused a lot of confusion for participants who were unsure of what they should be doing. Participants reported enjoying game aspect of River Crossing and overall preferred this game over Neural Poise. They expressed general interest in using the technology at home, and felt that if it had an interesting game, they were open to integrating it into their routine rehabilitation program.

5.7.4 Discussion

The off-the-shelf VR games utilised in this session did not inherently encourage participants with CLBP to move in the directions that would be expected. The CLBP participants would substitute different movements to achieve the goal in the game, avoiding back movements. This was reflected in the mean heart rate reserve recorded during the games that indicated only very light intensity activity was being performed. While we did confirm that the MoCap suit does restrict a person's RoM the effect was only small indicating that the lack of movement observed was primary due to the game requirements. Slightly greater movement variability was associated with the freely structured Neural Poise experience compared to the River Crossing experience.

Participants preferred the more structured River Crossing experience compared to Neural Poise. Overall, the participants felt that the VR technology was usable and enjoyable and would consider incorporating it in their ongoing pain management program. They indicated their preference for targeted and structured games.

5.8 Session 2

Codesign of VR experiences:

Based on the results of the first study, the clinical, research and technology development team collaborated to co-design the next experience based on feedback from the participants of session 1, the questionnaire results, and the Motion Capture and other signal-based recordings. The VR which was developed for Session 2 was done in collaboration with clinical experts informed by clinical data and the feedback participants provided in session 1. The resulting game was “River Raft”; participants steered themselves down a river, rotating and flexing their lumbar spine. The clinical objective of this experience was to have participants make thoracic spinal rotation left to right as they steered a boat down a river.

Except for the pen and paper questionnaires, all measures that were taken in the first session were repeated. In the co-design of the River Raft experience, the clinicians indicated that spinal rotational movements in both seated and standing positions were required and worked with the development team to create a bespoke activity to elicit these movements. Feedback from the participants was obtained at the end of each session.

5.8.1 VR Experiences

River Raft

The goal of River Raft was to encourage trunk rotation and side to side movement. Participants found themselves in a boat on a river and were provided with a long staff which represented their paddle in the game. In the middle of the staff a VR hand controller was attached which provided feedback on the level of rotation being achieved. The boat moved forward with the currant of the river, and participants were responsible for steering the craft to avoid the banks of the winding river (figure 8). Steering was achieved by dipping the paddle into the water on their left to turn the boat right and on the right to turn the boat left. The experience had no defined end point that concluded the experience. Participants were given 5 minutes in the game before being instructed to stop.

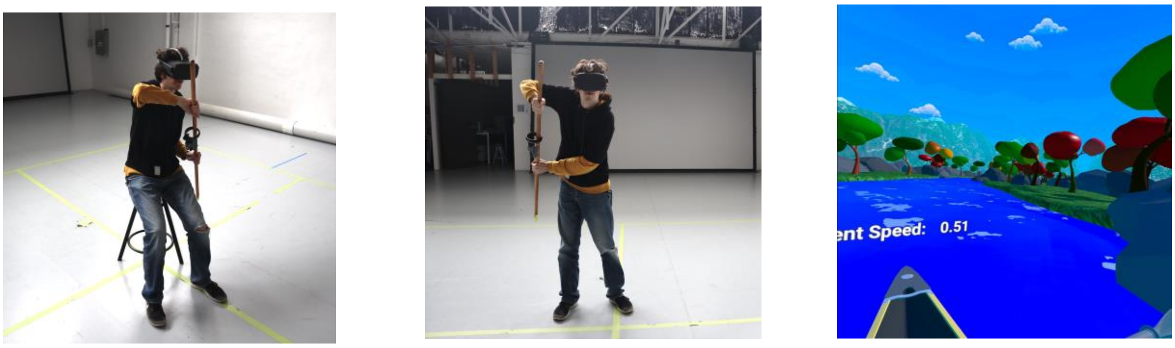

Figure 8: Left image is a participant playing River Raft in the seated position, middle image is the same participant in the standing position for River Raft. Right image shows the VR environment viewed by participants.

5.8.2 Results

MoCap

Differences in trunk motion were elicited between seated and standing variations of the River Raft VR experience (Figure 12). Whilst trunk rotation was identified to be similar between seated (mean: 32°; CI 95%: 24 - 40) and standing (mean: 28) River Raft experiences, secondary trunk motion was noted to decrease when seated. Lateral trunk flexion decreased by 26% (seated: mean: 26°; standing: mean: 34°) and trunk flexion by 24% (seated: mean: 22; standing: mean: 29°).

When considering differences in movement patterns between those with CLBP and without-CLBP, those with CLBP were noted to elicit greater motion about all trunk axes compared to those without-CLBP across both the seated and standing River Raft VR experiences (Figure 9). Whilst average differences in trunk flexion RoM were less than 5°, larger differences were noted for both rotation and lateral flexion. Those with CLBP were observed to adopt twice as much RoM about the lateral flexion axis in contrast to those without-CLBP across both seated and standing experiences. For both CLBP and without-CLBP groups a large degree of variability in RoM about each axis of rotation was noted. The implications of this are that people with CLBP are not utilising the small, targeted muscles automatically, rather using larger, compensatory movements. This must be noted for clinical implementation, to identify and isolate movements for people who may undertake this rehabilitation remotely.

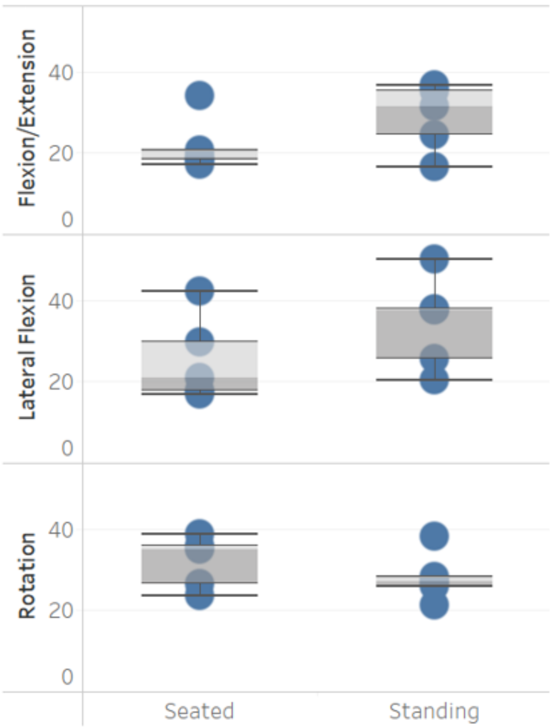

Figure 9: Trunk RoM during session 2 seated and standing River Raft VR experience.

Heart Rate

Mean heart rate reserve (HRR) response for both River Raft conditions (Seated, Standing) during session 2 indicated that the exercise was of very light intensity (<30%HRR) activity, except for two participants, during the Standing condition who also recorded <17% and <6% of light intensity activity (30-39%HRR), and 34% and 20% of moderate intensity (40-59%HRR).

Interviews

Participants reported liking the colourful scenery within the VR environment, however all participants experienced motion sickness to varying degrees in the seated position.

5.8.3 Summary

The bespoke developed VR game demonstrated that they were able to elicit some clinically desired movements in the trunk, particularly for people without CLBP, who were using the small, targeted movements. The heart rate reserve was predominantly reported in the safe range between very light and light intensity suggesting it is safe for people who are some risks of adverse cardiac events. Finally, based on participant feedback it was clear that the game required further development to remove the type of motion in the game that induces motion sickness.

5.9 Session 3

Codesign and Overview

Based on the results from sessions 1 and 2, the clinical, research and technology development team and collaborated to co-design the next the VR games for session 3.

Changes to the River Raft game that were made for Session 3 was done in collaboration with clinical experts and was informed by the feedback participants provided in session 2. The task in the game was changed to address the motion sickness that was induced in the first version. In the revised version, participants actions now propelled the boat forward rather than passively steering the boat down the river which should address the motion sickness. To control for movements in occurring in the lower extremities which ideally should main fixed when performing trunk rotation clinical advisers recommended participants be seated during River Raft.

Based on the MoCap data presented in session 2 showing that games could be designed to elicit certain movements, two more games that were developed for session 3 in consultation with clinical advisers. These were “Zen Garden” and “Planetarium” and were designed elicit different motions beneficial to addressing CLBP.

To support participants in preforming the intended RoMs in each game , participants were provided with explicit movement instructions prior to them participating in each experience. The target movements are detailed in each of the VR experience descriptions.

5.9.1 VR experiences

River Raft

In this exercise participants played the game only in the seated position. To reduce motion sickness, the steering of the boat became automated, and the participants target body movements now propelled the boat forwards. To target the amount of rotation occurring in the z-axis compared to the previous session, participants were provided with direct movement instructions. Participants were explicitly told to hold the staff in two hands and to use a wide underhanded grip on the staff to maximise the range of motion. The boat accelerated when the paddle was rotated 80 degrees from the starting forward position to their left and right in an alternating fashion on the z-axis. A digital opponent was added to race against to further gamify the experience by providing a challenge for participants to overcome. The digital opponent also acted as a pace setter so participants would not under or overexert themselves. The experience ended once participants reached the finish line. The experience ran for under 5mins with the time took to complete River Raft varying based on each participants rowing speed.

Planetarium

The Planetarium VR experience was developed to add a slower paced game to the batch of mini games being designed (figure 10). The goal for Planetarium was to encourage lumbar flexion. This was a seated experience and designed to be a free form, creative experience. Participants found themselves in a planetarium with our solar system's sun, planets and a small blue rocket-ship laid out at their feet.

Participants could see cartoon hands in the game that floated in space which providing them with real time feedback to where their hands were. Participants spent their time bending over in their chair to pick up the objects on the ground, lifting them up above their heads, then releasing them into the sky where the objects remained for some time floating in space. By adding more objects into the sky, participants could make their own solar system that hung above them rotating.

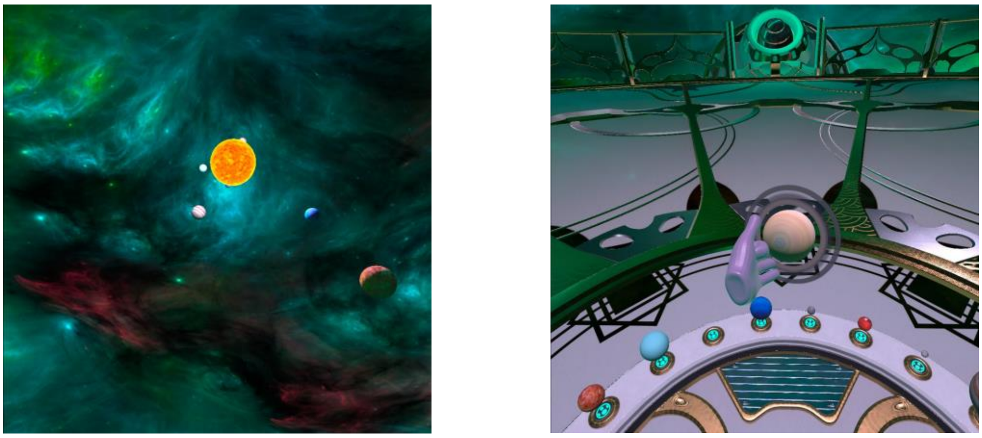

Figure 10: The left image is the sky scape of Planetarium's VR environment with the sun and planet objects placed by a participant. Right image is the floor of the Planetarium's VR environment with the selection of space objects to pick up.

Added complexity was achieved by requiring participants to maintain planets in the sky. If placed poorly planets would slowly drop, requiring participants to pick them up and relaunch into the virtual space. To pick up objects and release them, participants used the buttons on the VR hand controller, pressing down to select and hold an object and then releasing the button to let go of the object. Participants could also hit a rest button that brought all objects back to their feet.

Zen Garden

The Zen VR experience was developed as the second slower paced game being developed. The goal for the Zen Garden challenge was to encourage lumbar flexion, spinal rotation and side bending. This was a free flow creative game. Participants found themselves in a Japanese styled room with a large sand pit in the middle. During the experience participants were instructed to use the sand pit as a drawing surface. On one of the walls was a selection of drawing tools which they could use, or they could commence the experience with a stick in their VR representation of a hand. Participants were instructed not to walk through or stand in the sand pit, but they could walk around it. This limitation as to where the participant could stand in the space meant participants were required to bend forward to reach and draw in the sandpit.

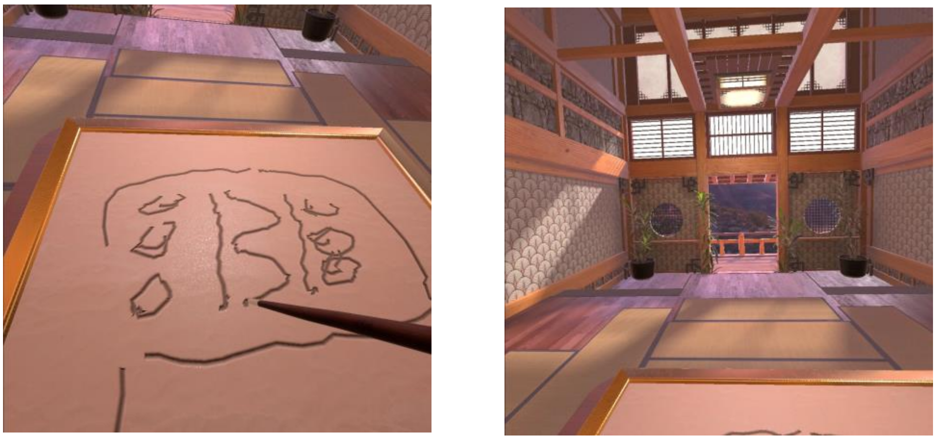

Figure 11: Left image is the Zen Garden VR environment. Right image shows the sand pit and stick drawing tool. Not in view is the wall of drawing tools.

5.9.2 Results

MoCap

All VR experiences elicited trunk motion about each axis of rotation regardless of if the experience was structured or free flowing (Figure 12). The Zen Garden VR experience was noted to elicit the least amount of motion about all trunk axes of rotation (lateral flexion: 30 ± 9°; rotation: 33± 10°; flexion/extension: 30 ± 10°). Motion observed during the River Raft VR experience was in keeping with that noted during session 2, with the experience more specifically targeting lateral flexion (40 ± 12°) and rotation (77 ± 19°) of the trunk. In contrast, the Planetarium VR experience did not encourage as large rotation ROM (51 ± 18°) but instead was noted to elicit similar motion about all axes (lateral flexion: 52 ± 15°; flexion/extension: 58 ± 15°) which was close to twice that within the Zen Garden VR experience.

Variations in movement pattern adopted by those with CLBP and those without CLBP could be observed across each VR experience within Session 3 (Figure 13). During the Planetarium VR experience rotation ROM was less in those with CLBP (mean: 36°) than for those without CLBP (mean: 61°). This disparity in rotation between groups was no longer observed within either

River Raft or Zen Garden VR experiences, where during the free-flowing Zen Garden experience minimal difference in trunk rotation was observed (CLBP: mean: 31°; without CLBP: mean: 35°).

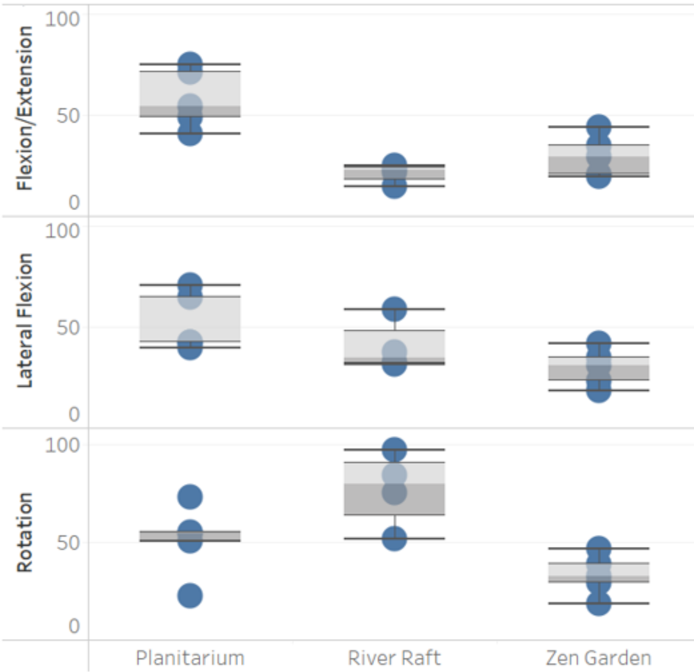

Figure 12: Trunk ROM during session 3 VR experiences

Figure 13: Trunk ROM during each VR Experience within session 3 according to condition and participant group

Heart Rate

During session 3, mean heart rate reserve (HRR) response for the Zen Garden VR experience consisted of only very light intensity (<30%HRR) activity, while River Raft and Planetarium heart rate reserve (HRR) results were mixed. For Planetarium, 4/6 participants maintained very light intensity (<30%HRR) activity across the experience while two participants recorded <45% (CLBP; P02) and <5% (without-CLBP; P12) of light intensity (30-39%HRR) activity. Participant P02 also recorded 20% of moderate intensity (40-59%HRR) activity. For River Raft, half of the participants maintained very light intensity (<30%HRR) activity across the experience.

Light intensity (30-39%HRR) activity was recorded on average for <11% ± .01% during the experience. Without CLBP participants P11 and P12 who notably reached the finish line of the River Raft course 1.31min and 1.34 min which is 1.91min faster than the average completion time recorded during this session 11% and 67% moderate intensity (40-59%HRR) activity and 68% and 4% vigorous intensity (40-59%HRR) activity.

Interview data

Overall participants reported enjoying the VR games that they experienced as part of session 3. Participants varied in which of the games that they preferred which suggests having a range of games to choose from is import. They also reported that having clear instructions was important to them and was helpful in navigating the VR technology.

5.9.3 Summary

In session 3 we found that between our in-house developed VR games we were able to elect a range of desired lumbar movements potentially beneficial to people experiencing CLBP. MoCap data indicated that the amount of RoM elicited was within the range recommended by clinicians. Planetarium was the most successful experience as it not only encouraged a variety of different target movements but the RoM elicited was also the largest compared to the other games.

The heart rate reserve indicated that all 3 games were safe low intensity games with Zen Garden reported in the lowest range and River Raft and Planetarium typically not exceeding light intensity. As such these games would be safe for people at high risk of adverse cardiac events to participate in. Finally, we established that providing participants explicit movement instructions assisted participants comprehension of the game requirements and was successful in electing the target movements. Pairing purposefully designed VR games with explicit movement instructions provides us with RoM outcomes that show potential to benefit people with CLBP.

5.10 Session 4

Co-design

At this stage of the process, we reviewed the co-design process, which included all past feedback from the participants, the questionnaire results, the Motion Capture and HR data. This knowledge was used to inform the design of 2 more games in collaboration with clinical experts. These new games were Gyration Station and Treasure Hunt and were designed to increase the range of choice people had in game and add an additional back movement not been targeted previously. One further game was also developed but later abandoned due to safety concerns.

The game Gyration Station involved light exercise where the goal was to encourage for the first time a pelvic rotation motion. The Treasure Hunt VR experience was developed to be a slow-paced game that like Zen Garden encouraged lumbar flexion but in a different environment for people disinclined to be motivated by creative experiences. A list of explicit movement instructions was prepared for participants to undertake in the VR experience.

For session 4, participants experienced 5 games. The same recording measures were repeat in this session that had been conducted in the previous sessions. The aim of this session was to access the movement and HR produced during the 2 new games. Secondly additional analysis of the motion capture data was conducted to provide a more comprehensive overview of the movement elicited during the games.

5.10.1 VR experiences

Gyration Station

The goal for Gyration Station was to encourage pelvic rotation. Participants found themselves in a nylon lit room, standing on a platform looking up at an animated robot (See Figure 14). In this experience participants placed both hand controllers on their hips (See Figure 14) and were instructed to rotate their hips. Music was played to the participant through the headset and this music was affected by the participants pelvic rotation. The participant would progress through the game if they kept the music in tune, spinning too fast would not give them progress and spinning slowly would slow progress.

Participants stood on the virtual standing platform within a ring. As participants rotated, a red dot tracked with the participant's movements providing them with movement feedback. When the dot fell within the ring it indicated that their movement was not large enough to sustain the music hence halting the progress of the game. The participant was instructed to switch from clockwise to counterclockwise at the halfway point. To enhance the enjoyment of the experience, participants could watch the robot dance to the music as they conducted their own hip rotations.

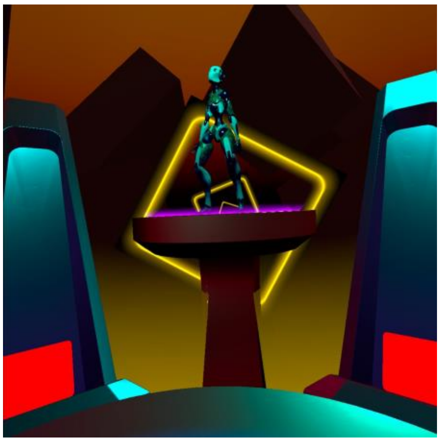

Figure 14: Left image is the Gyration Station VR environment with the dancing robot. Right image is a participant making the pelvic rotation with the correct placement of the hand controls.

Treasure Hunt

The Treasure Hunt VR experience was developed to be a slow-paced game with a goal to encourage lumbar flexion. Participants found themselves on an archaeological dig site where they could walk within a roped off area (See Figure 15). In this experience participants saw a metal detector that extended from their right hand that they could move back and forth to find hidden treasure beneath the ground. The hand controller lightly vibrated throughout the experience and this vibration became stronger as the participant neared the hidden location of a treasure.

When the metal detector was over the location of the treasure a yellow cross appeared and the metal detector was changed for a shovel, indicating the dig location. Participants were required to bend close to the ground and make a digging motion until the treasure appeared (See Figure 15). Once the treasure was revealed, the participant could pick it up with their left hand. The shovel then changed back to the metal detector and the participant could recommence their search for additional treasures. There were 12 treasures to find, and participants were given a maximum of 5min in the experience. It was very rare for a participant to locate all 12 treasures in this timeframe.

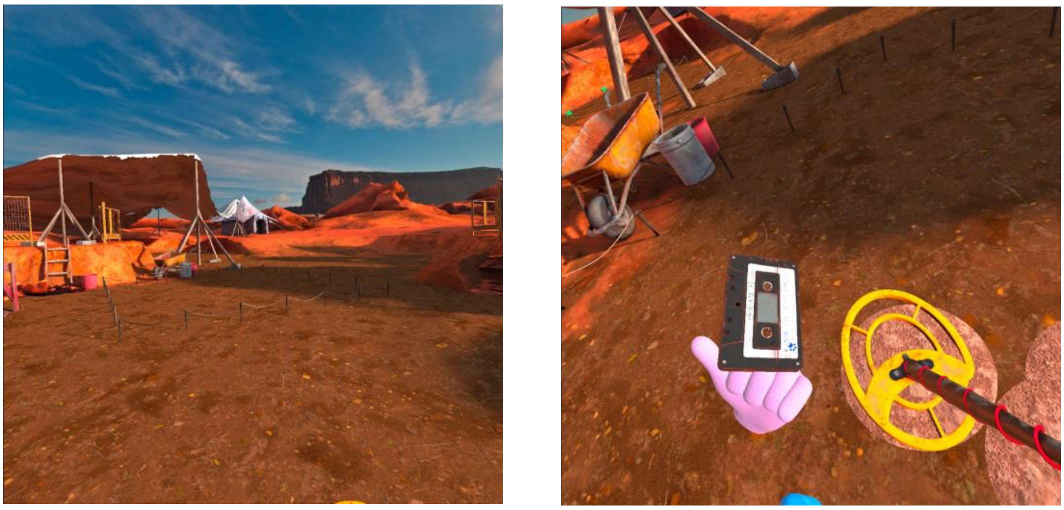

Figure 15: Left image is of the Treasure Hunt VR environment. The roped off area marked the safe zone for participants in move in. Right image shows the participant's metal detector, and an example of a treasure that this participant has successfully unearthed.

5.10.2 Results

MoCap

Across all VR experiences within session 4, movement was observed about each trunk axis of rotation (Figure 16) to a varying extent, suggesting that experience elicited subtle variations in trunk motion. Gyration Station elicited the lowest RoM about each axis (flexion/extension: mean: 14°; lateral flexion: mean: 16°; rotation: mean: 13°), approaching half as much RoM compared to other VR experiences. Whilst RoM about the flexion/extension axis of rotation was similar across experiences, the River Raft VR experience demonstrated greater specificity in eliciting the largest trunk rotation RoM (mean: 66°), that was also in keeping with observations during session 3.

The low-moderate intensity and predominantly intermittent nature of each of the VR experiences was observed by participants spending on average across all axes of trunk rotation 33 ± 18 % of time moving (Figure 17). Of all experiences, the River Raft VR experience required the most sustained motion, particularly for trunk rotation (mean: 88%) followed by lateral flexion (mean: 56°) and flexion/extension (mean: 46°).

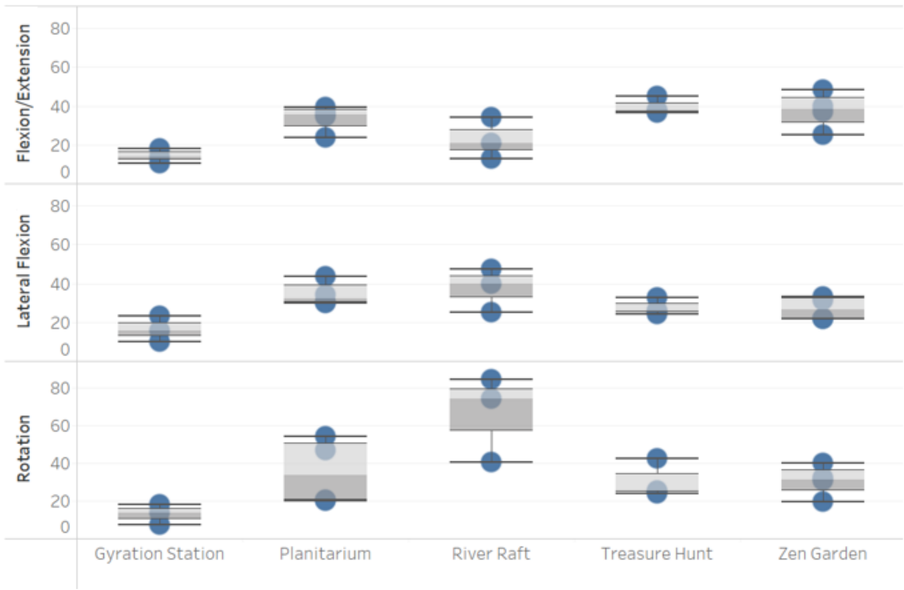

Figure 16: Trunk RoM during session 4 VR experiences

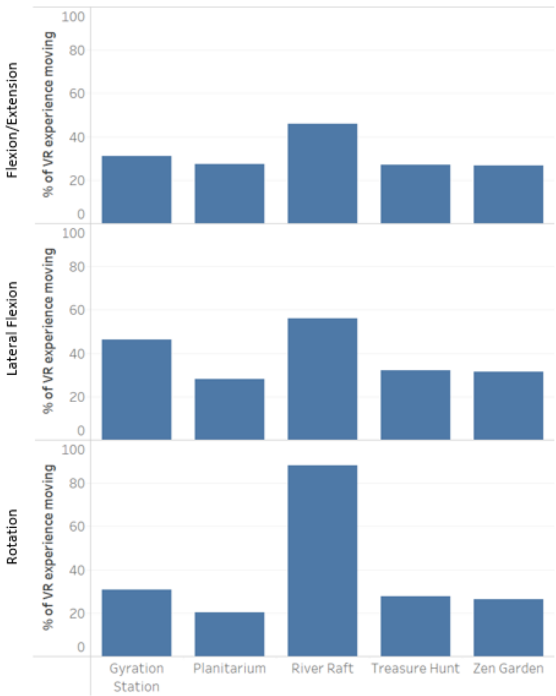

Figure 17: Average duration of VR Experience associated with eliciting trunk RoM.

Heart Rate

During session 4, only without-CLBP participant had HR data that could be reported. Mean heart rate reserve (HRR) response for all VR experiences (River Raft, Zen Garden, Planetarium, Gyration Station, Treasure Hunt) included periods of very light intensity (<30%HRR) and light intensity (30-39%HRR) activity. Both River Raft and Zen Garden recorded 55% and 2% of moderate intensity (40-59%HRR) activity respectively.

5.10.3 Summary

In session 4, all 5 games were trialled and found that all games were able to elicit desired trunk movements when participants undertook them under directions. MoCap data indicated that the RoM elicited was within the range indicated as satisfactory by clinicians for all VR games. At the end of session 4, we were confident that the co-designed games met both user desires to engage and clinician directed exercise requirements.

One further game was developed and rejected by clinicians and researchers. This was called 'glider' and involved people pretending to be a glider and stepping over obstacles. This was abandoned following safety concerns when a participant was in the VR headset and likely to fall on their own.

5.11 Session 5 – Feasibility study

5.11.1 Overview

Having completed the co-design process and satisfied with the VR experiences, a final session with participants was undertaken to (a) test usability and utility of the games (b) identify whether the games would elicit desired movement and (c) understand the perspectives of the end users as to potential for home-based engagement. Twenty participants with CLBP were recruited to validate the final 5 VR experiences. All participants were new to the project. Tools and procedures used were rationalised; pen and paper questionnaires reduced and MoCap was replaced by EMG data. Feedback from the participants was obtained at the end of each session.

5.11.2 Procedure

Twenty new participants with CLBP were recruited for this session. On arrival signed informed consent was obtained from all participants. A reimbursement of a $50 gift card was provided to all participants and first year students gained credit points towards their subject for participating.

The procedure for this session comprised an abbreviated version of measures conducted in the co-design sessions (MSSQ, GAD-7, ODI, SF-12, PSEQ and BPI – see tables 7 and 8). Each participant undertook 3 of the 5 VR experiences that were developed during the co-design sessions. The 5 VR experiences were counterbalanced for running order and experiences selected prior to data collection in an excel spread sheet. After the VR experiences the participants were asked a set of questions regarding their thoughts about the sessions, how it made them feel and if they would use this technology in the future.

5.11.3 Results

Participants

Twenty new CLBP participants (Male = 5, Female = 14, Non-Binary = 1) were involved in this final data collection. These participants had not been involved in the previous co-design section of the project. Participant's average age in years was (M=29, SD=12) ranging from 19 to 62. See Table 15 for individual demographic information.

Low back pain experienced by these participants was reported between the minimal to moderate disability level as measured by the ODI. On the BPI, participants ranged between middle and low for both pain sub scales Severity (M =4, SD =1) and Interference (M =3, SD =1.60).

Participants reported using a range of treatments, eight out of the 20 participants reported taking analgesic medications to assist with the pain and 4/8 combined that with physiotherapy or exercise and 3 participants reported some form of exercise and stretching for pain management. Anxiety measured by GAD ranged between Minimal to Severe (table 7).

ID	Gender	Age	BMI	MSSQ	Resting HR	GAD-7	Diagnoses
P13	NB	28	Obese Class I	12	104	Moderate	
P14	M	25	Healthy	52	78	Moderate	
P15	F	31	Overweight	25	82	Severe	
P16	M	27	Obese Class II	65	89	Minimal	
P17	F	37	Healthy	12	83	Mild	
P18	M	20	Overweight	45	88	Severe	Depression
P19	F	19	Obese Class I	45	118	Minimal	
P20	F	21	Overweight	70	101	Severe	ADHD
P21	F	26	Overweight	0	97	Mild	
P22	F	35	Obese Class I	15	104	Mild	Anxiety
P23	F	21	Healthy	55	148	Mild	
P24	F	25	Healthy	55	77	Moderate	
P25	F	20	Healthy	75	-	Moderate	Anxiety & Endometriosis
P26	F	27	Underweight	65	105	Severe	
P27	F	62	Healthy	0	88	Minimal	
P28	F	60	Obese Class I	20	117	Minimal	
P29	F	19	Overweight	10	69	Moderate	
P33	M	33	Obese Class I	92.5	67	Moderate	
P34	M	21	Healthy	50	56	Minimal	
P35	F	29	Overweight	0	-	Mild	

Table 14: Participant demographic information

Age = reported in years, M = male, F= female, NB = non-binary, BMI = Body Mass Index, MSSQ= Motion Sickness Susceptibility Questionnaire, GAD-7 = General anxiety disorder

ID	Back Pain (ODI)	Physical (SF-12)	Self- Efficacy (PSEQ)	Severity (BPI)	Interference (BPI)	Treatment
P13	Moderate	42	Minimal	5.25	3.57	Ibuprofen/paracetamol
P14	Minimal	46	Minimal	1.25	1.71	Rehab exercises, strength and hypertrophy training from gym coach
P15	Moderate	36	Mild	2.5	3.57	THC, CBD, endone, paracetamol, Voltaren
P16	Moderate	42	Minimal	3	5.86	Paracetamol, Voltaren, Palexia, physio, light exercise, Lyrica, massage
P17	Moderate	33	Mild	4.25	4.29	Physiotherapy, ibuprofen
P18	Minimal	46	Minimal	4.5	1.86	Yoga
P19	Minimal	46	Minimal	2.5	1.43	Paracetamol, Nurofen
P20	Moderate	39	Moderate	5.25	5.43	Panadeine, Nurofen
P21	Moderate	39	Minimal	3.75	3.29	Chiro, Physio, Acupuncture, Muscle relaxants
P22	Moderate	27	Mild	4	4.57	Physio, Myotherapy, Ibuprofen, Voltaren, OT, heat-pack, Endone
P23	Minimal	57	Minimal	2.75	1.14	
P24	Moderate	60	Minimal	5.5	2.29	Physio
P25	Minimal	54	Severe	4.25	1.57	Physio, paracetamol, Nurofen, Prodipine
P26	Moderate	43	Minimal	6	2.43	
P27	Minimal	53	Minimal	3	0.71	Paracetamol
P28	Moderate	36	Mild	4.75	2.86	Modic, rest
P29	Minimal	57	Minimal	3	2.71	
P33	Minimal	48	Minimal	4.25	2.57	Pilates, Voltaren, Panadol
P34	Minimal	45	Minimal	2	1.43	
P35	Minimal	52	Minimal	3	2.43	Chiro, Physio, Acupuncture, massage and stretching

Table: 15 Health and Pain related measurements

ODL = Oswestry Disability Index, SF-12 = Short Form (12) Health Survey, PSEQ = Pain Self-Efficacy Questionnaire, BPI = Brief Pain Inventory

Heart Rate

With the River Raft (n=9) exercise, the mean heart rate reserve (HRR) response for the processed length of the VR experience consisted of only very light intensity (<30%HRR) activity for 6/9 participants. Three participants recorded a mean total duration of 17% ± 34% light intensity (30-39%HRR) activity.

During the Zen Garden (n=6) exercise, half the participants maintained very light intensity (<30%HRR) activity across the full length of the processed VR experience while the other participants recorded a mean duration of 4% ± 5% of light intensity (30-39%HRR) activity. Participant P19 recorded 0.3% moderate intensity (40-59%HRR) activity.

During the Planetarium (n=8) exercise the mean heart rate reserve (HRR) was reported as very light intensity (<30%HRR) activity for the full VR experience duration in 7 participants. P17 recorded <5% of light intensity (30-39%HRR), 11% of moderate intensity (40-59%HRR) and 24% vigorous intensity (60-89%HRR) activity.

During the Treasure Hunt (n=9), 4 participants maintained very light intensity (<30%HRR) activity across the duration of the VR experience. Five participants recorded a mean duration of 2% ± 3% light intensity (30-39%HRR) activity, 3 of those participants recorded a mean duration of 2% ± 4% moderate intensity (40-59%HRR) activity and 2 of those participants recorded a mean duration of 1% ± 3% vigorous (60- 89%HRR) activity.

During the Gyration Station (n=8) exercise, 6 participants maintained very light intensity (<30%HRR) activity across the VR experience while participant P13 and P17 recorded a duration of 19% and 8% light intensity (30-39%HRR) activity and 19% and 4% moderate intensity (40-59%HRR) activity respectively.

Interview qualitative analysis

Participants spoke positively about their VR experiences in all cases, and a word cloud has been generated to demonstrate this in figure 18. Most participants reported finding the technology user friendly however older participants reported needing support to learn how to use the hand controllers. Participants reported experiencing three different types of benefits during the VR games which included feelings of relaxation, reduced pain following the experience and motivation to move. One participant reported a negative in that wearing the head set aggravated chronic pain that they also experienced in their neck.

Participants were keen to use this technology remotely at home, but some reported not having the available space in their residence. Others expressed concern about the cost of purchase of the technology. Participants were interested in experiences that were engaging and have enough range in the experiences to not become boring in the long run. They also wanted app tracking feedback with goal attainment.

Figure 18: Word frequency map.

sEMG

As the participants were not wearing the MoCap suit, sEMG data was found to be preserved. Given that this study was for feasibility rather than movement detection, it was decided not to use MoCap in this instance, but to collect EMG data as an indication of movement of targeted muscles. The duration that each muscle was observed to be active during each VR experience is presented in Table 9 and is expressed as a percentage of the total VR experience time. Whilst the intensity of muscle activity was not quantified, during each VR experience, muscle activation was maintained between 32% to 68% of the total VR experience time. The responses for each muscle were noted to vary between VR experiences.

	Zen Garden	River Rafting	Treasure Hunt	Planetarium	Gyration Station
L External oblique	31 ± 23	54 ± 29	44 ± 27	61 ± 27	49 ± 22
L Latissimus dorsi	59 ± 33	61 ± 43	62 ± 35	49 ± 28	58 ± 32
L Multifidi	63 ± 31	58 ± 34	62± 28	59 ± 27	57 ± 20
L Erector spinae	59 ± 31	47 ± 33	48 ± 34	38 ± 18	55 ± 28
R External oblique	37 ± 22	49 ± 31	40 ± 27	68 ± 25	49 ± 37
R Latissimus dorsi	61 ± 26	62± 39	62 ± 27	46 ± 25	61 ± 30
R Multifidi	60 ± 29	58± 35	47 ± 34	48 ± 27	67 ± 22
R Erector spinae	60 ± 32	41 ± 32	48 ± 35	35 ± 16	53 ± 31

Table 16: Mean and SD of muscle contraction time expressed as a percentage of total VR experience time.

L = left, R = right

5.11.4 Discussion

The feasibility study in session 5 demonstrated that for person with CLBP ranging from mild to severe could safely participate in all VR experiences and using sEMG demonstrated that each game activated the sets of muscles located around the torso that should be targeted during strength building exercises used to treat CLBP. Participants reported enjoying their experience and wanted games that were engaging to keep them motivated to perform their exercises. They also wanted feedback on their progress which could be in the form of an app and/or their physiotherapy or other allied health practitioner. The biggest barriers report by participants on the uptake of VR technology was and cost and the space at home to safely play the games.

5.12 Session 6: Video Movement Analysis

5.12.1 Overview

The feasibility study demonstrated the utility of the games for participants; a movement analysis was undertaken with two clinicians (exercise physiologist/biomechanist and physiotherapist) to ascertain clinical utility of the final versions of our co-designed VR experiences. We videoed 3 participants undertaking the VR experiences then asked 2 clinicians to independently observe and document the movements and muscles activated.

5.12.2 Methods

Three people with no history of chronic pain were recruited to participant in this stage of the project. Participant gave their written, informed consent prior to commencing the session. A brief demographic questionnaire was completed at the start of the session. Participants were informed about safety in VR, how to wear the headset and adjust for comfort and how to use the hand controllers. Once participants were ready to enter the VR environment they were led into the middle of a large empty space. Surrounding this space were 3 Canon cameras in a triangle formation pointing towards the centre of the space. Their placement enabled full body capture of each movement. Participants completed all 5 final versions of the VR experiences that had been developed. This included the amended River Raft game and Planetarium, Treasure Hunt, Gyration and Zen Garden. At the start of each experience all three cameras were set to video record. For the VR experiences without a defined end point, this included Planetarium, Treasure Hunt and Zen Garden, participants were given 5mins within the VR environment before being instructed to finish that experience and return to the VR's game menu.

In a blinded observational movement analysis, these videos were sent to two different clinicians. Reviewer 1 was an accredited exercise scientist (blue tables) and reviewer 2 was a physiotherapist (green tables). Each reviewer was asked to consider the movement contribution of the trunk, pelvis, and hip that they observed in each experience across the 3 participants videoed. The clinicians were also asked to specify the muscles activated for each of the movements of interest during each VR experience.

5.12.3 Results

The three participants recruited were females of a similar height and weight aged 28 to 48 years. Recorded heights were within a range of 10cm, and weights were within a 15kg range (see Table 10).

	Gender	Age	Height	Weight
P30	F	28yr	173 cm	69.0 kg
P31	F	48yr	167 cm	58.2 kg
P32	F	35yr	163 cm	56.7 kg

Table 17 Demographic information of movement analysis participants

Independent video analysis by the reviewers presented in Tables 11, 12 and 13, and identifies which muscles the experts observed to be activated during each VR experience. Asterisks were assigned to represent the relative contribution of muscles of the trunk, pelvis, and hip movement during the VR experiences.

Trunk flexion was identified as a dominant movement by both reviewers in Gyration Station, Planetarium, Zen Garden and Treasure Hunt. During the River Raft experience rotation of the trunk was the dominant movement observed by both reviewers. Planetarium and Zen Garden were observed by both reviewers to induce movement that included flexion, extension, lateral flexion and rotation of the trunk, with varying degrees of dominance to produce the movement.

Anterior tilt of the pelvis was observed during 4 of the 5 VR experiences by both reviewers and all 5 VR experiences, all be it a small relative contribution during river rafting, for 1 reviewer. There were differences in the ability of the 2 reviewers to isolate the muscle contribution of the pelvis with reviewer 1 likely having greater experience identifying the relative contribution of muscles of the pelvis contributing to movements. During Planetarium, River Raft or Zen Garden there was no or very limited contribution from muscles of the pelvis to movements during these experiences.

Zen Garden and Treasure Hunt both elicited some extension and flexion of the hip with reviewers differing on their assessment of the contribution of other movements.

In conclusion, there was moderate to high agreement between the two reviewers as to the muscles activated and the amount of movement, however, this is sufficient for pilot data for further objective movement analysis.

	Reviewer 1	**Trunk**		
	Flexion	Extension	Lateral Flexion	Rotation
	Rectus abdominis External oblique Internal oblique	Erector spinae TransversospinalisInterspinales	Quadratus lumborum Erector spinae Internal oblique External oblique Intertransversarii	Internal oblique External oblique Transversospinalis
Gyration Station	***		**	
Planetarium	****	***	*	**
River Raft				*****
Zen Garden	***	*	*	*
Treasure Hunt	*****	**	*	
	Reviewer2		Trunk	
	Flexion	Extension	Lateral Flexion	Rotation
	Rectus abdominis, psoas major	Lumbar multifidus, erector spinae	Quadratus lumborum, lumbar multifidus	Internal oblique, external oblique
Gyration Station	**		**	*****
Planetarium	**	*	*	***
River Raft				*****
Zen Garden	****		*	
Treasure Hunt	****	*		

Table 18 Observational Movement Analysis of five VR Experiences for trunk

1.Asterisks * represent relative contribution of muscles to the movement observed by reviewers. No asterisk= no contribution from those muscles to the movement observed, *****= muscles contributed greatly to the movement observed. Shaded area represents dominant movement.

	Reviewer 1	Pelvis		
	Anterior tilt	Posterior tilt	Lateral tilt	Rotation
	Iliopsoas Rectus abdominis Tensor fascia latae Internal oblique	Gluteus maximus, Biceps Femoris Semitendinosus Semimembranosu Quadratus lumborum Erector spinae External oblique	Psoas major/minor Gluteus medius Gluteus minimus Tensor fascia latae	Rectus abdominis Iliopsoas Internal oblique External oblique
Gyration Station	***	**		*****
Planetarium	*			
River Raft				
Zen Garden	*			
Treasure Hunt	***			
	Reviewer2		Pelvis	
	Anterior tilt	Posterior tilt	Lateral-medial tilt	
	Lumbar multifidus	Rectus abdominis	Iliocostalis lumborum, quadratus lumborum	
Gyration Station	**	**	*****	
Planetarium	**	**	**	
River Raft	*	*	*****	
Zen Garden	**	**	**	
Treasure Hunt	**	****	*	

Table 19 Observational Movement Analysis of five VR Experiences for pelvis

1.Asterisks * represent relative contribution of muscles to the movement observed by reviewers. No asterisk= no contribution from those muscles to the movement observed, *****= muscles contributed greatly to the movement observed. Shaded area represents dominant movement.

		Reviewer 1		**Hip**			
		Extension	Flexion	Abduction	Adduction	Internal rotation	External rotation
		Gluteus maximus Biceps Femoris Semitendinosus Semimembranosus	Rectus femoris Iliopsoas PectineusTensor fascia latae	Gluteus medius Gluteus maximus Tensor fascia latae	Adductor magnus Adductor longus Adductor brevis Gracilis	Gluteus minimusGluteus medius	Gluteus maximus Piriformis Gemellus inferior Obturator externus Obturator internus Quadratus femoris
	Gyration Station						
	Planetarium						
	River Raft						
	Zen Garden	*	*				
	Treasure Hunt	**	***				
Activities		Reviewer 2		Hip			
		Extension	Flexion	Abduction	Adduction	Internal/External Rotation	
		Gluteus maximus, hamstring	Psoas major, iliacus	Gluteus medius, gluteus minimus, tensor fascia latae	Adductor longus, adductor magnus, adductor brevis, gracilis, pectineus	Quadratus femoris, gamellei, gluteus minimus, obturator internus, gluteus medius, obturator externus, piriformis, gluteus maximus	
	Gyration Station	*	*	****			
	Planetarium						
	River Raft						
	Zen Garden	*	*				
	Treasure Hunt		***				

Table 20: Observational Movement Analysis of two VR Experiences for hip

1.Asterisks * represent relative contribution of muscles to the movement observed by reviewers. No asterisk= no contribution from those muscles to the movement observed, *****= muscles contributed greatly to the movement observed. Shaded area represents dominant movement.

6. Summary

The final version of the 5 VR experiences enabled the training and examination of a variety of movements of the trunk, pelvis and hip with different relative contributions of muscles depending on the individual experience. Two of the games, Zen Garden and Treasure Hunt, produced movements in all 3 body regions (trunk, pelvis and hip) that are typically areas of target during movement orientated rehabilitation from lower back pain.

With the knowledge of the movements and muscles associated with the different experiences, it would also be possible to specifically target muscles and movements in isolation. For example, River Raft enabled rotation of the trunk with little movement of the pelvis or hips, whilst Gyration Station produced considerable rotation of the pelvis.

What would be important to consider, is that after clinical assessment of the chronic back pain and determination of the rehabilitation required, whether the selection of an individual VR experience or combination of experiences would enable the type of movement(s) and activation of the desired muscles or muscle groups to be elicited to optimise the outcomes for an individual with chronic lower back pain.

This product is co-designed to specifically address a clinical need and has been demonstrated to do this. In addition, there is growing evidence that VR can be used to treat chronic pain; but there is more effectiveness in VR experiences that are specifically designed for purpose rather than re-purposing existing VR experiences. We demonstrated that in our findings. Our systematic review will be submitted for publication late 2023 or early 2024 and demonstrates the most up to date evidence in this regard; this product is informed by the most up-to-date evidence.

Hardware for virtual reality took great leaps, firstly using smart phone technologies between 2010 and 2014 and then again in portable headsets and quality between 2016-2020 and we undertook a review in 2020 of these headsets. The changes between 2020 and 2023 have been incremental but have involved changes in the proprietary nature of VR gaming; namely, Meta owning the Quest range of headsets. The Quest headsets are the most cost-effective headsets for their price point, but there are issues with translating these directly into practice in terms of privacy and other data. This can be managed but need to be addressed for any clinical applications.

Augmented and Mixed Reality have not translated into practice at the rate initially expected, yet still has great potential. One of the issues found with AR was the unreliability and the lack of utility of the headsets, and the lack of interface. Once this has been resolved, similar co-design products show definite potential particularly for home monitoring. On the other hand, AR content creation tools have improved exponentially, particularly through Adobe (adobe Aero). However, again, licencing and data protection will need to be established for further developments.

Finally, VR and AR show promise for the management of chronic pain, and with careful consideration should be a good tool for empowering persons with low back pain to self-manage their conditions in collaboration with their health professionals. This has the potential to enable clinicians to prescribe effective home-based treatment and with remote monitoring via existing (e.g., PhysiApp) or bespoke applications, also measure adherence to treatment throughout experiences. However, this will require further research to test the effectiveness, cost effectiveness in both short- and long-term delivery.

7. Recommendations:

1. Undertake Patent registration for the 5 VR experiences for low back pain.
2. To undertake a phase one clinical trial to test utility of the VR on a wider scale.
    a. Integrate remote monitoring through wearable technologies with the VR so that remote telehealth consultations can be undertaken and included in clinical trial.
    b. Include a cost benefit analysis, including provision of headsets.
3. Longitudinal study to establish treatment effectiveness and adherence over extended periods compared to usual treatment or as an adjunct to usual treatment.
4. Establish clinical protocols for delivery of VR experiences.
    a. In clinical settings (i.e., Exercise Physiology or Physiotherapy clinic)
    b. In home settings
    c. In institutional settings
5. Publication of systematic review data
6. Publication of co-design methodology and feasibility data post patent data
7. Further refinement of VR experiences for everyday use in home settings.

8. References for Headset Comparison

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