8-20-2019 10:00 AM

Quantifying the Outcomes of a Virtual Reality (VR)-Based Gamified Neck Rehabilitation

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Health and Rehabilitation Sciences

Abstract

Neck pain is a major global public health concern and adds a significant financial burden to both the healthcare system as well as people suffering from it. Additionally, it presents measurement and evaluation challenges for clinicians as well as adherence challenges and treatment barriers for the patients. We have developed a virtual reality (VR)-based video game that can be used to capture outcomes that may aid in the assessment and treatment of neck pain. We investigated: (i) performance metrics of overall accuracy, accuracy based on movement difficulty, duration, and total envelope of movement; (ii) stability across sessions; (iii) accuracy across difficulty levels; (iv) association between gaming experience and performance; and (v) any adverse effects resulting from VR immersion in healthy people (N = 52). Results demonstrate poor stability across sessions, significantly higher accuracy in single-plane movements, no effect of prior gaming experience on performance, and no severe adverse effects of VR immersion. Results suggest that duration and single-plane accuracy demonstrate the potential for identifying people with neck pain or impaired mobility. Lack of association between prior gaming experiences coupled with no severe adverse symptoms suggests that VR may be a feasible tool to be used for neck rehabilitation.

Keywords

Virtual reality, gamification, video game, neck, pain, rehabilitation, adherence, measurement

Lay Summary

Neck pain is a major global public health concern and adds a significant financial burden to both the healthcare system as well as people suffering from it. Additionally, it presents measurement and evaluation challenges for clinicians as well as adherence challenges and treatment barriers for the patients. We have developed a virtual reality (VR)-based video game that can be used to capture outcomes that may aid in the assessment and treatment of neck pain. As it is indeed novel, safety and prudence dictated that we needed to first study the experience and performance of the new rehabilitation gaming platform in otherwise healthy people before implementing it in those with compromised necks who may be more vulnerable to symptom worsening or other adverse effects. Understanding 'normal' performance will also be critical for identifying 'abnormal' performance when we get to that point.

We investigated: (i) performance metrics of overall accuracy, accuracy based on movement difficulty, duration, and total envelope of movement; (ii) stability across sessions; (iii) accuracy across difficulty levels; (iv) association between gaming experience and performance; and (v) any adverse effects resulting from VR immersion in healthy people (N = 52). Results demonstrate poor consistency across sessions, better accuracy in single-plane movements, no effect of prior gaming experience on performance, and no severe adverse effects of VR immersion. These results suggest that duration and single-plane accuracy demonstrate the potential for identifying people with neck pain or impaired mobility. Lack of association between prior gaming experiences coupled with no severe adverse symptoms suggests that VR may be a feasible tool to be used for neck rehabilitation.

Co-Authorship Statement

This thesis contains one manuscript that will be prepared for submission (Chapter 2 – Scoping Review). Shahan Salim was the primary author of the review and it was conceived, designed, analyzed, interpreted, and written by the primary author with invaluable input and guidance from Dr. David Walton, Associate Professor in the School of Physical Therapy, Faculty of Health Sciences, Western University. Michael Lukacs (Ph.D. student, Health and Rehabilitation Science, Western University) served as a secondary reviewer to determine whether each study met the inclusion/exclusion criteria to be used in the review. Dr. Julia Treleaven (School of Health and Rehabilitation Sciences, Faculty of Health and Behavioral Sciences, University of Queensland) and Dr. Hilla Sarig-Bahat (School of Physiotherapy, University of Haifa) reviewed selected studies after the databases had been searched to ensure they were not aware of any other studies that might have been missed.

Dedication

قَالُوْا سُبْحٰنَكَ لَا عِلْمَ لَنَاۤ اِلَّا مَا عَلَّمْتَنَا ؕ اِنَّكَ اَنْتَ الْعَلِيْمُ الْحَكِيْمُ

سورة البقرة

Exalted are You; we have no knowledge except what You have taught us. Indeed, it is You who is the Knowing, the Wise

Surah Al-Baqarah

Acknowledgments

The completion of my thesis would not have been possible without a number of key individuals. I would like to sincerely thank the following people for their ongoing support, encouragement, and assistance over the past two years:

Dr. David Walton for being a continuous source of inspiration, encouragement, and guidance. Thank you for allowing me to be my own individual and always supporting my ideas. Over the past two years, I have learned many things working and studying under your supervision – all of which will serve me immensely in my future work. But most of all, you've taught me to be a better human being. Thank you, for accepting me as a graduate student and taking a chance on a long shot.

Dr. Ana Luisa Trejos for her engineering expertise. There were a number of times over the past two years when I faced technical challenges. My mind was always at ease knowing that if all else failed, you were only one email away for me to approach for help. Thank you for being generous with your time and your resources.

Dr. Mike Katchabaw for his game design expertise. Thank you for your support and guidance during this process.

Dr. Jennifer Irwin for being a mentor during my time at Western University. Your support has meant the world to me.

Dr. Meital Avivi-Reich for your continuous support, guidance, and encouragement over the years. Thank you for always believing in me.

Husayn Kara and Helen Phan for all your help. This project would not have been possible without you guys. Thank you for being generous with your time.

PIRL Lab Family - *Doubts kill more dreams than failure ever will.* Thank you for never letting me forget that.

London Friends for always being there. It's been a fun ride!

Toronto Friends for keeping me humble and grounded.

And most importantly…

My family: Mummy, Papa and Misbah. For all that you do. For your continuous sacrifices. For being the cornerstone of support. Any good in me comes from you. Thank you.

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Glossary

Name	**Description**
Evaluation	Making judgements on the intensity and magnitude of neck pain/mobility.
Exergame	Video games that require user to physically move in order to play.
Fitness	The condition of being physically fit enough to play an exergame.
Intensity	The measure of amount of exertion required to play an exergame.
Kinematics	Branch of biomechanics measuring movement and position of a joint.

Chapter 1

1 Introduction

Adherence can have a significant impact on the success and outcome of prescribed treatment. Defined as “the extent to which a person’s behavior...corresponds with agreed recommendations from a healthcare provider”,[1] adherence has been associated with better outcomes than lack of adherence.[2] Adherence to physical therapy remains one of the biggest challenges in the field of rehabilitation sciences.[2,3] From a patient perspective, physical therapy can be complicated, frustrating and tedious, and requires both time and monetary commitments. This is compounded as rehabilitation science has yet to advance sufficiently to enable clinicians to monitor their patients’ during their day-to-day or rehabilitation routines. Ubiquitous and consumer accessible technologies can allow clinicians to address both of these problems. Video games, in particular, in combination with physical therapy have the potential to make treatment intrinsically motivating without adding significant cost to clinicians, patients, or the healthcare system overall.[4] The term “gamification” is defined as the use of game design elements in non-game contexts.[5] The idea is to use elements from video games in a vast range of real-life contexts to deal with real issues, as these components can be an effective medium to engage and motivate users.

1.1 Barriers in treatment

Adherence, or lack thereof, can impact the success of prescribed treatment. Patient non-adherence is estimated to be as high as 70% in physical therapy, [2] which suggests that the majority of patients do not adhere to the recommended treatment. The concept of adherence is multidimensional and relates to attendance at appointments, following advice, undertaking prescribed exercise programs, frequency of exercise, correct performance, and doing more or less than advised. Physical therapy patients face a multitude of barriers that could reduce adherence to a prescribed treatment plan. Beyond structural or systematic barriers, adherence can also be adversely affected by low self-efficacy, depression, anxiety, helplessness, poor social support, increased pain levels, and greater perceived number of barriers.[2] Factors associated with the patient-provider interaction can also reduce adherence, including misinterpretation of instructions, complex treatment regimens, and the subsequent frustration as a result of these complexities. Finally, physical therapy as a treatment option has its own barriers. It is not entirely covered by Medicare and Medicaid in the United States and provincial and territorial coverage in Canada varies widely, while publicly funded programs endure prolonged wait times.[6]

1.2 Failure to adopt innovative technologies

Technology has rapidly advanced in the past decade, and many areas of healthcare have embraced the use of advanced technologies. As physical therapy continues to transform from a hands-on to a hands-off approach,[4] physical therapists and their clients would benefit from intervention strategies that are engaging, can provide opportunities for clients to manage their own care, and can be customized to match the abilities of the client. However, off the shelf technologies lack customization options and as a result, control of important rehabilitation parameters such as speed, duration, and difficulty of interventions are not available. As a result, these ubiquitous and readily available technologies have yet to make a significant impact on rehabilitation as they have in other areas of healthcare. Using inexpensive and readily available technologies can help raise motivation and engagement levels without adding significant costs to clinicians, patients, or the overall healthcare system.

If adherence can be improved with clinic-based treatment, then simulating that treatment, environment, and even the clinicians themselves in patients' homes can potentially improve patient adherence without adding significant cost to the overall healthcare system. Gamification can help change behavioral patterns and encourage positive habits in people. Well-designed video games can be engaging and immersive and combining them with virtual reality (VR) and internet of things (IoT) technologies can simulate rehabilitation exercises. If these innovations can be harnessed, they could give clinicians control over key rehabilitation parameters, and allow them to monitor their patient's progress in real time while improving the enjoyment of physical therapy exercises.

It is with this in mind that the Pain and Quality of Life Integrative Research Lab (PIRL) and The Wearable Biomechatronics Laboratory at Western University developed a VR-based video game that required neck movements for users to complete levels. The design and development of the custom-built VR software was a result of significant collaboration between engineering and health science researchers in an effort to ensure that the developed product had clinical relevance and maintained industry-standard programming, graphic quality, and gamification principles.

1.3 Chapters Breakdown

The remainder of this thesis begins in Chapter 2 with a scoping review of existing scholarship on the use of VR technologies in neck rehabilitation. Chapter 3 describes the game design process and rationale behind the decisions made during game development. Chapter 4 describes the study objectives and methodology; reports results; discusses the main findings and limitations, and concludes with a review of the research questions and pointing to the potential for the future of VR-based gamified rehabilitation for neck pain.

Chapter 2

2 Scoping review

With the lifetime incidence of neck pain estimated to be around 67% to 71%[7–9] and a point prevalence of 22%,[8] it is a major global public health concern.[10] It is the fourth most common contributor to years lived with disability,[11,12] and therefore adds significant financial burden to both the healthcare system (in direct and indirect costs) as well as people suffering from neck pain.[7,13]

It is to be noted that neck pain has persisted as a common chronic pain condition and continues to be one of the leading causes of disability over the last twenty years.[12] This seems to indicate that research and rehabilitation practices in neck pain have been unable to determine its etiology or effective treatment.[14] Unlike other diseases, neck pain (and ultimately neck rehabilitation) presents unique challenges to both clinicians and patients. From the clinicians' perspective, the head and the neck tend to be difficult to rehabilitate due to many complex and subtle movements associated with this region. This also makes neck exercises difficult to accomplish precisely.

The problems of evaluation and management are compounded by neck-specific movement impairments that have been difficult to quantify using traditional means available to most clinicians (simple manual goniometers or inclinometers). Traditional assessment of cervical movement kinematics and quantification of mobility levels and evaluation of the effectiveness of prescribed exercises are commonly accomplished by instructing patients to move their heads through specific planes of motion.[15] However, with no globally accepted gold standard for assessment, a variety of devices and protocols have been used for clinical and research purposes.[16] These include visual range of motion (ROM) estimation,[17,18] inclinometers,[18,19] goniometers and potentiometers[20] to assess static ROM, radiometers, and in rare cases more sophisticated optic,[21] ultrasonic,[22,23] and electromagnetic 2-dimensional dynamic tracking systems[15,24,25] have been used.

Anatomically, neck pain may involve one or more neurovascular and/or musculoskeletal structures such as nerves, facets joints, intervertebral joints, discs, bones, periosteum, muscles, and ligaments all of which may be primary drivers of the pain experience.[26,27] However, to date, cervical imaging studies have been unable to consistently identify tissues responsible for neck pain and as such have been largely unable to associate structural lesions with clinical symptoms.[27–29] As a result, patient self-report of disability and function, clinical evaluation of movement impairment, and clinical assessment of disability and impairment of body function remain the conventional approach for the evaluation of neck pain.[27,28]

The subtle, non-engaging and repetitive nature of strengthening or rehabilitation exercises often lead to difficulties with exercise adherence due to boredom. Adherence as a concept is multidimensional and relates to multiple factors such as attendance at appointments, following advice, undertaking prescribed exercise, correct performance of the exercise, and doing more or less than advised.[30] Non-adherence remains one of the biggest challenges in the field of rehabilitation[2] and may partly explain why many attempts at neck rehabilitation fail to achieve strong effects.[31]

Consumer-facing electronics are nearing global saturation meaning almost every person now has at least one device with an embedded IMU.[32] When combined with new and engaging user interfaces such as virtual reality (VR), these now accessible technologies hold considerable potential when applied to neck pain and rehabilitation.

2.1 Review Question/Objective

The current scoping review sought to synthesize and map the current use of VR technology in neck rehabilitation. This scoping review is useful for rehabilitation scientists and clinicians, applied scientists, and software engineers and developers seeking knowledge on the current state of the evidence and lay of the land in the use of VR-based technologies in neck rehabilitation, and identifies gaps in the research field. Therefore, the purpose of this study is to use Arskey and O'Malley's scoping review methodology to address the following research questions:[33]

- How is virtual reality technology being used in neck pain and rehabilitation?
- What are the outcome measures reported in the studies addressing the use of VR in neck pain rehabilitation?

2.2 Inclusion Criteria

The current review considered participants of any age with any neck condition using VR as a tool for assessment, intervention, research, and usability and feasibility. The review considered all published English-language quantitative studies and excluded all reviews.

2.3 Methods

2.3.1 Search strategy

Literature published in English was collected from twelve databases: ACM Digital Library, BIOSIS Previews, CINAHL, Computing Research Repository, EMBASE, IEEE Xplore Digital Library, MathSciNet, Medline, PubMed, Scopus, SPIE Digital Library, and Web of Science. The search strategy of all the databases consisted of searching for the keywords "Neck pain" and "Virtual reality". The reference list of all identified papers was searched for additional studies.

2.3.2 Study selection

Titles and abstracts of the articles were independently reviewed by two authors (SS and ML). If the articles were representative of the inclusion criteria, the articles went through two full-text independent reviews by the two authors (SS and ML). If disagreement arose, a third reviewer (DW) was consulted.

2.3.3 Charting data

If an article was eligible for inclusion in this review, data related to the use of VR in neck pain were extracted by the lead author and reviewed by a second author. The data extracted were entered into data extraction records and synthesized in summary format. Data were systematically charted on Microsoft Excel and information on authorship, article type, population, and the context of VR use were recorded on this form. The extracted data were synthesized for ease of presentation through qualitative evaluation within each of the four domains of assessment, intervention, research, and usability/feasibility. As a scoping review, the intention was to synthesize the broader corpus of published evidence as a survey of the broader landscape on VR use in neck pain, rather than perform the quantitative synthesis of published results, which is appropriate for a new field with few authors working in the space.

2.3.4 Definitions

Assessment: If the scope the study included the use of VR in the measurement of neck-related outcomes, making a judgment on these outcomes, or any psychometric properties related to the use of VR for neck rehabilitation.

Intervention: If the scope of the study included the use of VR in the management or care of patients with neck-related disabilities, or an interventional capacity to cause a change in a neck-related outcome.

Research tool: If the scope of the study included the use of VR in a systematic investigation of neck-related disabilities, management, treatment, or measurement to establish new facts or reach new conclusions not pertaining to assessment or treatment.

Usability and feasibility: If the scope of the study included the use of VR in the measurement of any user reported adverse effects, acceptability and/or tolerance, or providing a metric for adherence to treatment.

Cohen's kappa was used to determine the agreement between the two rater's Inter-rater agreement for inclusion/exclusion of the 18 articles was excellent ($\kappa = .90$ (95% CI, .71 to 1.0), $p < .0005$).

2.4 Results

Across all databases, a total of 116 hits were returned using the search terms defined above. Of those, 98 duplicates were removed and 25 failed to meet the inclusion criteria. An additional two publications were identified through backward searching of the citation lists, and subsequently, one publication was removed due to inability to access. The remaining 18 articles were then collated in Excel for further review, classification into one of the 4 domains, and synthesis.

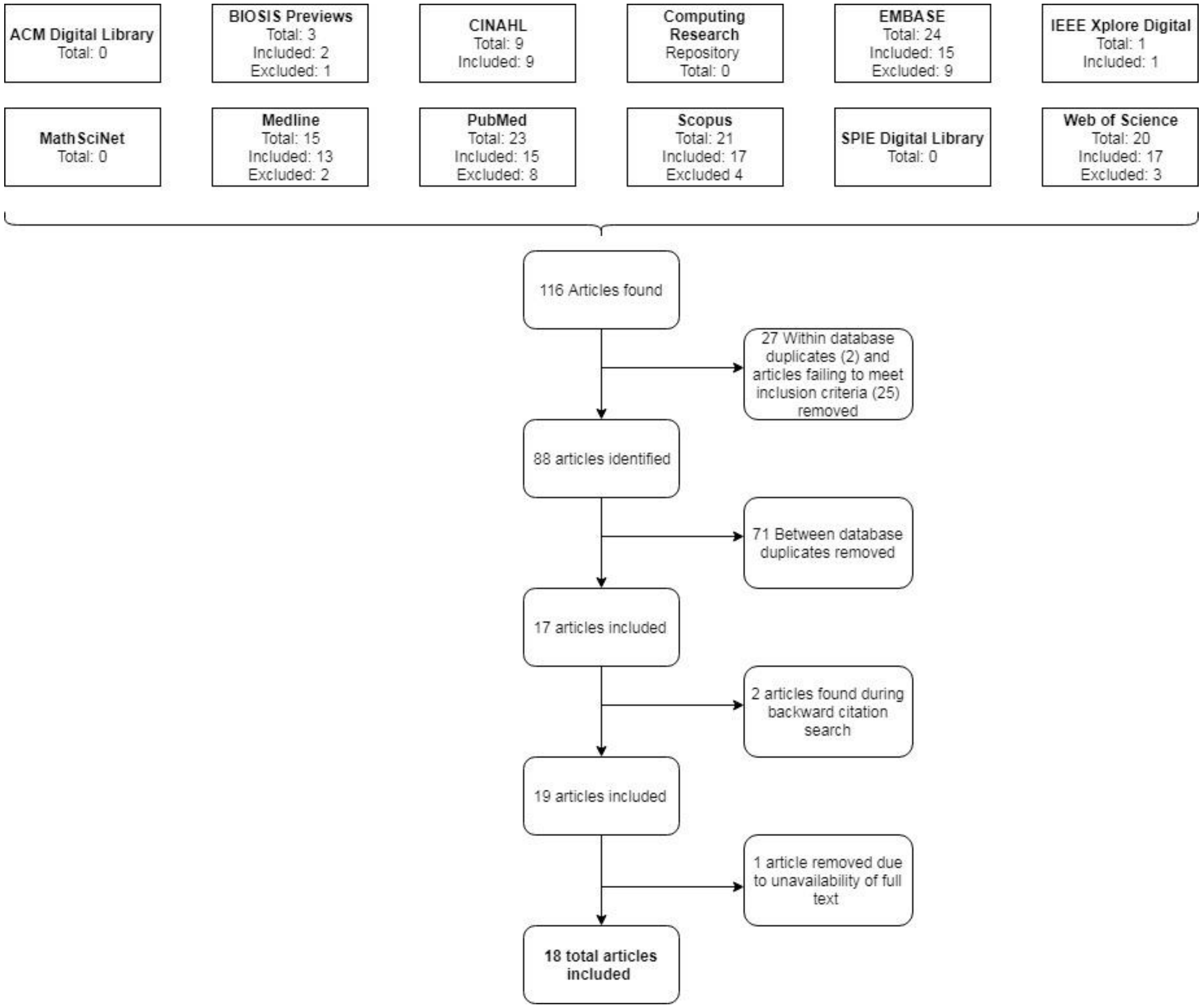

Figure 2-1: Flowchart of the study selection and inclusion process

Table 1: Studies by categories and their targeted outcome

Categories	Authors	Year	Outcomes Targeted
Assessment	Sarig-Bahat, Weiss, and Laufer[34]	2009	ROM
	Sarig-Bahat, Weiss, and Laufer[35]	2010a	ROM
	Sarig-Bahat *et al.*[36]	2015a	Peak velocity, mean velocity, smoothness, acceleration, accuracy
	Sarig-Bahat *et al.*[37]	2016a	Peak velocity, mean velocity, smoothness, acceleration
	Mihajlovic *et al.*[38]	2018	ROM
Intervention	Harvie *et al.*[39]	2015	Rotation gain
	Sarig-Bahat *et al.*[40]	2015b	Improvement in ROM, peak velocity, mean velocity, acceleration, static head stability, accuracy
	Sarig-Bahat *et al.*[41]	2017	Improvement in velocity, smoothness, acceleration, accuracy, ROM
Research Tool	Bell *et al.*[42]	2009	ROM
	Sarig-Bahat, Weiss, and Laufer[43]	2010b	Peak velocity, mean velocity smoothness, acceleration
	Bell *et al.*[44]	2011	ROM
	Sarig-Bahat *et al.*[45]	2014	ROM, peak velocity, mean velocity, smoothness
	Sarig-Bahat *et al.*[46]	2016b	Peak velocity, mean velocity smoothness, acceleration
	Treleaven, Chen, and Sarig-Bahat[47]	2016	ROM, peak velocity, mean velocity, smoothness, acceleration, accuracy
	Williams *et al.*[48]	2017	ROM, peak velocity, mean velocity, smoothness, acceleration, accuracy
	Chen *et al.*[49]	2017	ROM
Usability & Feasibility	Treleaven *et al.*[50]	2015	Simulation sickness
	Tyrrell *et al.*[51]	2017	Simulation sickness

2.4.1 Assessment

2.4.1.1 Range of motion

Range of motion (ROM) is a commonly used outcome to measure the full movement potential available to a joint or a body part.[52] Three out of the five studies classified under this domain used the motion-tracking capabilities of VR hardware to target ROM as a measurement.[34,35,38] Sarig-Bahat *et al.* (2009) used a VR-based testing protocol for the measurement of full-cycle (flexion/extension, right rotation/left rotation) cervical ROM and compared it to conventional assessment (3 repeated movements in extension, flexion, left rotation, right rotation, left lateral flexion, and right flexion directions) in an asymptomatic population. In a population of 30 healthy participants, VR-ROM was greater (bias of 7.2º in flexion/extension and 16.1º in rotation) than conventional assessments and established its intra and inter-tester reliability, demonstrating an advantage of VR for evaluating cervical ROM.[34] Sarig-Bahat *et al.* (2010a) used a VR-based testing protocol to measure cervical ROM in people with chronic neck pain and compared them with asymptomatic participants. In a sample of 25 participants suffering from chronic neck pain and 42 with no history of neck pain, they observed reduced ROM using both conventional and VR-based assessment in participants with neck pain. Significantly greater ROM ($p < 0.05$) was observed using VR-based assessment (for right rotation, left rotation, and extension) in comparison to conventional assessment in both groups. The VR-based assessment was the more sensitive metric when discriminating between those with and without neck pain, while the conventional assessment was more specific leading the authors to endorse conventional assessment for discriminative purposes.[35] Mihajlovic *et al.* used a custom-developed VR-based "serious exergame" for the assessment of three motion-based exercises (each prioritizing yaw, pitch, or roll) in two different virtual environments (classic – where the virtual environment is an empty space containing few textures vs. realistic – highly realistic VR environment rendered in high detail). In a sample of 30 participants, the study found that the best tracking scores were obtained for pitch exercise (flexion/extension) – indicating that the pitch exercise was the easiest to perform.

ROM measured under the highly realistic VR scenario was slightly higher than the classic VR environment.[38]

2.4.1.2 Velocity of movement

Two of the five studies used the VR to evaluate the velocity of cervical movement.[36,37] Peak velocity refers to the maximal velocity value recorded from motion initiation to target hit, and mean velocity refers to the mean value of velocity from motion initiation to target hit.[53] Sarig-Bahat *et al.* (2015a) used the VR-based testing protocol to measure cervical kinematic characteristics during interactive motion in 33 patients with neck pain and compared them with 22 asymptomatic participants. Results showed significant ($p < 0.05$) and strong effect-size differences in both mean and peak velocities. Those with chronic neck pain moved slowly throughout the trial (lower mean velocity) and accelerated to lower peak velocities than control participants. Regression analysis and ROC curves showed strong group differences, sensitivity, and specificity for VR-based velocity as a discriminate tool. Sensitivity (range: 0.91-1.0) and specificity (range: 0.86-0.95) was deemed excellent for discriminating between the two known groups.[36] Sarig-Bahat *et al.* (2016a) used a VR-based testing protocol to measure cervical kinematics including velocity, symmetry, and smoothness to explore intra and inter-tester reliability, and defined the minimal detectable change in these kinematic measures. In a sample of 44 healthy participants, the results demonstrate moderate to good reliability of cervical kinematics velocity profile in flexion, extension, and left and right rotation. Global peak velocity (average of the four directions) appear to have the best reliability in all movement directions and good reliability in left rotation, right rotation, extension, and flexion. Global mean velocity showed good reliability with the exception of left rotation that showed only moderate reliability. Minimum detectable change for peak velocity ranged from 41 to 53 °/s, while mean velocity ranged from 20 to 25 °/s.[37]

2.4.1.3 Smoothness of movement

Two of the five studies used VR motion-tracking to evaluate the smoothness of movement as a measurement.[36,37] Smoothness was obtained by observing the number of velocity peaks (NVP) from motion initiation to target hit, indicating motion smoothness or its reciprocal termed jerk. Normal smooth motion should have only one peak velocity. NVP was defined by counting the number of times the acceleration curve changed signs (i.e., crossed the zero line).[36] Sarig-Bahat *et al.* (2015a) observed a significant ($p < 0.05$) and strong effect-size difference in all directions and showed strong group differences, sensitivity, and specificity for discriminating between people with neck pain and those with otherwise healthy necks. Good sensitivity was observed in flexion (0.88) and left rotation (0.85) while good specificity was observed in flexion (0.73), extension (1.0), and right rotation (0.82).[36] Sarig-Bahat *et al.* (2016a) observed good test-retest reliability in smoothness measures.[37]

2.4.1.4 Acceleration of movement

Two of the six studies used the VR in the measurement of acceleration of movement as a measurement.[36,37] Acceleration was obtained by calculating time from motion initiation to peak velocity moment, as a percentage of total movement time, representing the ratio between acceleration to deceleration phase in the velocity profile.[36] Thus a healthy neck will present a bell-shaped velocity profile with a 1:1 acceleration-deceleration ratio.[36,54,55] Sarig-Bahat *et al.* (2015a) found a strong effect size (Cohen's d) of range 82% – 85% for all directions save for left rotation which was not clinically useful. Furthermore, cervical motion showed less acceleration-deceleration symmetry in comparison to the control group.[36] Sarig-Bahat *et al.* (2016a) observed moderate reliability (ICC range 0.60-0.70) in acceleration for all directions except flexion, which showed poor reliability.[37]

2.4.1.5 Accuracy of movement

One of the six studies used the VR in the measurement of accuracy of movement. Movement accuracy was defined as the difference between the target position and the participant's head location in degrees. Sarig-Bahat *et al.* (2015a) observed significant ($p < 0.05$) group differences in both x and y axis for extension, and in y axis for right and left rotations.[36]

2.4.2 Intervention

2.4.2.1 Range of Motion

Three of the six studies evaluated the effectiveness of VR for increasing ROM in those with impaired neck mobility.[39–41] Harvie *et al.* used the VR to alter visual-proprioceptive feedback during neck rotation, and evaluated the degree of movement achieved prior to pain onset, under a hypothesis that the *illusion* of less actual movement would increase real-world range before pain, while the illusion of greater movement would decrease real-world range. Using a VR technique known as redirected walking, these researchers modulated visual-proprioceptive feedback by tracking real-world movement and then feeding this back into the virtual environment in an understated or overstated form. In this way, rotation gain (the degree to which real rotation is translated into virtual rotation) can be manipulated such that virtual and physical differ, thus creating the illusion that more or less movement is actually happening. In a sample of 24 participants, they found that when vision understated true rotation, pain-free real-world ROM increased by 6% (p = .006, d = 0.67); and when vision overstated true rotation, pain-free ROM was decreased by 7% (p = 0.001, d = 0.80). They concluded that visual-proprioceptive information modulates pain threshold during head rotation in people with neck pain and that VR can be used to induce such visual-proprioceptive illusions.[39] Sarig-Bahat *et al.* (2015b) investigated the effect of kinematic training with and without the use of a VR device in people with chronic neck pain using ROM as an outcome. In a sample of 32 participants randomly assigned into either real-world kinematic training (KT) or VR training (KTVR) groups, they observed significant improvement in ROM in left and right rotation and flexion in both groups at both immediate and three months post-intervention ($p < 0.05$); and extension ROM was greater in the KTVR group at three month post-intervention.[40] Sarig-Bahat *et al.* (2017) compared short-and intermediate-term effects of home-based kinematic training in people with chronic neck pain and healthy controls and evaluated the difference in ROM increase between VR or a laser-based delivery method. In a sample of 90 participants, 76 completed a one-month follow-up, and 56 the three-month follow-up. These authors observed moderate improvements in the ROM in all directions. Both interventions showed medium effect sizes (Cohen's d -0.14 – 0.10 in VR vs. control; -0.15 – 0.21 in laser vs. control) and both were better than no training. After 4 weeks of training, both interventions resulted in similar improvements in pain, disability, health status, and cervical kinematics.[41]

2.4.2.2 Velocity of movement

Two of the three studies evaluated the effectiveness of VR to improve the velocity of movement as an intervention outcome.[40,41] Sarig-Bahat *et al.* (2015b) observed a significant improvement in velocity in the VR group versus the group that just did kinematic training ($p < 0.05$); while three-month post-intervention results showed a greater proportion of improved participants in the group trained with a laser than those who used VR.[40] Sarig-Bahat *et al.* (2017) reported significant improvements ($p < 0.01$) in both mean and peak velocities in all directions in VR-based groups, and moderate improvements in most directions in laser-based groups.[41]

2.4.2.3 Acceleration of movement

Two of the three studies used VR to improve the acceleration of movement as an intervention outcome.[40,41] Sarig-Bahat *et al.* (2015b) observed significant small to moderate improvements in acceleration (measured as time from motion initiation to peak velocity moment, as a percentage of total movement time, representing the ratio between acceleration to deceleration phase in the velocity profile) in the extension and right rotation movements post-intervention ($p < 0.05$), and in all planes of movement except flexion in three-month post-intervention in KTVR group. Small to moderate improvements were reported in flexion and left rotation improvements post-intervention, and in all directions except extension three-month post-intervention [40] Sarig-Bahat *et al.* (2017) observed a small to moderate but significant ($p < 0.05$) increase in time to peak velocity in all directions in both VR and laser-based groups, except for extension in the former, and extension and right rotation in the latter which were not significant.[41]

2.4.2.4 Accuracy of movement

Two of the three studies used VR to target the accuracy of movement as an intervention outcome.[40,41] Movement accuracy was defined as the difference between the target position and the participant's head location in degrees. Sarig-Bahat *et al.* (2015b) reported significantly improved accuracy for rotation and flexion-extension in three-month post-intervention ($p < 0.05$).[40] In an independent sample, Sarig-Bahat *et al.* (2017) reported a significantly moderate decrease in accuracy error in all directions in VR ($p < 0.05$), except for extension which was not significant. Small but non-significant decrease in all directions except right rotation was reported in the laser-based group.[41]

2.4.2.5 Smoothness of movement

One study evaluated the effectiveness of VR to improve the smoothness of movement as an intervention outcome. Sarig-Bahat *et al.* (2017) observed a small to moderate decrease in smoothness (measured as the number of velocity peaks) in both VR and laser-based groups, with the exception of a small but non-significant increase in the flexion direction in the VR-based group.[41]

2.4.2.6 Static head stability

One of the three studies explored the effectiveness of a custom VR application to improve static head stability (defined as the sway in pitch and yaw from the mid-position and calculated in terms of 3D mean and standard deviation amplitude) as an intervention outcome. Sarig-Bahat *et al.* (2015b) observed a small and non-significant decrease in accuracy of flexion/extension in both post and three-month post-intervention, and a small but significant decrease in rotation three-month post-intervention ($p < 0.05$) in the VR group. A small but non-significant decrease was also reported in flexion/extension and rotation post and three-month post-intervention except flexion/extension three-month post-intervention which was significant ($p < 0.05$). Both VR and laser-based had no difference between them.[40]

2.4.3 Research Tool

2.4.3.1 Range of Motion

Six studies used VR as a tool to obtain ROM as a research outcome in trials of other interventions.[42,44,45,47–49] Bell *et al.* (2009) applied VR feedback control to repeatedly measure the primary motions and flexion/extensions as a function of axial rotation to test the impact of an ill-fitting cervical orthosis on ROM. In a sample of 12 healthy participants, the results demonstrated too big brace allowed more motion in flexion/extension but less than too small brace in axial rotation. Both too big and too small brace were similar in the amount of motion they were able to restrict in lateral bending. In combined motion, both the too big and too small brace allowed more motion than the correct size.[42] In an independent sample, Bell *et al.* (2011) used VR to compare ROM of participants that had undergone anterior cervical decompression and fusion operation (ACDF) to age-matched healthy non-operative participants. A total of 18 control, 25 preoperative, and 110 postoperative (who were divided into groups according to the number of operated levels where a level was considered to be a functional spinal unit) were included. A comparison of the maximum ROM of primary motions demonstrated a small to moderate decreasing trend in ROM as the number of fused levels increased. ROM was lower in preoperative groups than in control groups. Early postoperative groups experienced an improved ROM relative to preoperative levels, though their ROM was still lower than the control. Using VR as the measurement tool, the patterns of ROM change from pre- to post-operative appeared to be moderated in different ways by the number of cervical levels fused. [44] Treleaven *et al.* (2016) used cervical kinematics captured from VR and explored their association with factors such as dizziness handicap, visual disturbances, functional balance, joint position error, neck pain intensity, neck-related disability, and fear of neck motion in a sample of 39 participants with idiopathic neck pain or whiplash. They found that relationships between the VR-based kinematic metrics and other clinical variables were most notable in the horizontal (rotation) plane compared to the sagittal (flexion/extension) plane. A mild to moderate correlation was observed between ROM and pain intensity (VAS) and disability (NDI) in the horizontal plane. No significant correlations were observed between ROM and self-rated fear of motion save for a moderate correlation ($r = -0.519$, $p < 0.05$) between ROM in the sagittal plane and fear of movement in the whiplash group only. The results suggest that sign and symptoms of sensimotor dysfunction such as dizziness, visual disturbances, and balance deficits are related to the ability to move the head fully and quickly in patients with neck pain regardless of the etiology of the pain.[47] Williams *et al.* used VR to examine the changes in kinematics between asymptomatic control, subjects with neck pain, and people with vestibular pathology. In a sample of 54 participants (20 control, 20 neck pain, 14 vestibular pathology) no significant differences in the VR-based ROM between the three groups were observed.[48] Chen *et al.* (2017) used the Oculus Rift DK1 VR HMD to compare the performance of neck exercises in people with chronic neck pain and asymptomatic population while under the influence of altered visual feedback. The study was divided into two parts: the first part used a metric termed *just noticeable difference* (JND, threshold at which the participants did not notice that their visual feedback had been altered) for individuals without neck pain; the second part determined the JND for chronic neck pain and then evaluated performance in VR when under manipulated visual feedback with control-display (ratio of the mapping between a patient's movement in VR and the corresponding visual feedback). The study demonstrated that the visual feedback in VR could override muscle proprioceptive cues at or within JND.[49] Finally, Sarig-Bahat *et al.* (2014) used VR to investigate the relationship between motion impairments and people's subjective reports of pain intensity, disability, and fear of motion. In a sample of 25 participants with chronic neck pain, they observed that the cervical ROM was significantly and moderately correlated with pain intensity (VAS) and fear of motion in all four movement directions; while the disability (NDI) showed significant fair to moderate correlation only with flexion and right rotation ROM ($p < 0.05$).[45]

2.4.3.2 Velocity of movement

Six studies used VR as a tool to obtain the velocity of movement as a focus of research.[43,45–48] Sarig-Bahat *et al.* (2010b) used a customized VR assessment system to compare cervical kinematics during functional motion in patients with neck pain and asymptomatic individuals. In a sample of 25 participants with neck pain and 42 control participants, significant group differences for both mean and peak velocities were observed ($p < 0.0001$). Participants with neck pain showed lower mean and peak velocities when they were instructed to move towards a target as quickly as possible. Significant differences in direction of motion in both mean and peak velocities were also observed. A significant interaction was found between group and motion direction between both mean and peak velocities, in which the healthy participants moved slower when having to flex the neck to reach the target than when having to extend, while no difference in velocity was identified in those with neck pain. Additionally, evaluation of main effects revealed significantly higher mean and peak velocities in the horizontal plane (rotation) ($p < 0.04$) than in the vertical plane (flexion/extension).[43] In an independent sample, Sarig-Bahat *et al.* (2016b) used VR to evaluate fast cervical motion kinematics in different age groups in asymptomatic individuals. They found significant differences in velocity between the oldest age group (61–80) from the other three groups (18–30, 31–45, and 46–60) but no difference between the three younger groups ($p < 0.05$). Again it was velocity in the vertical plane (flexion/extension) that showed the greatest between-group differences, though rotation velocity also differed when comparing the oldest to the two youngest groups only. [46] Treleaven *et al.* (2016) observed mild to moderate relationships ($r = -0.302$ to 0.333) between the velocity of cervical rotation and self-reported pain and or disability, dizziness, visual disturbances, and dynamic balance in people with neck pain. Neck pain intensity (VAS) and disability (NDI) had a mild to moderate correlation with velocity in the horizontal plane only. No significant correlations were observed between velocity and fear of motion.[47] Williams *et al.* (2017) reported significantly lower mean velocity in both movement planes in a sample of 20 people with neck pain group compared to a matched control group. The third group with vestibular pathology moved with lower mean velocity compared to control, but faster than those with neck pain. While trends were observed for lower peak and mean velocities in the vestibular pathology group, the difference was non-significant in vestibular pathology and neck pain or the control group. An interesting finding was that in the vestibular group, there was a moderate but non-significant association between mean rotation velocity and a self-reported dizziness VAS.[48] Sarig-Bahat *et al.* (2014) observed significant moderate correlations between fear of motion (TSK) and both mean and peak velocities in all four movement directions ($p < 0.05$). Pain intensity (VAS) was significantly correlated with mean and peak velocities in extension ($p < 0.01$) and mean velocity in left rotation ($p < 0.01$) but no correlation was observed in flexion and right rotation measures. A fair to moderate correlation was observed between disability (NDI) and mean and peak velocities in all directions except flexion in peak velocity and left rotation in both mean and peak velocities.[45]

2.4.3.3 Acceleration of movement

Four studies used VR as a tool to obtain the acceleration of movement as a focus of research.[43,46–48] Acceleration is measured as time from motion initiation to peak velocity moment, as a percentage of total movement time, representing the ratio between acceleration to deceleration phase in the velocity profile. Sarig-Bahat *et al.* (2010b) observed no group differences between the response times of acceleration. Further analysis of the results indicated a significant difference between the group and the direction of motion for acceleration ($p < 0.005$).[43] In the age-based normative evaluation study, Sarig-Bahat *et al.* (2016b) found no age-based differences in acceleration, unlike other kinematic measures.[46] Treleaven *et al.* (2016) observed no significant correlations between fear of movement and acceleration in people with idiopathic or traumatic neck pain except flexion-extension plane in the whiplash group ($p < 0.05$). These authors suggested that signs and symptoms of sensimotor dysfunction such as dizziness, visual disturbances, and balance deficits are related to the ability to move the head fully and quickly in patients with neck pain, regardless of cause, but that the associations could not be explained by fear of movement.[47] Williams *et al.* (2017) observed significantly lower acceleration in both horizontal and vertical movement planes in their neck pain group in comparison to controls. Specifically, the neck pain group moved with greater variability in acceleration, deceleration, and altered symmetry compared to controls. Similar to velocity, those with vestibular pathology showed altered symmetrical profile (percentage of time from motion initiation to target hit, with 50% being optimal) in comparison to controls, but more symmetrical than neck pain participants.[48]

2.4.3.4 Smoothness of movement

Five studies used VR as a tool to obtain the smoothness of movement as an independent variable in research.[43,45–48] Sarig-Bahat *et al.* (2010b) observed staggered, slow drift to the target rather than one clear velocity peak in participants with neck pain. They also found that patients with neck pain showed a greater number of velocity peaks (NVPs) than control, indicating impaired motion smoothness (increased jerk). Significant differences in the number of velocity peaks in all direction of motion were also observed in the clinical sample ($p < 0.0001$).[43] In an independent sample, Sarig-Bahat *et al.* (2016b) also observed a difference in NVP between the youngest and the oldest age groups.[46] Treleaven *et al.* (2016) observed significant correlations between movement smoothness and pain, dizziness handicap, the step test, and visual disturbances. No significant correlations between smoothness and fear of movement in the horizontal plane were established, but a significant correlation was found in the sagittal plane in those with whiplash.[56] Williams *et al.* (2017) reported fewer velocity peaks in both movement planes in the neck pain group in comparison to controls suggesting more smoothness of motion.[48] Conversely, Sarig-Bahat (2014) *et al.* observed significant positive correlations between fear of motion and smoothness (NVP) in all four directions of movement. Pain intensity (VAS) correlations were similar to trends observed in velocities: positive correlations (more pain, more velocity peaks) were observed in all directions. A fair to moderate correlation was observed between disability (NDI) and NVP (greater disability resulting in a higher number of NVP indicating less smoothness).[45]

2.4.3.5 Accuracy of movement

Two studies used VR as a tool to obtain the accuracy of movement as an independent variable in neck pain research.[47,48] Treleaven *et al.* (2016) reported significant positive correlations (range -0.640 to 0.472) between pain, dizziness handicap, the step test and or visual disturbances and accuracy (the difference between the target position and participant's head location) in the horizontal plane. No significant correlations between accuracy in the horizontal plane and fear of movement were established.[47] Williams *et al.* (2017) reported lower accuracy in both movement planes in the neck pain and vestibular pathology groups, excluding flexion/extension in x displacement in the neck pain group, in comparison to controls. Fair to moderate positive correlations between visual symptoms and accuracy were observed in the rotation plane in the neck pain group while in the vestibular group, a negative significant moderate correlation was seen between accuracy and dizziness VAS in the sagittal plane.[48]

2.4.4 Usability and feasibility

2.4.4.1 Simulator sickness

Two studies explored the usability and feasibility of using VR as a tool for neck rehabilitation.[50,51] Treleaven *et al.* (2015) explored incidence, severity, and predisposing factors to simulator sickness (SS) when using VR amongst the asymptomatic population. In a sample of 32 participants, the incidence of motion sickness during VR immersion was 28%, and the mean severity was 17.2 mm on a 100-mm VAS. A significant difference in ROM time, total time, motion sickness susceptibility questionnaire short form (MSSQ) score, and simulation sickness questionnaire (SSQ) score was found between those who reported any level of simulation sickness and those reporting none ($p < 0.05$). Significant positive correlations were observed between simulator sickness severity and SSQ score, ROM time, and total time. Results indicate a relatively high incidence but low severity of simulator sickness, which was associated with the MSSQ child subsection (a measure of motion sickness susceptibility), and seemed to get worse with increasing exposure time.[50] Treleaven *et al.* (2017) explored SS and other side effects of VR in participants with neck pain and vestibular pathology compared to the asymptomatic population. In their sample of 54 participants (20 control, 20 neck pain, and 14 vestibular pathology participants), a significantly greater incidence of any SS in neck pain and vestibular pathology groups were reported.[51] No significant differences were observed when comparing SS measures between vestibular and neck pain groups. Significant mild-to-moderate positive correlations for the entire population were observed between SS measures and pre-VR visual symptoms and dizziness intensity.

2.5 Discussion

This scoping review sought to identify the current uses of VR in neck rehabilitation. The review revealed that the range of motion was the most common metric obtained using VR, followed by velocity, acceleration, smoothness, accuracy, and head stability. The clinical population used in the studies included people with neck pain, vestibular pathology, whiplash, and subjects that have undergone anterior cervical decompression and fusion operation.

Of the 18 studies included in this review, five used VR in the measurement of neck-related outcomes, make judgments on these outcomes or any psychometric properties related to the use of VR for neck rehabilitation. These studies used the motion tracking capabilities of VR hardware to track the traditional measure of neck pain/motion impairment. In comparison with conventional assessment, ROM obtained from VR-based assessments was higher in both people with and without neck pain, and VR-based assessments were also more sensitive when discriminating between those with and without neck pain. Finally, higher ROM was obtained when the VR environment was rendered in higher detail. These results imply that VR may have the potential to obtain a more accurate ROM overall and improving the overall aesthetics and graphics quality may influence ROM obtained. The studies also used VR to measure novel cervical kinematic metrics such as velocity, smoothness, acceleration, and accuracy of movement. Authors of these studies reported lower velocity of neck movement and accelerated to lower peak velocities, less smoothness, lower overall acceleration, and lower accuracy in people with neck pain. Furthermore, cervical kinematics have mostly demonstrated good sensitivity and specificity in discriminating between people with neck pain and those with otherwise healthy necks, suggesting that VR-based assessment may be a better tool to assess neck mobility and impairments.

Three studies used VR in the management or care of patients with neck-related disabilities, or in an interventional capacity to cause a change in a neck-related outcome. These studies used the effectiveness of VR for increasing both traditional ROM based assessments as well as novel cervical kinematic metrics in those with impaired neck mobility. They reported an increase in ROM when vision is manipulated, suggesting the analgesic effects of immersive VR use in neck pain may be similar to its distraction effect during painful procedures during cancer therapy, dental care, transurethral prostate ablation, and wound care and other painful procedures in burn patients. Furthermore, similar ROM was observed when people used VR-based and laser-based kinematic training. The studies also reported increases in velocity, acceleration, accuracy, and smoothness in VR-based kinematic training.

Eight studies used VR in a systematic investigation of neck-related disabilities, management, treatment, or measurement to establish new facts or reach new conclusions not pertaining to assessment or treatment. These studies used VR as a tool to obtain both traditional ROM based assessment as well as novel cervical kinematics as a research outcome in trials of other interventions. To that effect, VR was used to determine the impact of ill-fitting cervical orthoses, compare ROM of participants who had undergone ACDF operation and evaluate the correlation between ROM and self-reported measures such as pain intensity and disability, and fear of movement in people with whiplash and idiopathic neck pain. These studies also used VR to investigate velocity, acceleration, smoothness of movement and accuracy of movement in people in different age groups, as well as people with different types of neck-related impairments.

Finally, two studies used VR in the measurement of user-reported adverse effects, acceptability or tolerance. These studies reported positive correlations between simulation sickness and exposure time, and greater incidence of simulation sickness was observed in people with neck pain, indicating that the time spent in immersive VR may have an impact on simulation sickness.

2.6 Conclusion

A scoping review is intended to provide an overview of a field of inquiry without prioritizing the methodological quality of the research within or a formal appraisal of the risk of bias. As such, the results presented in this review should be interpreted cautiously. Additionally, 13 of the 18 primary sources included in this review were from the same lab or were co-authored by the same group of researchers, suggesting that much of the current knowledge in the field has been driven by a small group of researchers. This also suggests that it may not be a time for a systematic review of the research question. There appears to be room for additional research groups to contribute knowledge to the field of VR use for neck pain, as the results of the existing evidence to appear to indicate the technology holds promise for this vexing set of clinical conditions.

Chapter 3

3 Game design and gamification principles

Exergames are defined as "any types of video games/multimedia interactions that require the game player to physically move in order to play".[57] In combination with VR, these technologies have demonstrated the potential to improve adherence to therapy as the immersiveness of the VR and gamified "fun" nature of these video games can keep the users engaged.[58–62] With this in mind, we have developed a VR-based exergame with the intention that such a system may one day be used in the rehabilitation and future research of neck pain. To our knowledge, the venture represents only a handful of projects working on harnessing and developing consumer-facing VR-based exergames for neck rehabilitation and was developed as a result of significant collaboration between engineering and health science researchers. The purpose of this section is to briefly summarize the gameplay design process and the rationale behind the decisions.

Exergames are the most practical and effective in rehabilitation when they have specifically been designed for therapy.[57,63] In addition to the inability of off-the-shelf consoles to provide clinicians control over important rehabilitation parameters, they are often designed with the intention to maximize entertainment, between-player competition, and revenue. As a result, the sports and training science aspect play a secondary role in the design and development process of these games.[64] This necessitated the development of a video game that was designed and developed exclusively for neck rehabilitation. In doing so, it was also important to ensure that the video game was designed using gamification principles to ensure entertainment and graphic quality so that it was engaging to the users.

3.1 The theoretical framework used in the overall development

In overall development of the video game, we adapted the technology acceptance model (TAM). First created by Fred D. Davis, TAM proposes that the ease of use and perceived usefulness of technologies are predictors of user attitudes towards using technology. Ease of use was also considered to influence the perceived usefulness of the technology (Figure 3-1).[65,66] This formed the basis of the first principle of gameplay design: (i) ensure ease of use for both clinician and end-user platforms to maximize adherence.

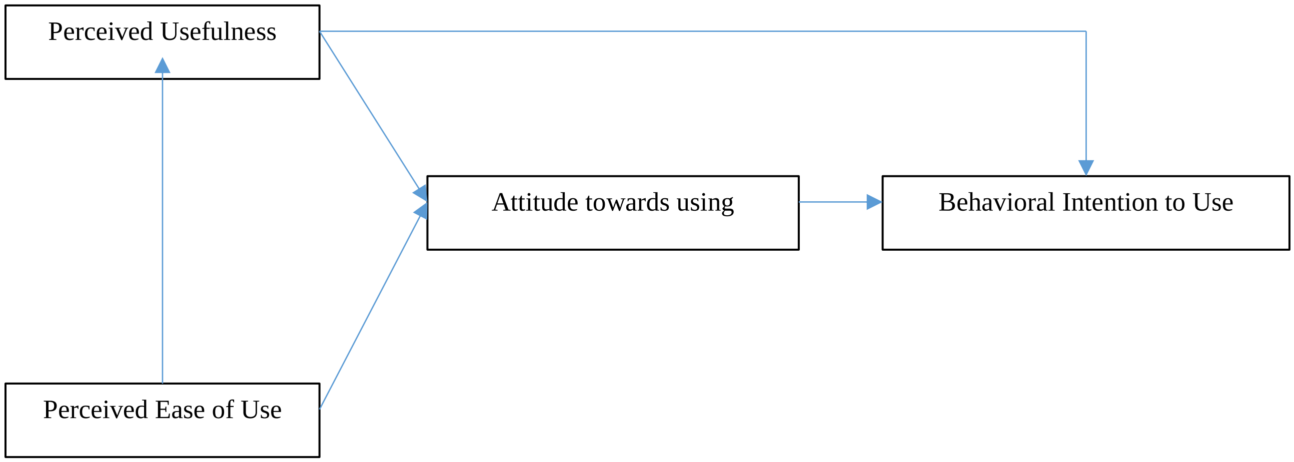

Figure 3-1: An abridged version of TAM.[65]

3.2 Game level design

In the development of gaming levels, we adapted the Self Determination Theory (SDT) which emphasizes motivation to perform a behavior.[67] Intrinsic motivation serves as the ultimate motivation in SDT and the enjoyment of doing the behavior is a defining characteristic of intrinsic motivation.[68] This formed the basis of the second principle of in-game level design: (ii) ensure the game provides adequate enjoyment for end-user ensuring engagement and adherence.

Unlike traditional (obesity-based) exergames where more intense and longer-duration game play should result in more health benefits,[67] we rationalized shorter duration and at lower intensity movements will mitigate the risk of worsening an existing condition, while at the same time pose an adequate challenge to the user. In order to maintain this fine balance, we adopted Sinclair, Hingston, and Masek's dual-flow model.[69] Mihály Csíkszentmihályi's concept of "flow" involves the experiences of immersion in the activity, control over one's environment, and increasing intrinsic motivation (enjoyment), and results from the user's increasing skill required to deal with increasingly difficult tasks.[67,70] Sinclair *et al.* extended the flow model with an effectiveness dimension that reflects an intensity-fitness balance.[71] Therefore, just as challenge-skill balance determines the attractiveness of the game (i.e., if challenge is low the users experience boredom; if challenge is high the users feel anxious), intensity-fitness balance determines effectiveness of the game (i.e., too high intensity will result in failure to play; too low intensity will result in a state of deterioration). Optimal exergaming experience is achieved when both attractiveness and effectiveness are in balance (Figure 3-2).[71] Unlike regular video games that increase difficulty level with time under the assumption that player's skill levels increased with playing time, the assumption does not translate to exergames as increasing intensity may lead to exhaustion and failure. This led to the adoption of our final game level design principle: (iii) to ensure the video game adapts dynamically to the player's performance.[69]

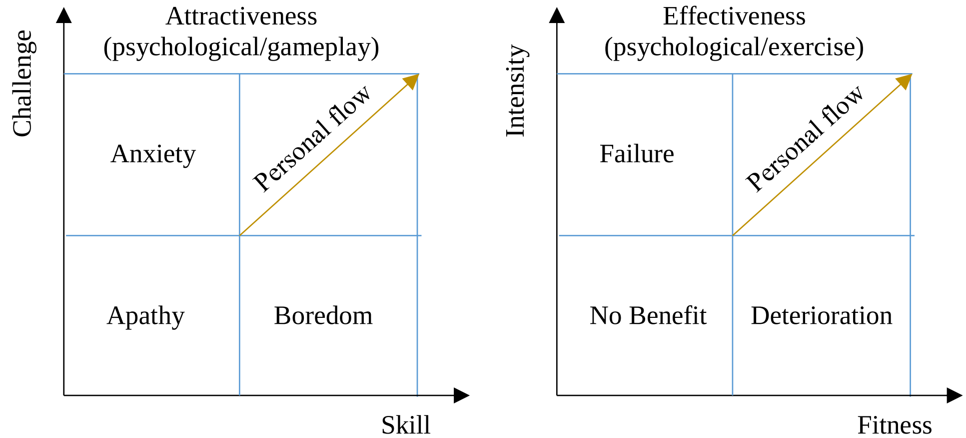

Figure 3-2: An extended dual flow model for exergames.[71]

3.3 The proposed system

The VR-based system that was developed consists of hardware components that support the virtual environment. The main hardware component used is the Oculus Rift VR headset, paired with a personal computer which meets the requirement for Oculus usage. The Oculus includes accelerometer, gyroscope, and magnetometers that sample at 1000 Hz to capture motion through 6 degrees of freedom: pitch/yaw/roll. Sagittal, transverse and horizontal translations in the real world are captured through two IR cameras that are positioned in front of the wearer to track an array of IR emitting diodes embedded within the headset.

The software was developed in Unity with the C# coding language. The system allows clinicians to input parameters to determine attributes that determine movements users should make during the game and the difficulty they should experience. These include the size of targets to be hit (accuracy), the frequency with which targets spawn (velocity of movement) and if needed the volume of the cone of play (range of motion). The system outputs quantifiable data relative to the user's progress in the game, in turn acting as motivation for the user and a novel indicator of improvement (outcome) for the clinician. Tracking the user's head movements during the virtual reality experience will allow clinicians to quantify parameters of impairments and limitations associated with neck pain, as well as analyze whether a prescribed treatment is effective in improving neck pain and overall neck mobility.

3.4 Gameplay design

The game requires players to navigate a simple paper plane avatar through a nondescript environment using only head and neck movements (Figure 3-3). Users are to hit objects (spheres) that appear in front of them by moving their heads through pre-defined movement patterns. The system dynamically calibrates the size of the playing area (the 'cone of play') and the velocity of movement based on real-time performance – if five were hit consecutively the game area expands. If 7 of 10 consecutive targets are missed, the game area contracts. The video game is divided into initial calibration of ROM and velocity followed by the actual game.

3.4.1 Calibration

3.4.1.1 Measurement of ROM

The simulation starts with a brief calibration period that requires the user to hit objects that appear near the edges of the cone of play, starting with a cone of 45 degrees out from the center of the field of vision. If the user hits 5 consecutive spheres that are presented at a frequency of 0.3 Hz (one every 3 seconds), the cone of play increases by 10 pixels. This continues until the cone of play is at a size beyond which the user can reliably hit at least 7 out of 10 consecutive targets. At that point, calibration moves onto the velocity stage.

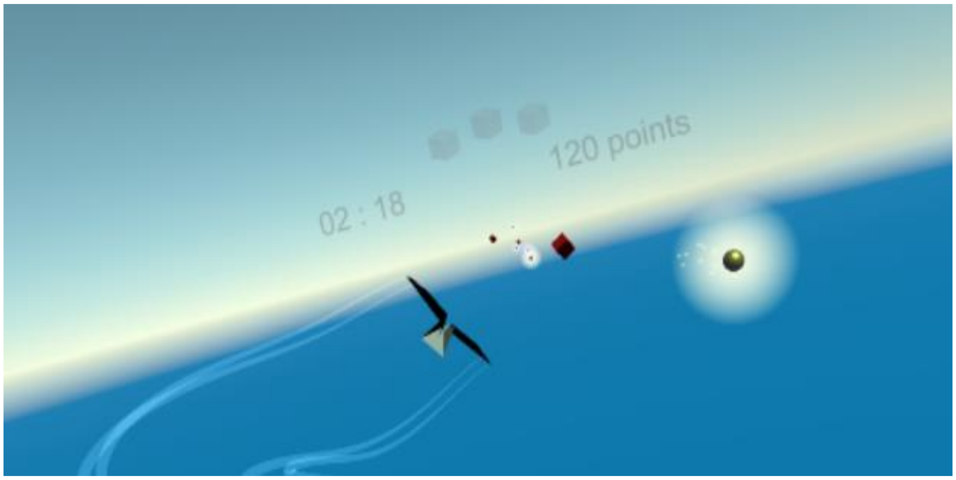

Figure 3-3: Virtual Reality User Interface

3.4.1.2 Measurement of velocity

The second component of calibration uses similar calculation metrics to assess the appropriate velocity of neck movement available to the user, using the cone of play as established in the measurement of ROM. Users are required to hit objects that appear in front of them. Every time the users hit 5 objects in a row, the ‘virtual’ velocity at which the plane appears to move forward through the environment will increase by 100 pixels per second, which in real-world terms increases the frequency at which the targets appear thus requiring faster head movements to hit them all. This continues until the velocity is at a rate beyond which the user can reliably hit at least 7 out of 10 consecutive targets. At the end of the two calibration steps, the game begins starting with the cone of play (range motion) and velocity of motion determined through the calibration.

3.4.2 Game play

The game starts by having the users hit randomly-appearing targets somewhere within the cone of play. At randomly generated periods a series of targets appear that form a shape (or trajectory) that requires the participant to follow for maximum points. These shapes have been classed into difficulty levels (easy, moderate, and hard) by virtue of the complexity of the shape (straight vs. curved lines) and the planes of movement required to hit the targets agreed upon by experts in neck mechanics and rehabilitation. The shapes are scaled to the cone of play, such that a cone of play of size 'zero' (no neck movement available) has the shapes look essentially like a straight line, where a large cone of play (e.g., 110 degrees from center) requires the neck to make large end-range multiplanar motions. After each level of difficulty, the simulation presents the recalibration of ROM. If the user hits 5 consecutive spheres, the cone of play increases by 10 pixels until the participant cannot reliably hit 7 out of 10 consecutive targets at which point the cone shrinks back to the last size at which the user was successful. The next set of 2 shapes (medium difficulty) are then presented scaled to the cone of play based on the users' performance during the recalibration period. Following that is another round of calibration, then the hardest shapes. The game ends after the final recalibration of the ROM after the most difficult set of shape is presented.

3.5 Safety precautions

In order to ensure that users did not develop new or exacerbate existing neck pain or trauma, the gameplay was calibrated so that users never advanced to the next stage of the game at their highest ROM calibration. The targets that appear in form of shapes are scaled two levels below the maximum calibrated ROM (i.e., if the maximum ROM was determined to be at a Level 3, targets that are presented as shapes are presented at Level 1) until the next calibration phase where the ROM is assessed again. Figure 3-4 presents a diagrammatic representation of gameplay design.

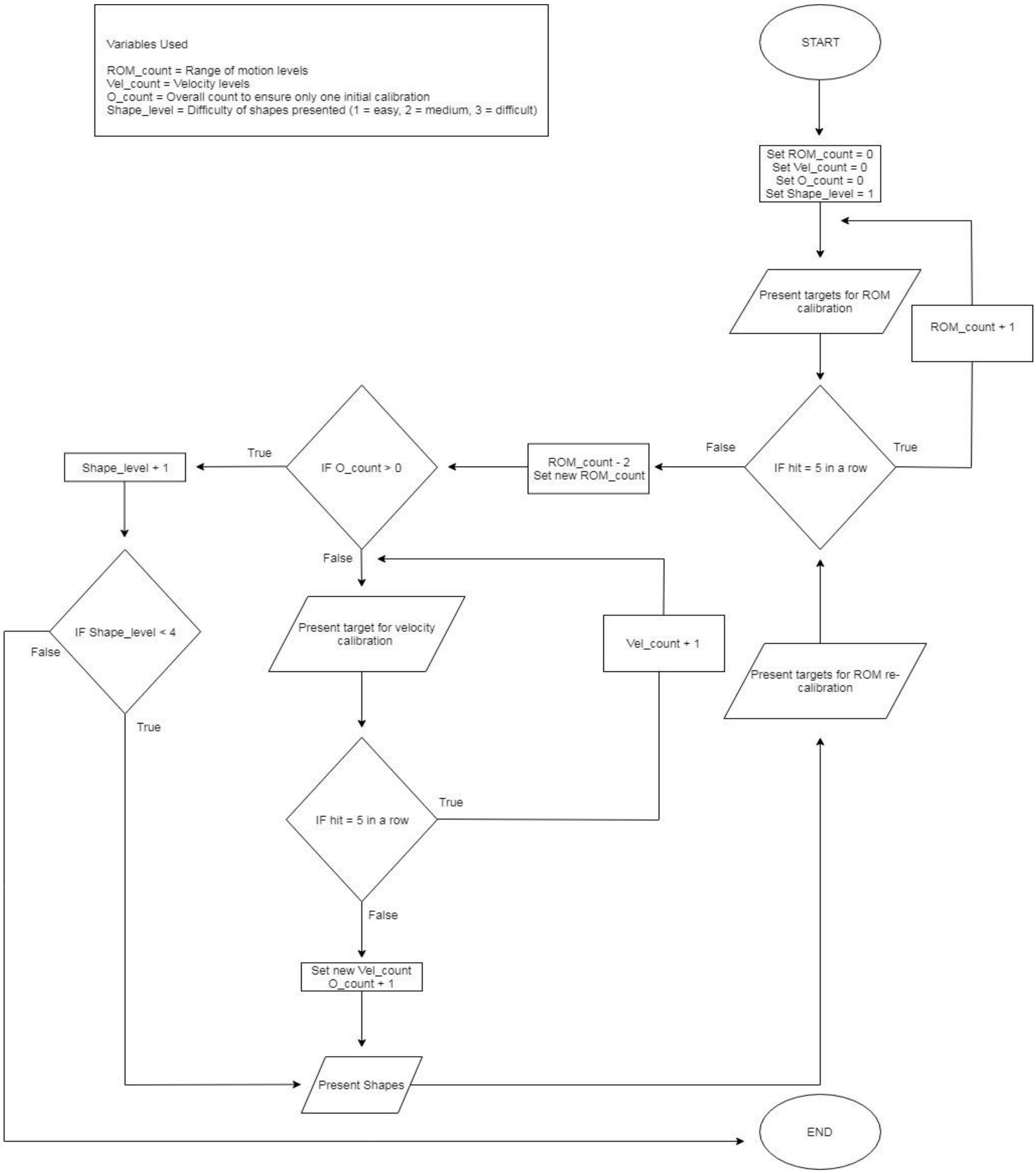

Figure 3-4: Process flowchart for gameplay design.

Chapter 4

4 Experimental Evaluation

4.1 Introduction

Neck rehabilitation presents a twofold problem for both patients and clinicians. The head and the neck tend to be difficult to rehabilitate due to the many complex, subtle movements associated with this multi-joint region. Additionally, the somewhat difficult, non-engaging and repetitive nature of strengthening or rehabilitation exercises often leads to boredom.[72]

Consumer-facing electronics, including those used for activity tracking, gaming, and mobile web access (e.g., smartphones) are nearing global saturation meaning almost every person now has at least one device with an embedded inertial measurement unit (IMU).[32] When combined with new and engaging user interfaces such as virtual or augmented reality, these accessible technologies hold considerable potential when applied to neck pain and rehabilitation. We have previously found that real-time movement analysis using a wearable IMU can provide richer detail in neck function and impairment than static end-range measurements, but this technology has yet to be translated into the clinic.[73]

As a step towards this, we have developed a new virtual reality (VR)-based video game that is designed to (i) allow clinicians to accurately quantify impairments in neck mobility, (ii) allow clinicians to quantify the effectiveness of prescribed exercise on those impairments, and (iii) be more engaging and intrinsically motivating for patients, with the goal of improving clinical outcomes. As it is indeed novel, safety and prudence dictated that we needed to first study the experience and performance of the new rehabilitation gaming platform in otherwise healthy people before implementing it in those with compromised necks who may be more vulnerable to symptom worsening or other adverse effects. Understanding ‘normal’ performance will also be critical for identifying ‘abnormal’ performance when we get to that point.

In Chapter 2, we identified movement accuracy as an outcome that has previously been associated with neck pain. We suspect that there may be other metrics that can be used to evaluate outcomes of neck-based interventions that we can capture from this new technology, but have yet to be explored in this population, including the area under the curve, and duration of play in a game that scales to performance. These metrics will be captured using the embedded sensors in the headset, software-based performance indicators, and custom-made algorithms. We will also capture metrics related to any adverse effects including dizziness, nausea or headaches in our healthy sample.

There are subsets of even the healthy population that either is unable to see in 3D VR due to depth perception problems or who experience VR motion sickness. This study will help us to identify and predict those who are *not* suitable for a VR-based intervention. These findings will be used to refine the protocol if necessary and set meaningful targets for comparison with a planned future clinical sample.

4.1.1 Aims, objectives, and hypotheses

The aim of this study was to capture information on the usability, feasibility, comfort, and the magnitude and consistency of 'normal' performance in healthy, pain-free participants. As a result, our intention was to address five research questions:

- What is ‘normal’ performance on the new VR system, in relation to the accuracy, magnitude, and duration?
- How stable are these metrics when tested again 5–7 days later? We hypothesized that these metrics should be stable across sessions.

- Was there a difference in accuracy across the difficulty of movement levels? We hypothesized that accuracy will decrease as difficulty increases.
- What is the 'average' experience of an otherwise healthy user? We hypothesized that there will be no severe adverse effects due to VR immersion.
- What is the influence of previous gaming experience on performance? We hypothesized that previous gaming experience may influence performance during the game.

4.1.2 Study design

This was an observational study design with both cross-sectional and repeated measures components. Game performance metrics (described below) were captured from a sample of 52 healthy adults in a single session and repeating the game on a second day, 5-7 days after the first. Participants provided verbal reports of the experiences during game including frequency/severity of any adverse events that they experienced (including dizziness, nausea, eye strain, or headache). We recruited primarily from students in a professional graduate degree program at Western (total population of 130) but also encouraged snowball sampling to recruit participants across the age range.

4.1.2.1 Sample size calculation

The sample size was estimated using the calculations provided by Walter and Eliasziw (1998) for reliability studies. Given two testing sessions, we estimated the mid-range reliability of ICC = 0.50. As we felt that a reliability estimates lower than ICC = 0.20 would indicate no clinical value, we chose a sample size that would provide 80% power for estimating an ICC of around 0.50 with a lower limit of the 95% confidence interval greater than 0.20. According to Walter and Eliasziw Table II (page. 106),[74] a total sample of 53 participants would satisfy these parameters.

4.1.2.2 Recruitment

Invitations to participate were disseminated through email and a dedicated Facebook group for each of the student cohorts currently enrolled in professional graduate programs at Western University. Flyers were also posted on Western's campus and email announcements were made via Western's Health and Rehabilitation Science weekly newsletters. Ethics approval for this study was obtained from the Western University Health Science Research Ethics Board (HSREB Project ID #112784)

4.1.2.3 Inclusion criteria

Males and females aged 18 years of age and above.

- A Brief Neck Disability Index (NDI-5) score less than 10% indicating no neck-related disability (score of $\leq 2/24$).[75]
- No self-reported history of neck pain requiring treatment, concussion, or other neck or vertebral trauma within the past 2 years.
- No self-reported history of ocular conditions such as amblyopia (lazy eye) and strabismus (cross eyes); congenital aphantasia (inability to visualize imagery); or stereoblindness (inability to perceive images spatially oriented in 3D).
- No history of migraines, benign paroxysmal positional vertigo (BPPV), eye saccades or other visual or movement-related disturbances.

4.1.3 Instrumentation

The project used an in-house designed VR simulation. The game required players to navigate a simple paper plane avatar through a nondescript environment using only head and neck movements

(Figure 3-3). Participants were required to hit objects (spheres) that appeared in front of them by moving their heads to guide the plane. The pattern of motion was pre-determined through standardized shapes established by the team of neck pain experts, though participants were unaware of the movements required. The system dynamically calibrated the size of the playing area (the ‘cone of play’) and the velocity of movement based on real-time performance - if five were hit consecutively the game area expanded. If 7 of 10 consecutive targets are missed, the game area contracted. The study used an Oculus Rift® headset to provide the VR experience. The Rift headset uses embedded motion sensors and optical sensors (stationary infra-red cameras) to capture motion through 6 degrees of freedom (pitch/yaw/roll and sagittal/transverse/horizontal translation).

4.1.4 Procedure

4.1.4.1 Screening

4.1.4.1.1 First pass screen

All participants were screened for neck pain or other related symptoms and ocular conditions using questionnaires. Participant metadata (age, sex, and email addresses), gaming, and previous VR experience were also be collected prior to VR immersion.

4.1.4.1.2 Second pass screen

The participants were then seated in front of a VR-enabled computer. Wide Velcro straps were firmly but comfortably secured across the lap and the thorax to limit motion captured to the neck. The Oculus Rift was then placed on the participant’s head and the simulation was started. Participants were immersed in ‘Oculus Dreamdeck’ a commercially available video simulation available for free on Oculus' native online marketplace. The simulation immerses players into a static virtual environment where events occur around them. The intention was for it to act as a tool to screen for depth perception problems as well as motion sickness. Following this, the participants were asked if they were able to appreciate the 3D; and if they had experienced any motion sickness or any other VR related adverse effects during the screening immersion. 'Oculus Dreamdeck' is developed by Oculus and contains content suitable for ages 13+.

4.1.4.2 Calibration

4.1.4.2.1 Measurement of Range of Motion (ROM)

After ensuring that they had not experienced any adverse effects, the participants were immersed in the in-house VR simulation. The simulation started with a brief calibration period that required participants to hit objects that appear near the edges of the cone of play, starting with a cone of 45 degrees out from the center of the field of vision. If the participant hit 5 consecutive spheres that are presented at a frequency of 1 per 3 seconds, the cone of play increased by 10 pixels. This continued until the cone of play was at a size beyond which the participant could not reliably hit at least 7 out of 10 consecutive targets.

4.1.4.2.2 Measurement of velocity

The second component of calibration used similar calculation metrics to assess the appropriate velocity of neck movement available to the participant, using the cone of play as established in step 1. The participant was required to hit objects that appeared in front of them. Every time the participants hit 5 objects in a row, the 'virtual' velocity at which the plane appears to move forward through the environment increased by 100 pixels per second, which in real-world terms increases the frequency at which the targets appeared thus requiring faster head movements to hit them all. This continued until the velocity was at a rate beyond which the participant could not reliably hit at least 7 out of 10 consecutive targets. At the end of the two calibration steps, the game began starting with the cone of play (range motion) and velocity of motion determined through the calibration.

4.1.4.3 Game play

Game play started by having the participant hit randomly-appearing targets somewhere within the cone of play. At randomly generated periods, a series of targets appeared that form a shape (or trajectory) that required the participants to follow, in order to achieve maximum points. These shapes were classed into difficulty levels (easy, moderate, and hard) by virtue of the complexity of the shape (straight vs. curved lines) and the planes of movement required to hit the targets.

4.1.4.4 Post-game play questionnaires

Following the game play, estimated to last approximately 15 minutes including the calibration stages, the participants were asked to fill out the Simulator Sickness Questionnaire (SSQ) to assess adverse effects of being immersed into the VR. They were also directly asked about their experience and any unpleasant side effects that they wished to report at that time. An email follow-up was sent the following day to ask about any latent adverse symptoms that may have arisen after leaving the lab. Participants were invited to return to the lab 3 to 5 days later to complete the exact same protocol but this time without the pre-screening and metadata forms, for a session lasting about 30 minutes total. All questionnaires are included in the appendices.

4.1.5 Outcomes

The performance was captured using the embedded Rift sensors and software running behind the scenes of the game. To optimize engagement and motivation, participants were presented with immediate feedback in terms of points based on accuracy drawn from the software.

4.1.5.1 Overall accuracy

Overall user accuracy was measured by recording the number of targets hit by the user and reported as a percentage of the total number of targets that were presented during the entire simulation.

4.1.5.2 Accuracy based on movement difficulty

User performance was measured by recording the number of targets hit by the user during the 3 levels of movement difficulty (easy, moderate and hard). This was determined in percentage by calculating the number of targets hit by the users from the total number of targets presented during each phase of game play.

4.1.5.3 Duration

The duration was measured as the user's total game play time. A higher duration would indicate better overall performance during game play. The duration was fixed during the play segments that were variable, but the calibration segments were variable. The longer the participant was in the calibration stage, meant the higher the stage they reached, and the better their performance.

4.1.5.4 Area Under the Curve

the total area under the curve was measured for the final ROM calibration phase after the hard movement session. This was achieved by first converting each *x* and the corresponding *y* coordinate, collected at 50 Hz, into vectors ($\sqrt{x^2+y^2}$). These vectors were then graphed in

MATLAB v2018b (The MathWorks Inc., Natick MA, United States), where movements during the various phases of the game were identified. Once the final ROM calibration phase was identified, the trapezoidal numerical integration (`trapz`) function was used to obtain the area under the curve for the phase (Figure 4-1).

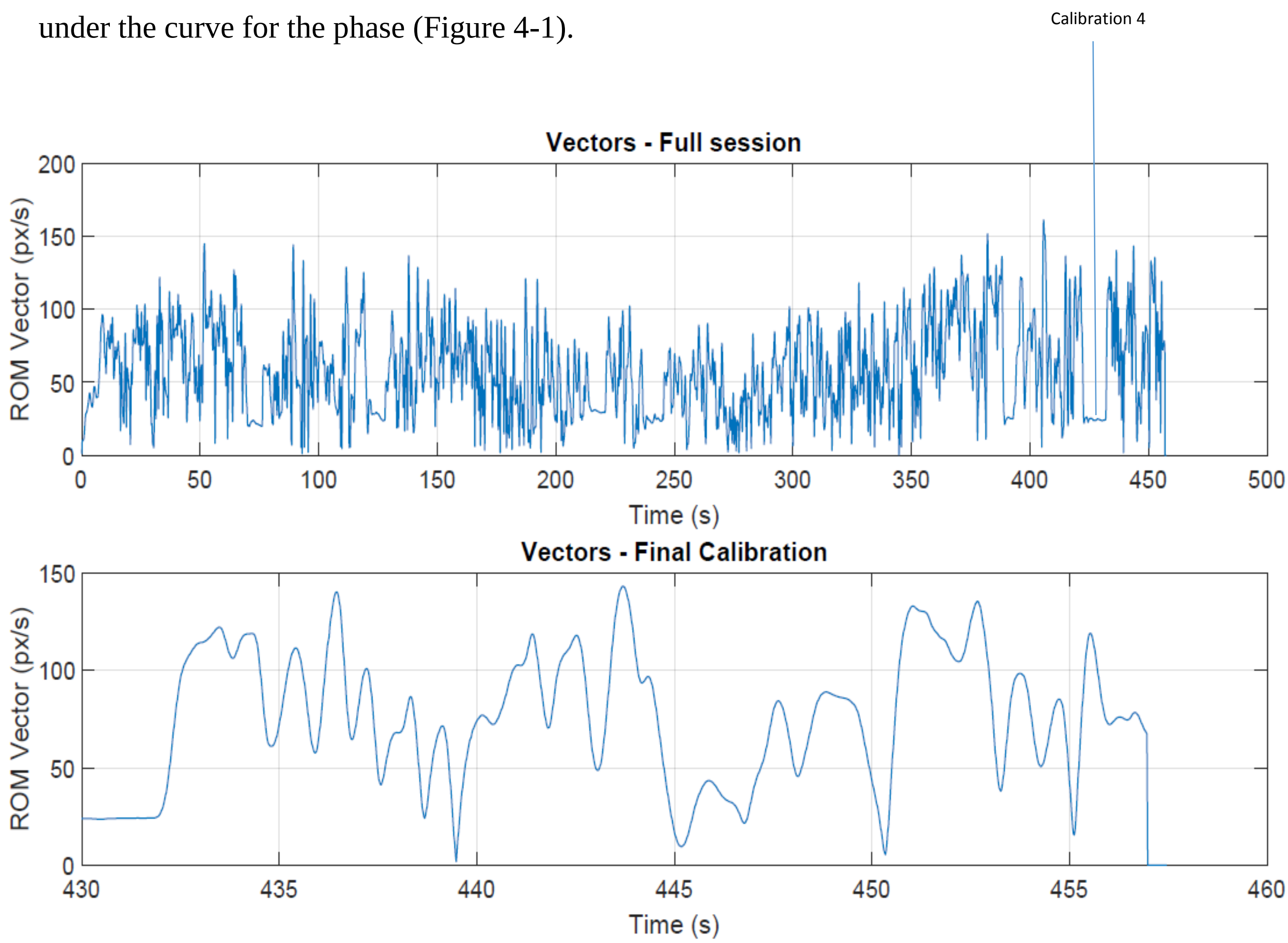

Figure 4-1: Above: Representation of ROM during the full session. Below: Representation of ROM movement during the final calibration phase.

Overall, the design and development of the custom-built VR software was a result of significant collaboration between applied engineering and health science researchers in an effort to ensure that the developed product had clinical relevance and maintained industry-standard programming, graphic quality, and gamification principles. Using this software, we recorded four metrics in healthy participants: overall accuracy of movement, the accuracy of movement at various levels of difficulties, duration of total game play, and area under the curve of total movement.

4.2 Results

Adherence can have a significant impact on the success and outcome of prescribed treatment. Neck rehabilitation, however, is difficult to perform and this combined with the non-engaging nature of prescribed exercises makes neck rehabilitation challenging. Ubiquitous and consumer accessible technologies such as video games and virtual reality (VR) can allow clinicians to address both of these problems. As a step towards this, we have developed a new VR-based video game that is designed to (i) allow clinicians to accurately quantify impairments in neck mobility, (ii) allow clinicians to quantify the effectiveness of prescribed exercise on those impairments, and (iii) be more engaging and intrinsically motivating for patients with the goal of improving clinical outcomes. We have identified the accuracy of movement, area under the curve, and the duration of play (an amalgam of accuracy and mobility performance) as variables to examine. As such, the aim of this initial study was to capture information on the magnitude and consistency of 'normal' performance, as well as to capture information on the usability, feasibility, and comfort in healthy, pain-free participants.

4.2.1 Methods

A total of 52 participants with healthy necks were recruited for the study. Participants were immersed in a VR-based video game to capture overall accuracy of movement, the accuracy of movement at various levels of difficulties, duration, and area under the curve. Data from two participants were excluded, as follows: one indicated an NDI score above the set inclusion criteria, while the other was unable to complete the tasks during the game due to difficulties with depth perception. As the intention was to estimate normative values, any data that were three or more standard deviations outside the mean were excluded from the analyses, and instead those participants were examined separately for any indications of why the performance was so far away from the rest of the sample.

4.2.2 Statistical Analyses

Participant responses to the baseline self-report tool, including demographics and prior gaming experience, were summarized descriptively (mean, median, range).

Question 1 (normative performance): I first explored the data for deviations from normality using a Shapiro-Wilks test. Where data were not normally distributed, a square root transformation was applied that resulted in adequately normal distributions for all primary variables. Means, standard deviation, range, and 95% confidence intervals were calculated for each of the primary outcomes (overall accuracy, accuracy by difficulty level, the total envelope of movement during play session 3, and the total duration of game play).

Question 2 (test-retest reliability): I first conducted a paired sample t-test analysis between the two sessions to provide context to the subsequent analysis. Then intra-class correlation coefficient (ICC) $\text{Type}_{2,1}$ was used to estimate chance-corrected agreement between the two testing days for each of the 6 metrics. To estimate sample size, I predicted an agreement of approximately $ICC_{2,1} = 0.50$ and together with the research team deemed that a value < 0.20 would not be clinically useful. Following the calculations provided by Walter and Eliasziw (1998),[74] a sample of n = 53 participants would be adequately powered to identify an ICC of 0.50 and to provide confidence that it is statistically greater than 0.20. ICCs were interpreted according to Koo as: <0.50 = poor reliability, 0.5 to 0.75 = moderate reliability, 0.75 to 0.90 = good reliability, >0.90 = excellent reliability.[76]

Question 3 (comparison of accuracy differences across difficulty levels): A repeated-measures analysis of variance (RM ANOVA) was calculated to compare mean accuracy during movement at the various levels of difficulty for the first session only, where shape (easy, medium, hard) was the repeated factor and accuracy (percent of targets hit within each shape) was the dependent variable. The Mauchly's sphericity test was used to check if the variance of the differences between the levels of movement difficulty were equal to test assumptions of RM ANOVA. Significant differences ($p < 0.05$) were further explored using a paired-samples t-test with Bonferroni correction for multiple comparisons ($p = 0.05/3 = 0.02$).

Question 4 (exploration of the association between performance and gaming experience): A one-way analysis of variance (ANOVA) was used to explore the difference in overall accuracy by the level of prior gaming experience. The Shapiro-Wilk tests of normality of residuals and Bartlett's test for homogeneity of variance were used to test assumptions of ANOVA. Significant main effects were further explored using Tukey's posthoc test.

Question 5 (average experience of VR immersion): Scores on the SSQ and Post-test SSQ were explored descriptively (frequencies) in Microsoft Excel. Statistical significance was set at 95% ($p < 0.05$). All statistical analyses were performed in Software for Statistic and Data science v. 13 (StataCorp LLC, College Station TX, United States).

4.2.3 Results

Data on population characteristics and their gaming and VR experience is presented in Table 2.

Table 2: Population characteristics, gaming, and VR experience.

	Characteristics	Sample
Population characteristics	Age in years (Mean (SD), Range)	25.2 (3.8), 18 - 36
	No. of females/males	24 / 26
	NDI score (Mean, (SD), Range)	0.2 (0.6), 0-2
Gaming experience	Never	58.0%
	A few days or less	28.0%
	Most days	12.0%
	Every day	2.0%
VR Experience	Never	42%
	Once/twice	50%
	A bit	8%

The results of Question 1 (normative data), standard deviations, and mean differences are reported in Table 3. The results demonstrate a significant difference in the means of duration, accuracy during hard movements, and area under the curve, while no difference was observed in overall accuracy and accuracy during easy and during moderate movements. ICC (test-retest) analysis between two sessions demonstrated poor reliability (< 0.5) for overall accuracy, accuracy during easy, moderate, and hard movements, duration, and area under the curve, though only the latter two demonstrated statistical significance.

Table 3: Mean scores and their standard deviations, mean differences and ICC (2,1) for all outcomes for both sessions (* indicates sig. < 0.05, ** indicates sig. < 0.001)

Outcomes	**Session 1 [Mean (SD), CI]**	**Session 2 [Mean (SD), CI]**	**Mean Difference (CI)**	**ICC $_{(2,1)}$ (95%CI)**
Overall accuracy (%)	58.7 (4.8), 47.1 - 68.4	59.8 (3.8), 51.5 - 68.9	1.1 (-0.23, 2.43)	0.2 (-0.3, 0.3)
Accuracy easy (%)	63.5 (14.5), 31.9 - 89.3	59.6 (10.5), 39.6 - 92.9	-3.9 (-7.9, 0.1)	0.2 (-0.1, 0.4)
Accuracy moderate (%)	54.2 (9.5), 31.9 - 71.9	50.5 (9.9), 22.4 - 66.2	-3.7 (-7.7, 0.3)	0.0 (-0.4, 0.2)
Accuracy hard (%)**	57.4 (9.1), 37.0 - 79.2	52.1 (8.8), 29.9 -69.8	-5.3 (-9.3, -1.3)	0.0 (-0.4, 0.1)
Duration (s)*	560.2 (212.9), 301 - 1143	683.4 (219.4), 328 - 1097	123.2 (119.2, 127.2)	0.5 (0.2, 0.7)
Area under curve (px)**	335389.5 (353781.6) 2349.8 - 1663900	497870.6 (426040.2), 4458.1 - 1933300	162481.1 (162477.1, 162485.1)	0.3 (0.0, 0.5)

Repeated measures ANOVA (association between accuracy and difficulty of movement) demonstrated a significant association between difficulty levels on participant accuracy performance (Wilk's Lambda = 0.49, F (2,48) = 24.60, $p < 0.05$). Further paired sample t-tests were used to make post hoc comparisons between difficulty levels. Results demonstrated significant difference between accuracy during easy and moderate [t (49) = 5.39, $p < 0.05$]; and easy and hard difficulty levels {session 1: [t (49) = 2.81, $p = 0.01$] while no statistically significant difference was observed between accuracy during moderate and hard movements. (Figure 4-2).

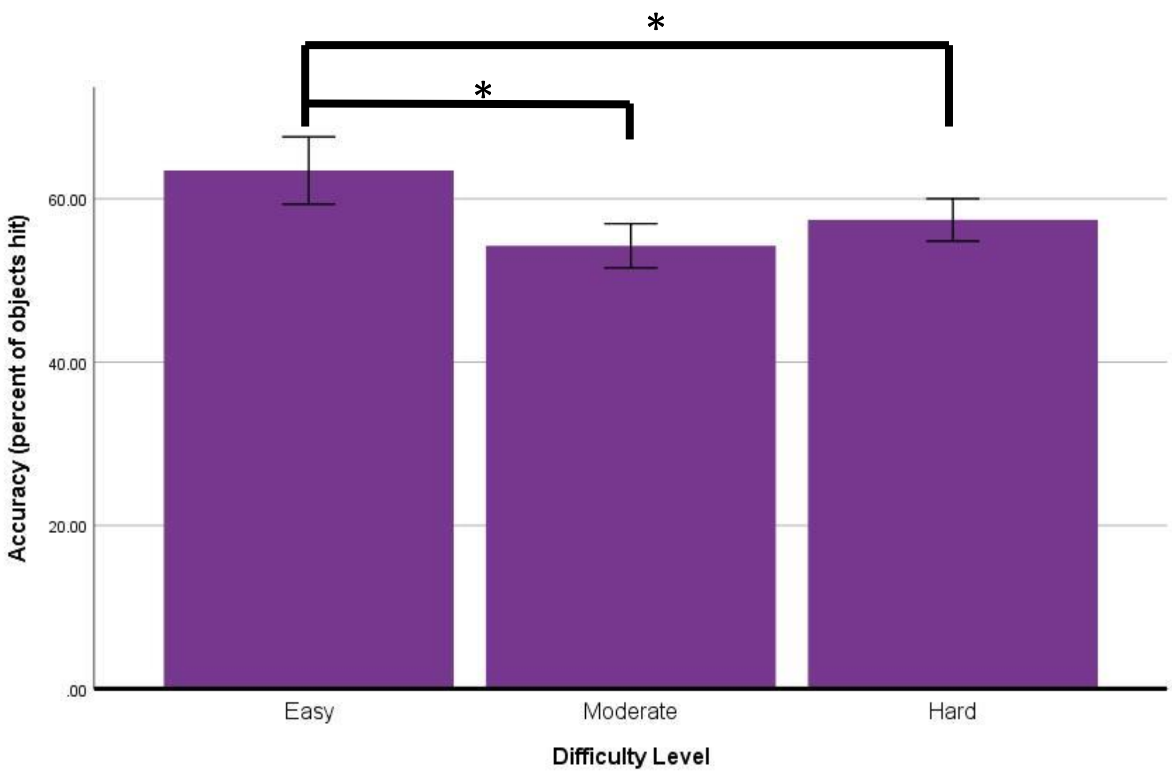

Figure 4-2: Results for paired-sample t-tests between levels of difficulty and overall accuracy for the first session. (* indicates sig. < 0.05)

The one-way ANOVA (comparison of overall accuracy and gaming experience) demonstrated no significant effect of prior gaming experience on overall accuracy performance during game play, Session1: [F (2,66) = 0.47]; Session 2: [F (3,46) = 0.30] Finally, all symptoms, their severity, and their incidence are reported in Table 4. No participants reported any severe adverse effects, four reported moderate adverse effects immediately after VR immersion; and three reported moderate adverse effects 24 hours post VR immersion.

Table 4: Simulator sickness symptoms as reported by the participants.

	Post-protocol				24h Post-protocol			
Symptoms	**None**	**Slight**	**Moderate**	**Severe**	**None**	**Slight**	**Moderate**	**Severe**
General discomfort	84.0%	16.0%	-	-	86.0%	14.0%	-	-
Fatigue	88.0%	12.0%	-	-	86.0%	14.0%	-	-
Headache	98.0%	2.0%	-	-	90.0%	10.0%	-	-
Eye strain	78.0%	20.0%	2.0%	-	90.0%	8.0%	2.0%	-
Difficulty focusing	94.0%	6.0%	-	-	92.0%	8.0%	-	-
Salivation increase	96.0%	4.0%	-	-	98.0%	2.0%	-	-
Sweating	82.0%	16.0%	2.0%	-	100.0%	-	-	-
Nausea	96.0%	4.0%	-	-	96.0%	4.0%	-	-
Difficulty concentrating	94.0%	6.0%	-	-	92.0%	8.0%	-	-
Fullness of head	84.0%	14.0%	2.0%	-	90.0%	6.0%	4.0%	-
Blurred vision	96.0%	2.0%	2.0%	-	96.0%	2.0%	2.0%	-
Dizziness with eyes open	98.0%	2.0%	-	-	98.0%	2.0%	-	-
Dizziness with eyes closed	98.0%	2.0%	-	-	100.0%	-	-	-
Vertigo	100.0%	-	-	-	100.0%	-	-	-
Stomach awareness	96.0%	4.0%	-	-	98.0%	2.0%	-	-
Burping	100.0%	-	-	-	100.0%	-	-	-

4.3 Discussion

Neck pain is a major global public health concern and results in significant costs to the healthcare system as well as the people that suffer from it. Unlike other diseases, neck pain presents unique challenges to both the clinician and the patients. From the clinicians' perspective, the head and the neck tend to be difficult to rehabilitate due to many complex and subtle movements associated with this region. Furthermore, the traditional means and tools available to most clinicians, compound the problems of evaluation and management of neck pain. From a patient's perspective, the subtle, non-engaging and repetitive nature of neck rehabilitation exercise seem to lead to difficulties with adherence. Consumer-facing activity tracking electronics, such as VR, hold considerable potential when applied to neck rehabilitation, as they are inexpensive and readily available. Integrating video games with VR technology may hold the answer to the question of solving challenges with neck rehabilitation.

With this in mind, we developed a virtual reality-based video game that would (i) allow clinicians to accurately quantify impairments in neck mobility, (ii) allow clinicians to quantify the effectiveness of prescribed exercise on those impairments, (iii) provide greater control over the parameters of gameplay to adapt to neck impairments, and (iv) be more engaging and intrinsically motivating for patients with the goal of improving clinical outcomes. Prior to moving this new technology into clinical practice, a number of questions needed to be explored.

In this study, I explored normative performance outcomes, specifically accuracy, the difficulty of movement-based accuracy, area under the curve, and duration, of a custom-made virtual reality-based video game that was developed to help solve both clinician and patient challenges in neck rehabilitation. The results of these investigations, as presented in Table 3, are expected to provide important guidance for future research on this platform, with particular value for comparing the performance of future clinical samples against these normative data from otherwise healthy participants. Next, I investigated the stability of these outcomes over time and found generally poor consistency for all metrics. I then explored the construct validity of assigning difficulty to the different gameplay sections (easy, moderate, hard) by comparing accuracy differences across the levels, under a hypothesis that accuracy should decrease as difficulty increased. The results partially supported these assertions, as I observed significant differences in accuracy between the easy and moderate, and easy and hard difficulty levels, but no difference between the moderate and hard levels. Next, I explored the association between performance during the prototype game and past gaming experience and observed no significant effect of prior gaming experience performance. Finally, I explored user experiences in the VR environment with a specific focus on adverse reactions and observed no severe adverse effects in this healthy population. All symptoms and their incidence are reported in Table 4.

In Question 1, performance metrics for overall and difficulty-based accuracy, duration, and area under the curve in the third calibration phase of the video game were explored in a sample of 50 healthy volunteers. Using the sensors onboard the Oculus Rift headset I was able to extract the total motion envelope using an area under the curve metric. The software then provided additional metrics: accuracy (proportion of targets successfully hit) and the total duration of gameplay. Through the design of the software, both motion envelope and accuracy were a factor of individual performance, in that those participants who continued to hit 5 out of 5 targets during the calibration phase, had their cone of play dynamically increase to the point that they were unable to hit 7 of 10. As such, those who performed better during the calibration phases would have then been presented with greater difficulty (larger cone of play) during the phases, and their overall duration of gameplay would have increased. These metrics were deemed important owing to prior research indicating that people with neck pain also present with a reduced cervical range of motion and reduced accuracy of movement, as usually measured through joint position sense error.[15,77,78] The research team agreed that these metrics were most likely to indicate impairment in people with neck pain, and were most likely to show improvement with effective treatment. Total duration was an amalgam of both mobility and accuracy, and as such can be conceptualized as an omnibus indicator of overall performance. The normative data indicate a skewed distribution of the data suggesting that future researchers should carefully evaluate data normality prior to conducting statistical analyses. As the software was custom-designed by our team for this study, there are no meaningful prior studies against which to compare the results.

In Question 2, I evaluated the stability of the metrics from Question 1 across two different testing sessions. This important measurement property should be established in order to provide meaning to change in the scores if the VR system is to be used as a tool for evaluating treatment effectiveness. That is, it is important to understand how stable the metrics are, or how much noise is in the system, to determine the degree to which changes in the scores are large enough to indicate real change beyond random error. Our findings demonstrate poor reliability for all measures, and the data obtained between the two sessions were not similar. Significant improvements were observed in the second session for the duration and area under the curve, while overall accuracy demonstrated no improvement. We attributed this improvement to the learning effect – the past experience of the gaming system and VR would have a positive influence on these outcomes. While a direct comparison of our custom-built software is unavailable, our results were contrary to prior studies that have reported stability across testing sessions, albeit in different outcomes. Lack of stability may be the result dynamic calibration property of the software. As the difficulty of movement was dynamically adjusted based on performance during the calibration phase, better performance during the calibration phases of the video game (by virtue of higher duration of game play as a consequence of the learning effect) resulted in a more challenging trajectory that required greater head movement (as observed by the greater area under the curve for the final calibration).

In Question 3, I tested the hypothesis that, if the difficulty in the 'movement shapes' (target trajectories) was indeed ordered as we thought – from easy, to moderate, to hard by virtue of the complexity of neck motions required for success – then accuracy should decrease as the difficulty level increased. Movements in the easy phase were limited to flexion/extension and rotation planes only; while moderate and hard difficulties consisted of multi-planar movements making accuracy harder to achieve. Accuracy was highest when the easy movement shapes were presented, being significantly greater than both moderate and hard movement shapes. We expected similar trends in performance in the overall accuracy of the moderate and hard phases of the game. However, the result indicated no significant difference in the accuracy between those two phases of the game. This would suggest that there may not have been a difference in difficulty between the two levels, and may need to be re-designed to increase movement difficulty in the hard phase.

In Question 4 I explored if past gaming experience on dedicated gaming consoles influences gaming performance. The genesis of this research question was motivated by the research team's desire to ultimately make this tool available to people of all demographics, and that participants that do not play video games would not be at a disadvantage when using this software. Contrary to previous research that has reported a positive association between gaming experience and gaming performance,[79] our results demonstrate that performance did not differ in people that had no gaming experience in comparison to those with various degrees of experience. This would support that this custom-built software may be appropriate for people of all demographics. Though our sample did not include any participant over the age of 36, we hope that the ease of gameplay will result in an increased self-efficacy in the older demographic. Research on technology adoption in older adults has reported a positive impact on longer-term technology adoption.[80]

Finally, in Question 5, I explored the average adverse effects of VR immersion. The Simulator Sickness Questionnaire (SSQ)[81] is commonly used to assess the subjective severity of simulator sickness (SS) – a syndrome that can be experienced as a side effect during and after exposure to the VR environment.[82] Items on the SSQ symptoms are traditionally grouped into three factors (nausea, oculomotor disturbance, and disorientation) and overall scores are calculated as an indicator of total severity.[82] Instead of going the traditional route, we examined the symptoms of SS independently to critically evaluate the usability and feasibility of this custom-built software. Our results demonstrate no severe adverse effects of simulator sickness in any participants both post-session and 24-hours post-session. Eye strain had the highest reported incidence, followed by general discomfort, and sweating immediately post protocol. Gameplay was fairly intense at higher levels, which might account for sweating. General discomfort and fatigue had the highest reported incidence 24-hours post-protocol, followed by headache. Tyrrell and colleagues also explored the incidence of simulator sickness 24-hours post protocol in a group of 32 participants with no neck pain while they played a video game that required them to move their heads to hit targets. In their study, no participants reported any symptoms of SS 24 hours post-protocol.[83] In comparison, 38% of people in our study reported at least one SS symptom after 24 hours. The reasons for the difference are difficult to determine through the nature of the studies, though could be due to the many factors that may impact the onset and severity of SS, including graphic quality, immersion time, motion sickness susceptibility, and the feeling of presence or "being there".[38,83,84]

4.3.1 Real-world solution: what do the results imply?

The implications of this study can be split twofold. First, the appropriateness of the use of the outcomes (accuracy, the difficulty of movement-based accuracy, duration, and total envelope of movement) in neck rehabilitation (Questions 1-3). Accuracy and total motion (or ROM) have previously demonstrated relevance in the evaluation and assessment of neck rehabilitation.[77,85] Further research may be required to investigate the cause of the lack of stability across sessions in these outcomes. Duration is a novel outcome that we explored in this study, and we suspect that the outcome may be different in a clinical population. Previous research on the accuracy of head movement as an outcome for neck rehabilitation has demonstrated reduced accuracy,[86] and improved accuracy post-intervention,[87] in people with neck pain. While more research is required, at the very least, duration and accuracy in a single plane of motion may assist clinicians to use these outcomes to correctly identify those with (sensitivity) or without (specificity) neck pain or mobility issues.

The second implication of this study is the overall acceptability of this VR-based gamified rehabilitation software (Questions 4-5). Our results demonstrate that individuals with no prior gaming experience on a dedicated gaming console had results that were similar to those with various degrees of gaming experience. We suspect that the ease of use of the system makes it a feasible tool to be used by people of all ages and levels of gaming experience. The results also demonstrate no significant adverse effects of VR immersion in the sample population. Previous research in the field of VR has demonstrated a negative association between the feeling of presence or immersion (subjective feeling of being in a VR)[88] and simulator sickness.[84] As the feeling of presence is affected by graphics quality and head mounted devices (HMD), we suspect that the advancement in VR technologies may further help reducing symptoms of simulator sickness.

4.3.2 Limitations and further research

Limitations of this study can be distinguished between research methodology and limitations in the design and development of this custom-build VR software. From a research methodology standpoint, this study failed to establish any stability in the outcomes across both sessions. This may be due to the learning effect, as participants became acclimated to the game and VR scenario. Furthermore, we suspect that some participants might have adopted strategies to exert themselves to a lesser degree a second time around, resulting in a lack of stability across sessions. The study also used snowball sampling as a recruitment strategy, and therefore may have resulted in sampling bias. As a result, only individuals who knew could tolerate VR (or at least didn't know they couldn't) would have volunteered. Therefore, estimates of adverse effects are likely not representative of the entire population.

From a design and development point of view, further development of back-end data collection platform to include customizability options, so that outcomes may be captured during select or all phases of the game. Next, calibration and measurement of ROM (currently measured in pixels) must be assessed and measured in degrees in order to be compared to industry gold standards and measure clinical significance. Participants also complained of difficulty in assessing target location in the VR and thus benefitting from line rendering (tracking guide to the next target) to make gaming easier. Additionally, occasional glitches occurred where a target appeared outside of the maximum range that a neck could move, meaning that target could not possibly be hit without moving the thorax, which in this case, was fixed with a belt. Finally, an overall improvement in gamification features would help increase participant enjoyment, while improved graphic quality should improve the feeling of presence, and subsequently reduce adverse simulator sickness symptoms.

The next steps in this line of research will be to use this custom-built VR software to capture conventional outcomes such as ROM, velocity, acceleration, and smoothness in the hopes of validating its potential as a tool for clinicians to use in the measurement and evaluation of neck pain.

Chapter 5

5 Conclusion

Neck pain is a major global public health concern and adds a significant financial burden to both the healthcare system as well as people suffering from it. Additionally, it presents measurement and evaluation challenges for clinicians, as well as adherence challenges and treatment barriers for the patients. Virtual reality has shown a considerable advantage over conventional assessment when used in neck rehabilitation. Combined with intrinsically motivating tools such as video games, the amalgamation of these two technologies could potentially mitigate the challenges and could potentially be used as a tool for neck rehabilitation. In this thesis, I explored the difficulties associated with neck pain and rehabilitation, both for clinicians and people suffering from it. I then investigated the use of VR technology in neck rehabilitation to date through an exhaustive scoping review. Next, we presented the design and development of the video game and the gamification principles behind it. Finally, we explored and presented the results of preliminary evaluations of gameplay performance, measurement, and experience in people without current neck pain.

This project was a result of significant collaboration between health science researchers as well as engineers. Health science researchers on the team ensured clinical relevance of the software and the outcomes measured, while the engineers ensured that the video game maintains industry-standard programming. The health science researchers on the team had software development experience and understood the capabilities and limitations of the code developed. A lesson learned as a result of this study was that the awareness of these capabilities and limitations allowed for better interdisciplinary cooperation within the research team.

To our knowledge this project represents one of the few collaborations between engineers and health science researchers working on harnessing and developing consumer-facing VR exergame for neck rehabilitation. As such, the contribution of this project to knowledge includes template for future exergame development, including game design decisions that may be used for future rehabilitation based exergames. As our results demonstrated poor reliability and noise, future researchers and developers will have to account for them if the intention is to track changes over time.

The combination of VR and gamification may have the potential for significant impact in the areas of chronic pain management, measurement, and evaluation. As the costs associated with VR technology decrease, and the flexibility and customizability of the gaming environment increases, it has the potential to become part of healthcare provider and clinician's toolkits and be integrated into a variety of medical settings for routine and painful procedures, physical therapy, pain rehabilitation, and chronic pain management. The results of this research will be a stepping-stone for the future, with the aim of creating a gaming platform that can be made available to other clinical and basic science research groups who wish to create specific games for different neck associated conditions.

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Appendices

Appendix A. Scatterplots of the performance values for all study participants in Session 1 and Session 2

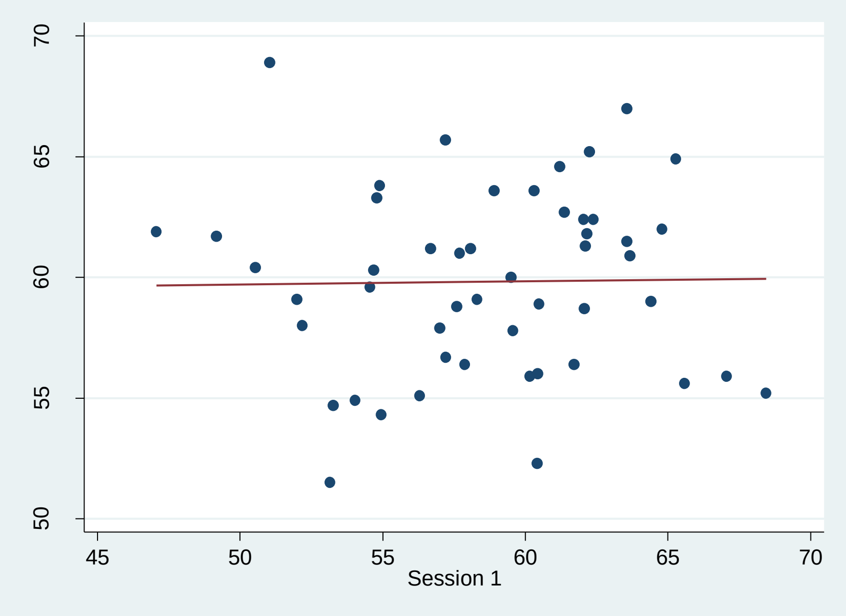

Figure A: Performance values for overall accuracy in Session 1 and 2

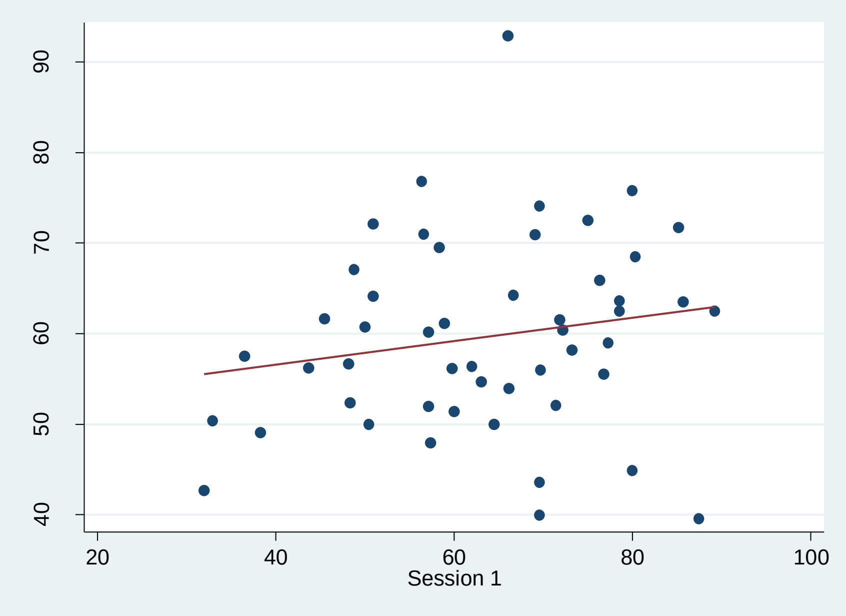

Figure B: Performance values for easy movements in Session 1 and 2

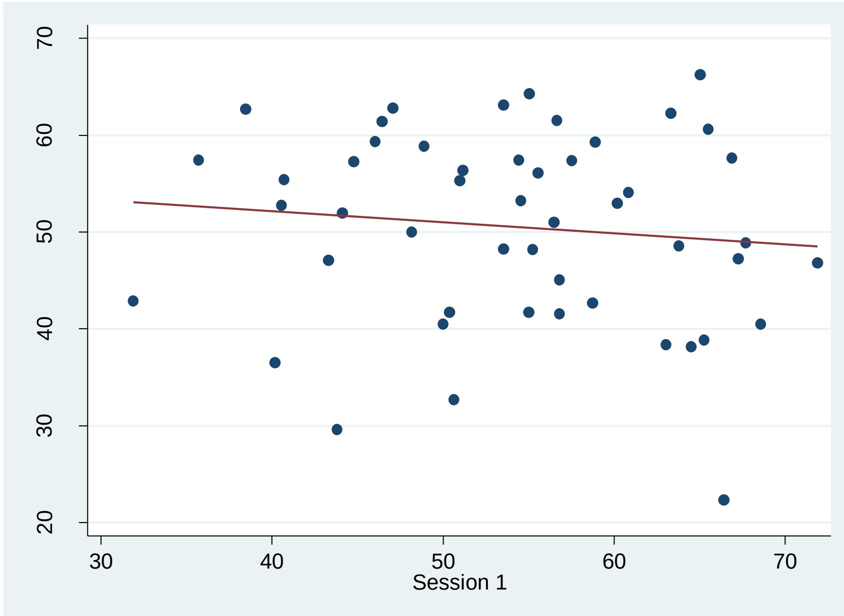

Figure C: Performance values for moderate movements in Session 1 and 2

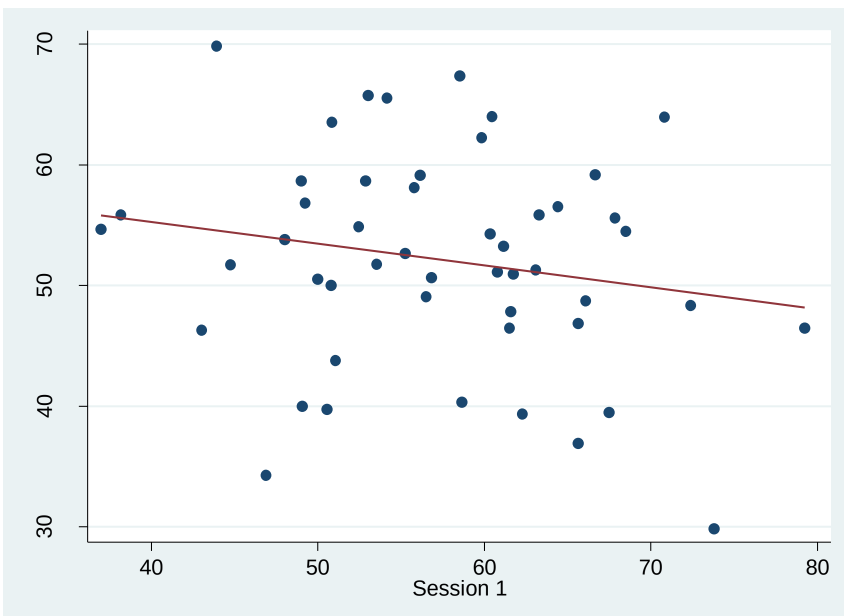

Figure D: Performance values for hard movements in Session 1 and 2

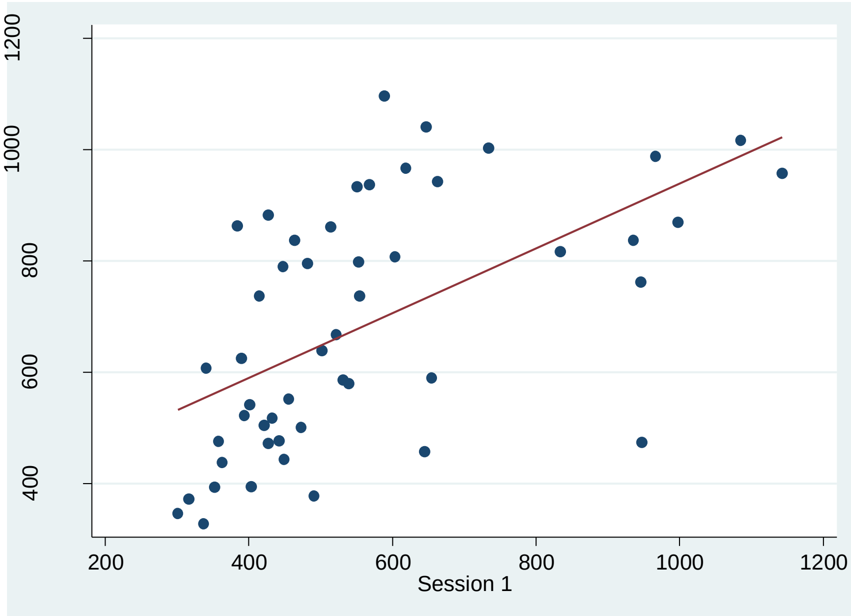

Figure E: Performance values for duration in Session 1 and 2

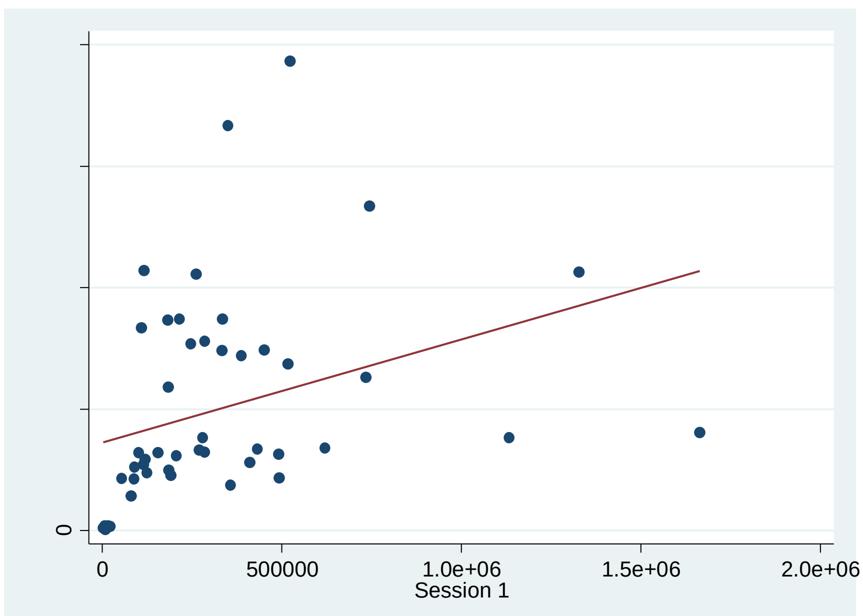

Figure F: Performance values for area under the curve in Session 1 and 2

Appendix B. Ethics Approval

Western Research

Date: 7 December 2018

To: Dr. Dave Walton

Project ID: 112784

Study Title: Quantifying Normal Performance Metrics of a Neck Rehabilitation Video Game in Asymptomatic People

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 18December2018

Date Approval Issued: 07/Dec/2018 09:44

REB Approval Expiry Date: 07/Dec/2019

Dear Dr. Dave Walton

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Flyer	Recruitment Materials	28/Nov/2018	2
General Information Questionnaire (DW)	Paper Survey	16/Oct/2018	1
Inquiry Email	Email Script	29/Nov/2018	1
LOI - Asymptomatic	Written Consent/Assent	03/Dec/2018	3
NDI-5	Paper Survey	16/Oct/2018	1
Post Study Questionnaire	Online Survey	16/Oct/2018	1
Post-protocol Email	Email Script	29/Nov/2018	1
Presence Questionnaire	Paper Survey	16/Oct/2018	1
Recruitment Email	Email Script	29/Nov/2018	1
Simulation Sickness Questionnaire	Paper Survey	16/Oct/2018	1
Study Protocol - Final	Protocol	16/Oct/2018	1

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
Ethics FlowChart	Flow Diagram	29/Nov/2018	2

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

Appendix C. General information questionnaire

General Characteristics

Year of Birth: __________ Month of Birth: __________

Sex: ◯ Male ◯ Female ◯ Other or prefer not to say

Indicate how often you play video games for recreation on a weekly basis using any of the following platforms:

	Never	A Few Days or Less	Most Days	Every Day
A dedicated 'gaming' system (e.g. Xbox, PlayStation, Switch)				
A personal computer				
A tablet, smartphone or other portable device				
Something else (e.g. Smart TV, Android or related box, Apple TV, etc..)				

What is your experience using a Virtual Reality device?

- ☐ I've never used Virtual Reality before
- ☐ I've used it once or twice
- ☐ I've used it quite a bit
- ☐ I consider myself a 'hardcore' frequent VR user

Medical History

1. Have you had neck pain requiring treatment, concussion, or other neck or vertebral trauma within the past 2 years?

◯ Yes ◯ No

2. Do you have a history of migraines, vertigo (BPPV), eye saccades or other visual or movement-related disturbances?

◯ Yes ◯ No

3. Do you have one of or a combination of amblyopia (lazy eye), strabismus (cross eyes), congenital aphantasia (inability to visualize imagery), or stereoblindness (inability to perceive images spatially oriented in 3D)?

◯ Yes ◯ No

4. Do you tend to experience motion sickness while traveling in a vehicle (car, train, bus, plane or boat)?

◯ Yes ◯ No

Appendix D. NDI-5

NECK DISABILITY INDEX - 5

Please rate the intensity of any neck pain you are experiencing *right now* with 0 = no pain, 10 = extreme pain

1	2	3	4	5	6	7	8	9	10

Person care

- ◯ I can look after myself normally without causing extra pain
- ◯ I can look after myself normally but it causes extra pain
- ◯ It is painful to look after myself and I am slow and careful
- ◯ I need some help but manage most of my personal care
- ◯ I need help every day in most aspects of self-care
- ◯ I do not get dressed, I was with difficulty and stay in bed

Concentration

- ◯ I can concentrate fully when I want to with no difficulty
- ◯ I can concentrate fully when I want to with slight difficulty
- ◯ I have a fair degree of difficulty in concentrating when I want to
- ◯ I have a lot of difficulty in concentrating when I want to
- ◯ I have a great deal of difficulty in concentrating when I want to
- ◯ I cannot concentrate at all

Work

- ◯ I can do as much work as I want to
- ◯ I can only do my usual work, but no more
- ◯ I can do <u>most</u> of my usual work, but no more
- ◯ I cannot do my usual work
- ◯ I can hardly do any work at all
- ◯ I can't do any work at all

Driving / Riding in a vehicle

- ◯ I can drive/ride in a vehicle without any neck pain
- ◯ I can drive/ride in a vehicle as long as I want with slight pain in my neck
- ◯ I can drive/ride in a vehicle as long as I want with moderate pain in my neck
- ◯ I can't drive/ride in a vehicle as long as I was because of pain in my neck
- ◯ I can't drive/ride in a vehicle at all

Recreation

- ◯ I am able to engage in all of my recreation activities with no neck pain at all
- ◯ I am able to engage in all of my recreation activities with some pain in my neck
- ◯ I am able to engage in most, but not all, of my usual recreation activities because of my neck pain
- ◯ I am able to engage in a few of my usual recreation activities because of pain in my neck
- ◯ I can hardly do any recreation activities because of pain in my neck
- ◯ I can't do any recreation activities at all

Appendix E. Simulator Sickness Questionnaire

SIMULATOR SICKNESS QUESTIONNAIRE

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Curriculum Vitae

Name:	Shahan Salim
Post-secondary Education and Degrees:	University of Toronto Toronto, Ontario, Canada B.Sc. (2015)
	Western University London, Ontario, Canada M.Sc. (2019)
Honours and Awards:	Applied Health Science Graduate Scholarship University of Waterloo Graduate Research Scholarship Collaborative Specialization in Musculoskeletal Health Research (CMHR) Fellowship Western Graduate Research Fellowship
Related Work Experience	Teaching Assistant (OT9663 & OT9642) Western University 2017-2019

Publications:

Shahan Salim, Michael J Lukacs. (2018). A Call for Interdisciplinary Collaboration between Video Game Designers and Health Care Professionals to Fight Obesity. Health Science Inquiry

Michael J Lukacs, **Shahan Salim** (2018). Exploring Immersive Technologies: The Potential for Innovation in Whiplash Research. Health Science Inquiry

Shahan Salim, Iyad Al-Nasri (2018). Using Gamification to Break Barriers to Adherence in Physical Therapy. Health Science Inquiry

David Walton, James Elliott, **Shahan Salim**, Iyad Al-Nasri. (2017). A reconceptualization of the Pain Numeric Rating Scale: Anchors and Clinically Important Differences. Journal of Hand Therapy.

Joshua Y Lee, Stacey D Guy, Michael J Lukacs, Zoe A Letwin, Mohamad F Fakhereddin, Iyad J Al-Nasri, **Shahan Salim**. (2017). Management of Fibromyalgia Syndrome: Cognitive-Behavioral Therapy (CBT) for Healthcare Professionals. University of Western Ontario Medical Journal.

Salim, S., (2016, October 2). A Moral Obligation. *Dawn News*. Available at http://www.dawn.com/news/1287399/a-moral-obligation