Development of novel data representations for virtual reality exergames

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Being physically active is important to people of all ages for supporting health and wellbeing. Engaging in regular physical activity has been shown to foster growth and development, improve physical and cognitive functions, relieve mental stress and depression, and reduce the risks of developing chronic diseases [1, 2, 3]. However, participation in physical activity can be low, especially among older adults living with dementia (OAwD), due to lack of motivation, safety and cost concerns, physical and cognitive limitations, and poor access to appropriate exercise opportunities [4, 5].

In addition to providing sustainable motivations in promoting physical activity engagement, virtual reality (VR) exergames have the potential to collect quantified, objective, and complementary information about the exergaming sessions through the use of motion-based technologies. While several studies have shown the potential of VR exergames as complementary interventions for exercise therapy in clinical practice, there has been limited research exploring how VR exergames can be used as tools to manage and administer exercise programs using the information collected in exergaming sessions.

This research explores metrics related to the performance of a person and creates data visualizations for the information collected through Exerfarm Valley, which is a head-mounted display virtual reality (HMD-VR) exergames system developed in part through this thesis work. The data visualizations resulting from this thesis research are intended to be used by exercise professionals in evaluating the client's performance during an exercise program and manage exercise therapy. The identified metrics for representing the player's performance during exergaming sessions could be applied to other exergames, potentially providing useful information about the client's status and exergaming sessions to exercise professionals. To the author's knowledge, this research represents the first data visualisations to be created for HMD-VR exergames through multi-disciplinary collaboration using user-centered design methods.

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Dedication

This is dedicated to my parents, who give me endless love, protect me from all possible dangers, and support me throughout my life.

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List of Abbreviations

ADL activities of daily living 25

DR distance rowed data visualization 48

EHR electronic health record 21

FROR functional reach and overhead reach data visualization 48

HMD-VR head-mounted display virtual reality iii, 2, 61

HRSR heart rate and (arm movement) stroke rate data visualization 48

IMUs inertial measurement units 23

MCI mild cognitive impairment iv, 2

METs metabolic equivalents 24

MIDE framework multidisciplinary iterative design of exergames (MIDE) framework 4, 16, 26, 64

MTDG motion trajectory during gameplay data visualization 48

NCDs non-commnicable diseases 6

OAwD older adults living with dementia iii, 1

PwD people living with dementia 6

RoM range of motion 8, 24, 33, 54

RPE rating of perceived exertion 25, 45, 53

VR virtual reality iii, 2

Chapter 1

Introduction

With the advancement of healthcare and the increase in life expectancy, 2 billion people of the world's population are expected to be 60 years and older by 2050 [8]. In line with such shift in population demographics, 23 percent of Canadians are estimated to be over 65 years old, and the average life expectancy of Canadians is estimated to increase to 85 by 2040 [9]. Intertwined with the ageing population, chronic diseases and age-related health conditions, including physical and mental deterioration, prevail worldwide. In the United States and Canada, approximately 25 percent of the older population experience a fall each year [9]. At least 80 percent of older adults live with a chronic condition such as cardiovascular disease, osteoarthritis, diabetes, dementia, depression, and obesity [10].

Physical activity and exercise have been recognized as a valuable part of preventive and therapeutic strategies for healthy living [11]. Research has shown that physical activity is associated with better health outcomes, both physically and mentally [12, 13]. Adults and older adults should maintain at least 150 minutes of moderate intensity physical activity or 75 minutes of vigorous intensity physical activity per week regularly to obtain important health benefits and keep fit [14]. Importantly, older adults (i.e., people over the age of 65) that are physically active exhibit higher levels of functional ability, lower rates of all-cause mortality, and lower risk of physical disabilities [15]. Despite its broad physical and mental benefits, physical activity is restricted among older adults, especially older adults living with dementia (OAwD), primarily due to the motor and cognitive changes associated with the condition, lack of motivation, poor self-efficacy, apathy, and limited access to exercise opportunities that meet their needs and capabilities [16, 17, 18].

Exergames, a combination of exercise and video games, have been shown to promote exercise participation in older adults and have demonstrated comparable or slightly better outcomes than conventional human-guided exercise training programs in terms of physical outcomes [19]. Virtual reality (VR) is an innovative strategy that can encourage physical activity participation, improve physical activity engagement, and offer exercise routines that require minimal guidance and supervision from the therapists [20] by providing realistic virtual environments and representations. Studies that explored VR exergames for older adults, especially for OAwD, have shown positive results in motivating players to engage in physical activity [19, 21, 22, 23, 24, 25].

With the unique capabilities of measuring additional quantifiable information about the exergaming sessions, exergames have been identified as complementary health monitor tools [26]. Many studies have been investigating the ways to visualize the data from motion-based technologies in facilitating the analysis of rehabilitation outcomes or assessment results [27, 28, 29, 30]. However, there is limited research in data visualizations of VR exergames to support exercise therapists in managing and administering exercise programs.

1.1 VR exergames project

The research described in this thesis is part of a larger interdisciplinary project: design, development, and evaluation of head-mounted display virtual reality (HMD-VR) exergames to promote physical activity in older adults. The VR exergames project uses OAwD or mild cognitive impairment (MCI) in order to create HMD-VR exergames that can be used by general older adult populations.

In collaboration with the industry partners (VR Vision [1] and Schlegel Villages [2]), the research team worked with people from different backgrounds to include multiple valuable perspectives. The VR exergames project aims to:

1. collaboratively design and develop a set of HMD-VR exergames, which we named Exerfarm Valley, that follows the current therapists' best practice in the exercise therapy for OAwD or MCI;

2. develop an intervention methodology to quantify the feasibility and validate the effectiveness of HMD-VR exergames in promoting physical activity engagement among OAwD or MCI.

[1] https://vrvisiongroup.com/

[2] https://schlegelvillages.com/

1.2 Objectives and research question

The research presented in this thesis explores data visualizations that could support the work of exercise therapists through collection and representations of objective information about exergaming sessions and players' performance during the sessions. The goal of this thesis research was to create novel data visualizations, using the information collected through HMD-VR exergames, that are easy to interpret and use by the exercise therapists to guide their evaluation of the client's performance and improve their engagement during exercise therapy delivery.

The research questions guiding this thesis work are:

1. What information can be used to represent older adult HMD-VR exergame player's physical performance?

2. How can physical performance information be presented in a way that is understandable and useful for the exercise therapists?

1.3 Thesis organization and key contributions

The remainder of the thesis is organized as follows:

Chapter 2 provides an overview of the problem space this research tackles. The context of this thesis work is described through reviews of physical activity, exergames and VR technology, and data visualizations.

Chapter 3 outlines the research activities related to the exploration of HMD-VR exergames metrics representing the player's performance and exergaming sessions. In this chapter, the co-creation process of Exerfarm Valley is explained with a focus on the identification of metrics that therapists would like to see about an exergaming session, which informs the work done in Chapter 4.

In Chapter 4, the development process and the evaluation results of data visualizations are described. Selected metrics were used to collaboratively generate the data visualizations with four exercise professionals based on their clinical experience. Twenty-four healthcare professional with experience in exercise therapy administration or management evaluated the proposed data visualizations using an online questionnaire. This chapter delivers the results and insights from this stage of research.

Chapter 5 presents conclusions and key contributions of this thesis research, as well as limitations and possible directions for future work.

This thesis research puts forward the following contributions:

- Identification of metrics that can be used to represent player's performance during an HMD-VR exergaming session.
- Creation and evaluation of novel data visualizations that could be used to support therapists' understanding of player's performance during a VR rowing exergame.
- Development of the multidisciplinary iterative design of exergames (MIDE) framework for guiding the process of collaborative design, development, and evaluation of VR exergames

Chapter 2

Background

This chapter provides an overview of the background and existing literature related to this thesis work. The first section of this chapter presents the overall context of this research project by introducing the target population and describing the proposed base problem space. Section 2.2 narrows the problem space, introducing exergames and VR technologies to define the solution intervention this research based upon. In section 2.3.2, the significance of this thesis work is emphasized by reviewing existing clinical practice and relevant literature on data visualizations.

2.1 Physical activity towards healthy ageing

This section provides the background of this thesis work through an overview of literature related to the research context. The related problem space is defined through discussions about the significance, benefits, and challenges of physical activity among the target population.

2.1.1 Ageing, dementia, and physical activity

As a result of declining fertility rate and rising life expectancy, the proportion of the population aged 65 and beyond increases rapidly worldwide. In 2018, the number of people aged 65 and beyond had outnumbered children under 5 [31]. The gap between the two populations will continue to grow due to a faster population change in older adults than all other age groups. In 2019, there are over 700 million people aged 65 and older, a number that is projected to double and take up 16 percent of the world's population by 2050 [32]. This phenomenon of population ageing not only is one of the most significant transformations of society in this century but also impacts nearly every aspect of people's lives [31]. The increasing number in the aged population also implies an increase in medical costs due to various age-related chronic diseases such as diabetes, depression, and dementia, as well as higher risks of injuries among the older adult population [8, 33]. Adding to the burden of non-commnicable diseases (NCDs) in the elderly population, insufficient physical activity increases the risk of developing and dying from NCDs [34].

Dementia, one of the major causes for disabilities later in life, is not part of the normal ageing process but affects mainly older adults [35, 36]. Accompanied by different symptoms such as impaired memory, language, and changes in behaviour, dementia affects the quality of life for people living with dementia (PwD) of all ages by affecting many aspects of their lives, including cognition, behaviour, mood, communication, and mobility [37, 38]. Currently, the worldwide number of PwD is estimated to be around 50 million, and this number is expected to double by 2030 [35].

Dementia can be overwhelming not only for the affected people but also for their caregivers, families, and society at large. In 2020, the national cost of dementia is calculated to be \$305 billion dollars for the United States, which is projected to be more than \$1.1 trillion dollars if no effective treatment is developed to slow, stop, or prevent the disease [39]. Dementia is the leading cause of dependency (i.e. the need for care) and disability among older adults [36]. Despite the growing concerns and the increasing medical costs for dementia, about 64 % of older adults still prefer living in their own homes to continue "ageing in place" [40]. In Canada alone, about 61% of OAwD live outside of long-term care facilities or nursing homes due to higher costs of institutional care as well as an increasing shortage of available staff [41, 42, 43]. In addition, OAwD are experience higher risks of falls in both long-term care and community settings, resulting in doubled fall-related hospital admissions compared to other older adults [44, 45].

2.1.2 Benefits of physical activity

Physical activity benefits people in all age groups in several different aspects of their lives. Studies suggest that physical activity is associated with numerous health benefits, resulting in better health status and increased quality of life across various populations [13, 46, 47]. With much evidence regarding the positive impacts of physical activity on physical fitness [13, 15, 3], physical activity has also shown positive benefits to cognitive function [2, 48] as well as mental health [49, 50, 51]. Furthermore, engaging in physical activity regularly has demonstrated long-term influence in preventing the development of age-related diseases, especially NCDs [1, 52].

Physical activity has been the subject of many studies targeting PwD due to its impact on cognition and potential in slowing down the progression of cognitive decline [53, 54, 48, 16]. Although dementia is a progressive neurodegenerative disease that has no cure or treatment yet, there is some evidence showing that regular physical activity engagement plays a main role in delaying cognitive decline [55, 56], improving cognition [54, 57], enhancing the quality of life and mental health [58, 59], and maintaining physical fitness [53, 60]. Though there is limited strong evidence from the research, physical activity seems promising as a preventive and therapeutic strategy for dementia [61, 62]. Engaging in physical activity, particularly aerobic and strength training, has been shown to improve the functional abilities in OAwD, such as enhanced balance and mobility, and reduced risk of falls [63, 64, 53].

2.1.3 Challenges of physical activity

Despite the numerous benefits of physical activity, insufficient physical activity is one of the leading risk factors for global mortality [65]. Insufficiently active people have a 20% to 30% increased risk of death compared to those that are sufficiently active [15]. In the United States, physical inactivity can account for almost 10% of death [66]. Barriers to physical activity vary depending on the context, age, gender, current level of physical activity, and other factors [67]. Major barriers for people to engage in physical activity are time, energy, motivation, illness, fear/injury, and lack of skills [4] in addition to the systematic barriers such as lack of information, safety concerns, and cost [5].

Because of the motor and cognitive changes associated with dementia, OAwD experience additional challenges to regular participation in physical activity [68, 16]. Limited physical abilities, including impaired body functions [69] and restricted mobility [70], as well as the fear of falls [71] make it harder for OAwD accessing structured exercise programs or engaging in physical activity. OAwD often have lower motivation to engage in physical activity due to depression, apathy, and low self-confidence [17, 16, 18, 72]. Difficulties in understanding exercise instructions due to impaired language processing abilities further decrease motivation of participating in physical activity for OAwD [73]. On the other hand, compliance with exercise regimens relies on appropriate guidance and supervision from therapists (e.g., physical, occupational, recreational therapists) [17, 74], which is not always resource-efficient or possible . The access to therapists' guidance and supervision can also be restricted by time, cost, and the availability of healthcare professionals with the expertise in tailoring exercise for OAwD or MCI [74].

2.2 Exergames as complimentary tools

The following section reviews the state of the art exergames, analyzes opportunities for advancing the technology intervention, and discusses the challenges in creating an effective solution to the proposed problem space.

2.2.1 Exergames

Many researchers have recommended reducing the screen-based sedentary behaviours, like watching television and playing video games, to prevent the development of obesity and cardiometabolic diseases among children and adolescents [75, 76, 77, 78]. Respondents in terminology consensus project have suggested adding "video games" in the examples to help define the "screen time" about sedentary behaviours [79]. However, playing video games is not always sedentary since some video games require the player(s) to be physically active. In particular, those interactive video games that integrate human movements as the main interface to elicit physical activities similar to exercise are also called exergames [80, 6]. From Wii Fit by Nintendo Wii, Your Shape Fitness Evolved on Microsoft Xbox Kinect, and the Just Dance game series using Sony Play Station, to Ring Fit Adventure and Rope Jump Challenge mini-game in Nintendo Switch, there have been many commercial exergames on the market over the past decade. Through appealing and fun game experience, compelling game challenges, and novel interactions, exergames are able to provide sustainable motivation for people to engage in physical activity [81]. In fact, exergames have been used to provide long-term motivation in different populations to support physical activity engagement in many settings for various purposes, including education [82], rehabilitation [83], and physical or cognitive training [84]. Exergames are showing promise as a potential alternative to conventional exercise programs by demonstrating comparable effectiveness as conventional human-guided exercise programs [19].

In addition to supporting physical activity engagement and promote exercise participation in older adults [85, 86, 84], exergames have shown potential in benefiting older adults' functional fitness by increasing the range of motion (RoM) [22], enhancing mobility [87], and improving balance [88, 20, 89]. Playing exergames can be mentally stimulating [90, 91] while also helping to improve older adults' mental health, enhance their quality of life [92, 93], and increase the social connections as well as encouraging interactions with the peers [94, 95]. There has also been increasing academic attention on exergames for OAwD, in motivating physical activity and delaying health declines, over the past few years [96, 97, 98, 99]. Many researchers adopted commercially available exergames and exergaming systems, with slight modifications tailoring to the needs and preferences of the target population, as the exercise interventions in their studies to investigate the effectiveness of exergames in promoting physical activity, maintaining functional fitness, reducing fall risks, and improving mobility [99, 98, 97]. Even though commercial products are developed for entertainment purposes target the general population, the findings of related works suggest a promising future of this technology [98, 99] in supporting exercise and promoting physical activity engagement. To better reflect the needs of OAwD, other researchers have been evaluating the efficacy of custom-designed exergames in promoting physical activity, and many guidelines have been proposed considering the physical as well as cognitive challenges OAwD face [100, 101, 102, 103].

2.2.2 VR technology and exergames

VR is a multi-sensory computerized environment that generates realistic visual, audio, and other sensations to create a simulated experience that can be similar to or completely different from the real world. Standard VR systems use either an HMD-VR headset or a multi-projected environment to simulate a user's presence in the virtual world. Before 2000, VR technology was mainly used in aerospace and flight training [104, 105, 106]. With the launch of the Oculus Rift in 2012, VR technologies started to become more affordable for healthcare applications and personal entertainment purposes.

Through VR environments players can:

- explore different environments despite real-world physical barriers [107, 108];
- enjoy immersed and stimulating experience, which may provide distractions to pain [109];
- focus attention more effectively through vivid and novel interactions in VR [110];
- become proficient in virtual environment and skills through training [91, 111].

Being able to provide above benefits through realistic virtual environments, VR exergames are showing promises as novel interventions to encourage physical activity participation and engagement in older adults [94]. VR exergames have not only demonstrated positive impacts on physical fitness, cognition, mood, and apathy among OAwD [112, 113] but also been well accepted by this population according to the exploratory studies [113, 24].

On the other hand, VR exergames can be challenging for players due to novel system interactions within virtual environments and diverse input devices (e.g., joysticks, hand-held controllers) [114]. Players may also experience motion sickness, seizures, and/or disorientation during or after VR usage due to intensive sensory cues presented in the virtual environments [114]. In addition, players may run into real-world objects and injure themselves by being unaware of their physical surroundings when immersed in a virtual environment while extended intensive gameplay may result in other injuries such as repetitive strain injuries from repeat rapid movements and noise-induced hearing loss by continuous (loud) auditory stimulus [114]. While proper fit of the headset changes for different people and even over time, physical fatigue and aroused physiological responses during the game also increase discomfort and hygiene concerns [114, 115]. For people with mobility or cognitive impairments, precise interactions and feedback in the game, such as grasping and haptic cues, may be hard to perform or interpret [114, 102]. For all these reasons, games must be carefully designed to fit the players' abilities to try and ensure they do more good than harm.

2.2.3 Challenges of exergames adoption in clinical settings

Despite the prevalence of the technology in academic studies and the bright future from the research results, the adoption rate of exergames is still low in the clinical settings and practices [116, 117]. Although many clinicians have reported trialing VR exergames at least once, more than 50% of VR exergames programs were dropped from the clinical practice or are rarely used; 85% of those who currently/continuously embrace the technology for clinical interventions use VR exergames at a frequency of once per month or less [117]. Commercially available exergames and exergaming systems, such as Nintendo Wii/WiiFit and Microsoft Xbox Kinect, have been predominately used by clinicians primarily due to the cost and accessibility issues [116, 117, 118]. However, clinicians also reported that the goals set in off-the-shelf non-customized commercial exergames and exergaming systems usually do not match clinical goals, sometimes even inappropriate for their clients [117, 118]. With the rapid development of emerging technology, keeping up with the current trend also poses difficulties in the technology adoption for healthcare professionals due to limited support for equipment set up and familiarization [116]. Most importantly, the quality of evidence for VR exergames is still considered poor [116], due to inconsistencies in the interventions and feasibility studies [112].

2.3 Metrics and data visualizations for exercise outcomes

The section provides a review of the literature regarding exercise therapists' current practice as well as the data visualization research for motion-based technologies.

2.3.1 Current practice among exercise therapy professionals

Physiotherapists document information of a client in clinical records, including the assessments and related findings as well as analysis, recommendations and goals for the proposed interventions, details of the care provided and care provider(s), outcomes of the care, and a summary of the episode of care when completed [119]. Clinical records, as important communication tools, allow physiotherapists and others to track the past and current status of a client, determine future care needs, provide evidence of the care delivered, and ensure collaborating as well as transferring during a patient's care smoothly. The record can be in any medium such as paper, electronic, audio, video, and photographs, as long as they are well-organized, understandable, and accurate. [120].

Currently, the quantitative information about a client's status and outcomes of the care is usually measured through periodic assessments (e.g. intake assessments at the beginning of the care, reassessments at the end of the care process). Both the physical and cognitive performance of an individual are assessed periodically through standardized tests. Restricted by the instruments and exercise programs, exercise therapists administer both clinically validated cognitive assessments (e.g., Montreal Cognitive Assessments [121], Mini-mental Score Examination [122], Clock Drawing Test [123], Trail Making Test [124]) and community adopted tests (e.g., Drop Ruler Test) to understand the general cognitive ability or specific cognitive status of the individual. Physical fitness and mobility are usually measured through clinical assessments such as Timed Up and Go [125], 6 Minute Walk [126], Four Square Step Test [127], and Senior Fitness Test [128]. However, specific physical function assessments, like balance and RoM, can be varied depending on the exercise therapists and situated programs. Within the same community program, Functional Reach Test [129] and Modified Functional Reach Test [130] can also be used inconsistently depending the administering exercise therapists, available testing instruments, and ability of the individual. Subjective information, for example quality of life and self-efficacy, may also be collected in the community programs as important measures about a client's overall status. Other detailed care delivery information, such as the attendance and client's feedback, are recorded through journal summary after each exercise session. Client's performance during an exercise session is usually assessed based on therapists' observations with limited usage of motion-based technologies in clinical practice.

2.3.2 Literature on data visualizations

Through motion-based technologies such as VR exergames, biomechanical information about the player's movements can be collected and analyzed to complement therapists' observations during an exercise session. However, data visualizations from the motion-based technologies to support exercise therapists' practice still remains relatively unexplored. Data visualizations are computer supported, interactive, visual representations of data using suitable method to deliver information and support cognitive processes [131]. Examples of data visualization techniques include: 1) bar graph, a graph that uses rectangle bars to represent categorical data; 2) line graph, a graphical method that connects a series of data points using line segments; 3) radar chart, a 2D chart that displays three or more quantitative variables on axes starting from the same point; 4) 3D graph, a type of graph that visualizes the relationships between data points in a 3D space.

In 2012, a group of researchers in the United Kingdom developed a prototype data visualization software to facilitate communications about the improvement of appropriate movements during rehabilitation process [28]. The software was designed to support a wide range of motion-capturing technologies under different rehabilitation settings and be flexible in interface and data visualization options depending on the therapeutic goals. The early prototype was presented to both stroke survivors and healthcare professionals in focus groups for feedback and improvements. Based on the requests from focus groups, the authors implemented the function to provide tailored data visualizations and information depending on the scenarios and individual preferences. The final prototype was developed and evaluated with a group of rehabilitation professionals to understand the potential of this technology through semi-structured interviews [132]. In particular, the concepts of data visualization were adored by most interviewees on its novelty and potential clinical benefits to both therapists and patients [132]. However, the software is still far from integration with current service provision, both technically and visually.

In order to provide quantifiable, reliable, and accurate information on an individual's overall functional capability, Kinect-based 3D reachable workspace analysis was proposed as a promising tool for clinical evaluation on upper extremities [29], which included some novel data visualizations generated from a statistical analysis. For example, 3D colored quadrants was used to visualize the workspace of an individual; a color-coded bar chart was used to compare relative surface area per quadrants for dominant and non-dominant arm between subjects. The concept of 3D workspace and quadrant visualization was also used in an upper limb rehabilitation virtual game using Microsoft Kinect [133]. In this game, the player was expected to catch fish that are swimming by and pick up golden coins while surrounded by swaying plants and rising bubbles under the sea. Different from the original study where the individual's range of motion was back-projected onto the quadrant sphere to create an overall representation of functional capabilities, the hand motion trajectories during the game were directly mapped to different quadrants as the fish were programmed to move along the sphere. The 3D workspace visualization not only provided a clear indication of an individual's range of motion in the 3D space but also highlighted different quadrants with colors to provide a visual representation of the individual's range of motion in different directions.

Ploderer et. al. co-created an interactive data visualization dashboard with therapists at a rehabilitation clinic to explore the potential of proper data visualizations in supporting the upper limb rehabilitation process [27]. After the initial problem identifications from informal interviews, the data visualization dashboard prototype was created and refined through multiple design workshops with active contributions from the therapists. Instead of investigating novel data representations, the prototype focused more on information organizations and presentations. The final dashboard includes five pages - patient overview, activity timeline, joint visualizations, heat-map of range of motion, and a biomechanical data spreadsheet. Eight therapists were invited to qualitatively evaluate the data visualization dashboard through interviews and observations. After the background exploratory interview on existing clinical practice and therapists' expectations of patient information, an observation was made on the therapists in exploring the dashboard prototype interactively without prior introductions/explanations about the dashboard elements. The usability and usefulness of the data visualizations as well as the dashboard prototype were evaluated through a semi-structured interview, and the feedback was positive. Most therapists preferred to use the designed page and reported potential usefulness of the data visualizations in communication and patient status overview. One recurring discussion point during evaluation process was the lack of contextual information in understanding movement data. While the authors stated there was room to improve the data visualization dashboard by including more contextual information, this research showed the potential of appropriate data visualizations in complimenting therapists' practice.

To tackle the challenges in obtaining objective measures of muscle functions in children, a gamified test based on a commercial 3D sensor (i.e., Microsoft Kinect) was developed to assess the upper limb function for clinical trials [134, 135]. The main objective of the study was to develop and evaluate a novel, children-friendly assessment protocol for measuring upper limb functions, where the effectiveness of the protocol was evaluated and represented using some interesting data visualization techniques. Specifically, the researchers recorded all movements of an individual's upper body part and displayed the traces on a planar view. While results were not given a numeric "score", the motion trajectory seems cleaner in the healthy participant compared to the participant with tremor when looking at the data visualization for a single participant [135]. With advanced data analysis on motion trajectories and data visualization techniques, this type of visualization could provide an overview of a participant's movements over a period of time and highlight information therapists need to be cautious about.

Another upper limb motion analysis methodology using Microsoft Kinect was developed to enable functional evaluations during physical rehabilitation [30]. This study aimed to develop and validate a novel methodology in performing 3D evaluations using the Kinect sensor for general clinics in place of optoelectronic devices, which is only affordable by some specialized centers. In this study, 41 parameters were obtained from the trajectory analysis, all of which are grouped based on properties (angular, length, or volumetric) in a radar chart. With outside yellow contour as 100% (healthy people normative data), a client's score of each parameter was visually presented through the size of the corresponding slice. The overall upper limb performance score was shown at the center of the radar chart. Although this study included little about the development and evaluation process of the data visualization, the radar chart presented in this study provides a novel example of comparing different attributes in clinical practice. The data visualization not only provides contextual information through the contour but also includes various performance evaluations of the clients on different levels (i.e., individual parameter, specific properties, general performance). However, applicability of the data visualization in daily clinics should be evaluated with the healthcare professionals.

Adding to the increasing academic efforts in exploring data visualizations to complement clinical practice, XRHealth[1] from industry has been deploying HMD-VR exergames for rehabilitation, training, and assessment purposes through intuitive data visualizations about player status and game performance. For example, the neck training application "Rotate" not only provides a visual summary for the range of neck motions in all directions but also highlights the improvement between sessions through an appropriate radar chart; another cognitive training application "Memorize" uses a bar chart to represent a player performance after the game, allowing visual comparisons between different sessions.

[1] https://www.xr.health/

2.4 Chapter summary

Exergames have demonstrated potential in promoting physical activity participation and providing comparable physical outcomes to conventional human-guided exercise programs [19]. There is growing evidence that HMD-VR technology, which is becoming more and more accessible to general users, may enhance the exergames experience through immersive environments and realistic interactions [94]. While VR exergames as an exercise intervention have been explored through some academic studies, the potential of VR exergames as complementary tools for therapists has remained relatively unexplored. In particular, the quantifiable information collected through exergaming systems and the game-related data could be used to provide a quantitative and precise overview of the player's performance and status. As current exercise practice relies primarily on periodic assessments and therapists' observations, data visualizations tailored to the needs of therapists could facilitate the current exercise therapy and support communications between different stakeholders. Together with HMD-VR exergames that are specifically designed for older adults, the output of the VR exergames project (which includes this MASc thesis research) aims to support existing exercise programs in long-term care facilities through improved physical activity engagement in older adults, increased variety of existing exercise interventions in the program, and reduced therapist workload using appropriate data visualizations.

Chapter 3

Design and development of Exerfarm Valley

This chapter details the design and development process of a custom-made HMD-VR exergames collection, which we named *Exerfarm Valley*, through a joint effort of academic researchers, industry professionals (i.e., healthcare professionals, game developers), and older adults, including those living with dementia. The information/metrics to be used to represent the player's performance is explored as a part of the design and development process for Exerfarm Valley. In this chapter, the creation process of Exerfarm Valley is described with a focus on research activities related to this thesis, namely, identifying potential metrics to represent the player performance. The metrics identified and research activities through the work described in this Chapter form the basis of: 1) the data visualization creation discussed in Chapter 4; and 2) the creation of the multidisciplinary iterative design of exergames (MIDE) framework, which is a framework for guiding the design, development, and evaluation of health-related serious games for older adults.

3.1 Collaborative design and development of Exerfarm Valley

3.1.1 Methodology

The process of design and development on Exerfarm Valley was carried out using user-centered design principles by a multi-disciplinary research team from the University of

Waterloo in collaboration with various stakeholders from the industry [7]. Partnering with the VR game development company, VR Vision, and the long-term care institution (Schlegel Villages), the research team was able to envision and develop a plausible solution with contributors from both industry partners (game designers and developers, technology specialists, healthcare professionals, and end-users).

Previous research project supervised by Dr. Jennifer Boger and Dr. Shi Cao employed user-centered design principles and demonstrated the potential of HMD-VR technologies among OAwD through a pilot study [25, 22, 24, 23]. In consultation with exercise therapists on recommended upper body movements and OAwD on usability, four scenarios (i.e., butterfly watching, fruit sorting, apple box lifting, rowing) in a farm environment were created that allowed players to perform activities in a seated position. Through a three week trial, the developed HMD-VR exergame prototype was able to promote similar motion and fitness outcomes compared to human-guided exercise sessions and was rated as being quite enjoyable by participants [22]. These results demonstrated promising potential for HMD-VR exergames in promoting physical activity engagement as well as being well accepted by both OAwD participants and exercise therapists.

Building on the previous research project, three brainstorming sessions and five discussion sessions were carried out within the University of Waterloo research team and with our industry partners to define the initial game design concept and therapeutic expectations of Exerfarm Valley. Discussions and consultation sessions started within the University of Waterloo research team weekly during the first three months of the project to define the initial structure of Exerfarm Valley system based on target population's capability, technology feasibility, and primary findings from previous research activities (i.e., literature reviews, previous research project investigated by a subgroup of the research team from the University of Waterloo [22, 23, 24, 25]). An initial brainstorming session was carried out with industry collaborators (one exercise therapist from Schlegel Villages, two VR technology specialists from VR Vision, and a healthcare professional from VR Vision) at the University of Waterloo Games Institute to explore potential ideas for the envisioned Exerfarm Valley system. One brainstorming session was carried out at each participating Schlegel Villages partnering location (the Village at St. Clair and the Village of Humber Heights) with exercise professionals from the institution to gather concepts of specific activities in different game stages (i.e., warm-up, conditioning, cool-down).

An iterative prototyping and testing process with stakeholders and end-users was used to implement the design requirements and research concepts using HMD-VR technology. Six playtesting sessions were carried out to refine the Exerfarm Valley prototype. In exploring and refining the main conditioning stage of Exerfarm Valley, two playtesting sessions with end-users and exercise therapists at participating long-term care homes of Schlegel

Table 3.1: Research activities carried out in co-designing Exerfarm Valley with collaborating game developers, exercise professionals, and OAwD.

Sessions	Objectives	Contributors	Methods	Outcomes
Game design concept creation	Envision game design concepts, activities, and narratives	UW [a], VRV [b], SV [c]	Brainstorming [136]	Game level design ideas
	Explore ideas on the exercise movements, activities, and game mechanics	UW, SV	Brainstorming [136]	Game mechanics design concepts
Exerfarm Valley prototype playtesting	Assess conditioning period mechanics (rowing), game visual, and technology acceptability	UW, OAwD [d], SV	semi-structured in-person individual playtesting session	Visual elements recommendations Rowing mechanics feedback
	COVID-19 Outbreak			
	Investigate improved conditioning period mechanics and game level design	UW, YMCA [e]	semi-structured remote focus group	Rowing mechanics and in-game navigation suggestions
	Evaluate warm-up and cool-down period mechanics as well as integrated Exerfarm Valley prototype	UW	Rapid iterative prototyping [136]	Game mechanics (rowing, fishing, tai-chi) feedback

[a] internal researchers from the University of Waterloo from different disciplines (i.e., Department of Systems Design Engineering, Department of Kinesiology)
[b] VR technologists and healthcare professionals from the partnering game development company, VR Vision
[c] exercise professionals (i.e., kinesiologists, recreational therapists, etc.) in the long-term care facilities of Schlegel Villages
[d] recruited OAwD from the collaborating long-term care facilities of Schlegel Villages
[e] community exercise professionals recruited during COVID-19 outbreak from local YMCA Canada associations

Villages and one remote feedback session with community exercise professionals (recruited during COVID-19 outbreak) were conducted. Due to limited time and accessibility to collaborating exercise professionals later in the process during COVID-19 outbreak, three internal playtesting sessions were carried out within the University of Waterloo research team via zoom to integrate the warm-up and cool-down stage of Exerfarm Valley. Table 3.1 summarizes the major research activities carried out with our industry partners during the process of co-creating the Exerfarm Valley.

3.1.2 Results

Exerfarm Valley is an HMD-VR exergames suite that allows users to immerse in a virtual productive farm environment with various activities that encourage exercise movements, which have been shown to benefit OAwD and are desired by therapists in practice. The Exerfarm Valley experience lasts 15 minutes in total and includes three different activities players can engage within a seated position; each corresponds to the recommended stage of an exercise session (i.e., warm-up, conditioning, and cool-down). At the end of each game, the player will be automatically transported to the next game with audio cues facilitating the transition between scenes and activities. The game is designed to promote exergaming engagement by requiring limited controller interactions (i.e., no button interactions) and supporting error-free explorations in the environment.

The details of each game stage are described as followed:

- **Tai-chi game (warm-up, Figure 3.1a):** The player is encouraged to perform a short Tai-chi routine on a beach with sunset on the horizon. The Tai-chi movements are guided using the metaphor of a floating leaf in the slight wind flow. The player needs to move along the suggested wind direction and hold the leaf to complete the suggested movements for 3 minutes in order to complete the full stretching routine of the upper limb and prepare for the next stage of exercise.

- **Rowing game (conditioning, Figure 3.1b):** The rowing game mechanic is expected to elicit exercise movements at an appropriate intensity, aiming to improve strength and aerobic fitness for OAwD. The player is transported to a rowboat with wooden oars attached to both of his/her virtual hands. The game includes different views (e.g., marsh, valley, waterfall) and some other animals, such as rabbits, fish, and dogs. The player is invited to explore the tropical environment accompanied by a virtual dolphin swimming along a specific path at an adequate space. However, the player can also choose to explore different scenery of the space in a different

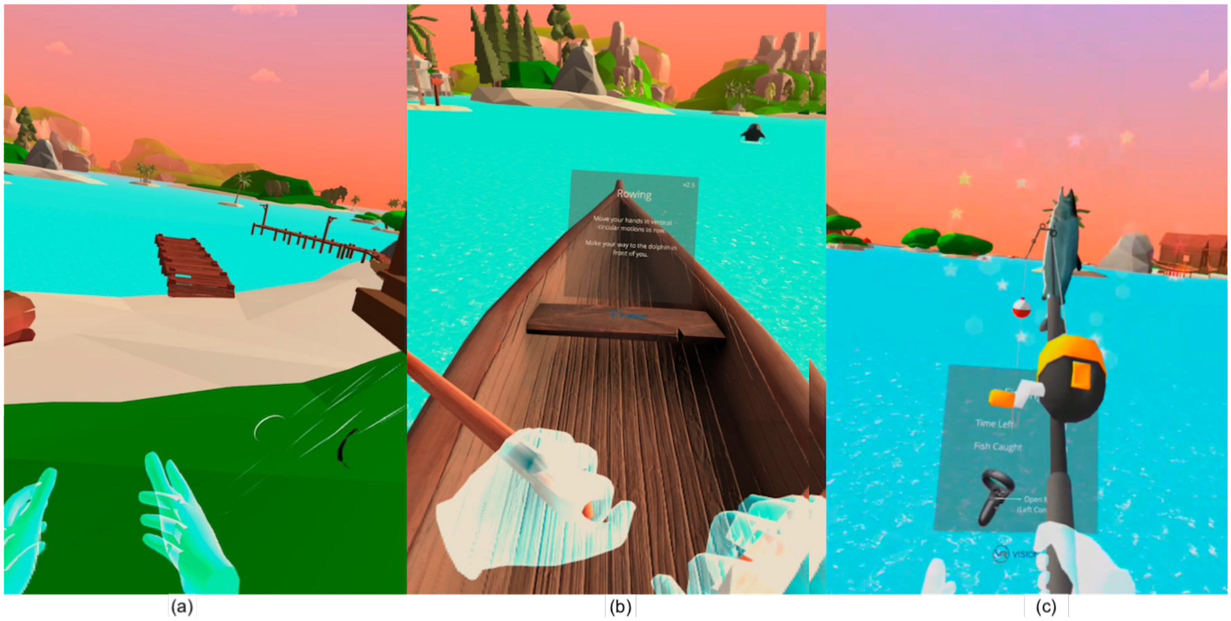


Figure 3.1: Exerfarm Valley screenshots of each game stage: (a) Tai-chi (warm-up); (b) rowing (conditioning); (c) fishing (cool-down).

path at their own pace without following the dolphin. Audio instructions recorded by an experienced exercise therapist will be played in this stage to provide guidance on movements and activities to be performed. This experience is expected to last 9 minutes in total.

- **Fishing game (cool-down, Figure 3.1c):** Transporting from the rowboat in a tropical area, the player is now holding a fishing rod using one of the virtual hands in a boat with a fish bucket. The player is expected to look around the lake and find a fishing spot, where fish jumps out of water. The fish line should then be thrown at the fishing spot to place a bait at the targeted location. Once the fish takes the bait, the controller, which corresponds to the virtual hand the rod is attached to, will start vibrating. The player will need to repeat a series of desired movements (shoulder/elbow flexion-extension) to retrieve the fish line and place the fish inside the fish bucket at the edge of the boat. The player is expected to catch as many fish as possible within 3 minutes of the gameplay.

The game incorporates various exercise activities in different stages to provide a complete training routine for upper-limb muscles. The game mechanics were designed to be realistic, intuitive, frustration-free, and adaptive to individual physical capabilities. For example, the height of the avatar in a boat can be calibrated to ensure smooth gameplay during the rowing stage. Although the default exergaming session duration is 15 minutes, therapists can manually adjust the length to 10 minutes or 20 minutes with the time of exercise stages being automatically configured (i.e., 20% warm-up, 60% conditioning, 20% cool-down). Moreover, encouraging narratives were used to enhance player's experience [137, 138, 139] and guide the player to perform target activities at a specific stage during the game. Exerfarm Valley system could also automatically capture specific game variables quantifying the player's performance as well as exergaming sessions and export the time-series data into a local file inside the HMD-VR headset for further data analysis.

3.1.3 Discussion

Exerfarm Valley complements the existing VR content (3D virtual environment, 360° video, and interactive games[1]) created by the company. In guiding the player to perform recommended movements through a complete exercise routine, Exerfarm Valley could add varieties to existing exercise programs delivered in the long-term care facilities. Integrating favorable gaming elements to the exercise routine through collaborative design process with the end-users, the game aims to provide sustainable motivations for older adults to engage in physical activity. Translating the performance during the game with real world events, an individual may improve their self-efficacy by consistent training and accomplishments. What's more, exercise professionals envisioned that the game may also help with reflex pain training since VR has been used in pain management. To be more specific, the immersed environment may create stimulating experience that allows an individual to be distracted from pain [109] or perform challenging movements that are usually considered as painful and impossible. In addition, the technology could complement existing administration process of exercise sessions through potential quantifiable, objective information about the player's performance and status during an exergaming session. As a complementary intervention for clinical exercise therapy, the information collected from Exerfarm Valley system can be used to intelligently adapt the game difficulty levels and integrated with the electronic health record (EHR) system.

[1] Contents accessible at https://realitywell.com/

3.2 Identification of potential metrics for Exerfarm Valley

3.2.1 Methodology

In parallel with the design and development activities for Exerfarm Valley, the potential metrics representing player performance were identified through seventeen consultation sessions with exercise therapists on the research team from both the University of Waterloo and industry partners. Throughout the process of technology scoping and game design, the potential information that could be collected through HMD-VR technology was explored with respect to the implications for exercise therapy.

Lead by the author, potential metrics and outcome measures of the Exerfarm Valley were explored as part of the initial design exploration process. During the six weekly discussion sessions within the core research team (Department of Kinesiology: 1 associate professor, 1 PhD candidate; Department of Systems Design Engineering: 1 MASc candidate, 1 postdoctoral fellow, 1 associate professor, 1 assistant professor) from the University of Waterloo at the beginning of the design and development process for Exerfarm Valley, feasible metrics and desired outcome measures were examined from a research perspective. Eight unstructured focus groups with five exercise therapists from Schlegel Villages (four at each partnering location; two therapists from the Village at St. Clair, three therapists from the Village of Humber Heights) were carried out to understand the current practice used in existing exercise programs and explore other metrics about exercise sessions that are valuable for therapists, which could not be captured through observations. Referring to the existing and desirable measures in clinical practice that help exercise therapists understand the progress of a client status during the exercise program, we identified a list of potential metrics that can be collected during exergaming sessions using clinical practice benchmarking [140, 141].

Two internal consultation sessions within the University of Waterloo research team (Department of Kinesiology: 2 associate professor, 2 PhD candidate; Department of Systems Design Engineering: 1 MASc candidate, 1 postdoctoral fellow, 1 associate professor, 1 assistant professor) were carried out from mid March, 2020 to April,2020 in refining the potential metrics, as shown in Appendix C.2, that can be collected in this research project. A final list of metrics was outlined in a Google Sheet (see Appendix C.1) and shared with four exercise professionals from local YMCA associations for feedback and suggestions. The four exercise professionals were asked to rank the metrics by indicating the importance of each individual measurement (i.e., crucial, important, good to have), describing how they would measure the metrics in practice, and providing recommendations on adding/removing specific measures to the list using the shared Google Sheet. To rank the importance of the specific metrics, the exercise therapists voted for the specific level by adding their initials to the corresponding cell. An informal discussion session was carried out to understand the disagreements between therapists on the importance of the metrics. A comprehensive list of all metrics to represent the player performance and exercise sessions was concluded to guide the creation of data visualizations later in this project.

3.2.2 Results

Table 3.2 summarizes the metrics identified for Exerfarm Valley, categorized by domain and outcome measures. The measures to be collected during the Exerfarm Valley exergaming sessions are illustrated in the column *example measures*. Implications of the identified measure related to physical activity and client status are summarized as the *application* of the metrics. The measures could be obtained from data collected through different sources: in-game data logging, external sensors (i.e., physical activity tracker - Actigraph, heart rate chest strap - Polar H10), and VR sensors (inertial measurement units (IMUs) in VR headset and controllers). Among all the metrics information, METs would be measured indirectly through physical movements using Actigraph and the measures about smoothness would be calculated based on data collected through the VR sensors. The importance of the measures were calculated by votes obtained from the exercise therapists. Specifically, the resulted rating is a representative of the number of votes each aspect received.

3.2.3 Discussion

As the proposed metrics represent the player's performance during an exergaming session, the exercise therapists can use it to manage the difficulties of exergames. Metrics such as smoothness of the movements and repetitions of the movements can be used to understand the progression of the client in a specific game level. The rapid change in movements indicates the progress of motor learning during the exergaming sessions, while the repetitions of a specific movement can reveal the adaptations of a client's physical status to the exergames intensity. Taking the rowing game in Exerfarm Valley system as an example, the exercise therapists may consider increasing the goal distance if the client has maintained a relatively fast stroke rate at all times. Inversely, the exercise therapists could decrease the goal distance for the clients who have trouble performing the correct rowing motion consistently or cannot reach expected goal distance.

Table 3.2: Metrics identified for Exerfarm Valley in representing player performance and exergaming sessions.

Domain	Outcome Measures	Example Measures	Application	Source of data	Importance
Physical (fitness)	Time played	Total time per session	Exercise volume	In-game data	**Important** (4)
	Repetitions	Number of specific movements performed	Exercise volume	In-game data	**Important** (4)
	Intensity	Heart rate	Exercise intensity	External sensor data	**Important** (4)
		Time in heart rate zones	Exercise intensity	External sensor data	Important (1), **good to have** (4) [a]
		Energy expenditure - Metabolic equivalents (METs)	Exercise volume	External sensor data	Important (1), **good to have** (3)
Physical (Kinematics)	Postural balance (seated)	Trunk acceleration, range of motion	Balance, fall risk	VR sensor data	**Crucial** (4)
	range of motion (RoM)	Wrist movements	Flexibility, RoM	VR sensor data	**Crucial** (4)
		Neck movements	Flexibility, RoM	VR sensor data	**Crucial** (4)
		Elbow/shoulder movemetns	Flexibility - postural control, RoM	VR sensor data	**Crucial** (4)
	Smoothness	Number of sudden changes in speed	Interruptions in movements	VR sensor data	**Crucial** (2), **important** (2)
		Change in accelerations	Shaking of hand/wrist while moving	VR sensor data	**Important** (2) [b]
Cognitive	Reaction time	Time of reaction after event	Balance, fall risk (reaction time is a predictor); simple processing/attention	In-game data	Crucial (1), **important** (3)
	Task switching (executive function)	Can change goals correctly	Balance, fall risk (task switching is a predictor); executive function	In-game data	Crucial (1), **important** (3)
	Head position	Head position	Attention, visual processing	VR sensor data	**Important** (4)
Cardiovascular health	Heart rate variability	Time and frequency domain feature	Cardiac risk/adaptability	External sensor data	**Important** (4)

[a] One exercise therapist voted for both "Important" and "Good to have"
[b] Only two exercise therapists voted for the importance

In addition to the objective information that can be collected during the exergaming sessions, exercise therapists mentioned the need to collect subjective measures, such as rating of perceived exertion (RPE) and mood, which are usually obtained through the after activity reflection journals or conversations with the clients and can help assess the exercise sessions or client's status. In particular, exercise therapists proposed to complement or substitute the measurement of heart rate with RPE in order to understand the exercise intensity more accurately based on the feelings of clients during the exergaming sessions. Therapists also highlighted the importance of other general information about a client, such as pain level and wellbeing, in understanding a client's status. As we aimed to identify the objective information that is hard to quantify in current practice, these metrics were not included in the proposed list of metrics for the Exerfarm Valley system.

In evaluating the outcomes of exercise programs, there has been a discrepancy between the exercise therapists from the industry and the exercise researchers from academia. For example, exercise therapists from both the community programs and long-term care facilities (Schlegel Villages) indicated that the range of motion is crucial in understanding the client's status, where academic researchers from the University of Waterloo preferred other strong outcomes about the cardiovascular health and fall risks. Range of motion, especially for neck and shoulder, was mentioned as the desirable information to be captured during multiple metrics consultation sessions in part because of the difficulties in measuring the results under current systems. Since the exercise professionals emphasized the translation between exergames and real-world events, many metrics are nominated based on their implications on the individual's quality of life and life events. For instance, the range of motion reveals one's ability to search for an object, reach an object, feed himself or herself, and perform many other events that are necessary to manage one's needs. Increased range of motion can be associated with enhanced functional quality of life, allowing an individual to perform more activities of daily living (ADL) [142].

In addition, both the reaction time and task switching ability in the game may have strong transferable implications to the real world if can be measured accurately and reliable since they are strong indicators related to fall risks [143, 144, 145, 146] and are not usually measured in long-term care facilities or community programs. Besides, improved task switching abilities can associate with better performance in the periodic assessments of exercise programs, where exercise therapists have reported that many clients are struggling for switching between cognitive tasks and physical tests. All measures, together with subjective information collected through client's reflection journals and conversations, can tie back to help exercise therapists evaluate the quality of life among their clients and managing the exercise sessions. The exergames may be adjusted accordingly to add or reduce the challenges during an exergaming session. The better the performance of the players during the exergaming sessions, the more confident they might be in performing similar activities independently, resulting in a higher quality of life in general.

3.3 Creation of the multidisciplinary iterative design of exergames (MIDE) framework

3.3.1 Methodology

In the process of planning and conducting research activities for the VR exergames project, we discovered that there is a lack of a comprehensive framework to guide the research and development process of serious games for health, including exergames, considering the contributions of various stakeholders. Many exergaming frameworks (e.g, DDE framework [147], gerontoludic design [148]) focus on specific game design elements and principles for the targeted populations, whereas other frameworks (e.g., MDA framework [149], PACT framework [150]) emphasize the importance of trans-disciplinary perspectives. Arising from the experience and literature, an initial discovery discussion session identifying the key contributors and components of the framework was carried out within the designated academic sub-team. The key stages, major outputs between processes, and research component details were finalized through two internal discussion sessions reflecting the research activities planned and conducted in the VR exergames project. The visual representation of the framework was refined through three design workshops.

The detailed research activities and contributions of the stakeholders in each stage can be found in our published work - Multidisciplinary Iterative Design of Exergames (MIDE), which is a framework for supporting the design,development, and evaluation of exergames for health [6].

3.3.2 Results

The multidisciplinary iterative design of exergames (MIDE) framework integrates a multidisciplinary, iterative, user-centered approach that acknowledges the unique contributions of each contributor in different phases and the necessity of coalescence among different perspectives in order to create exergaming systems that support the target population under the specified context.

The MIDE framework is separated into three different phases, as shown in Figure 3.2:

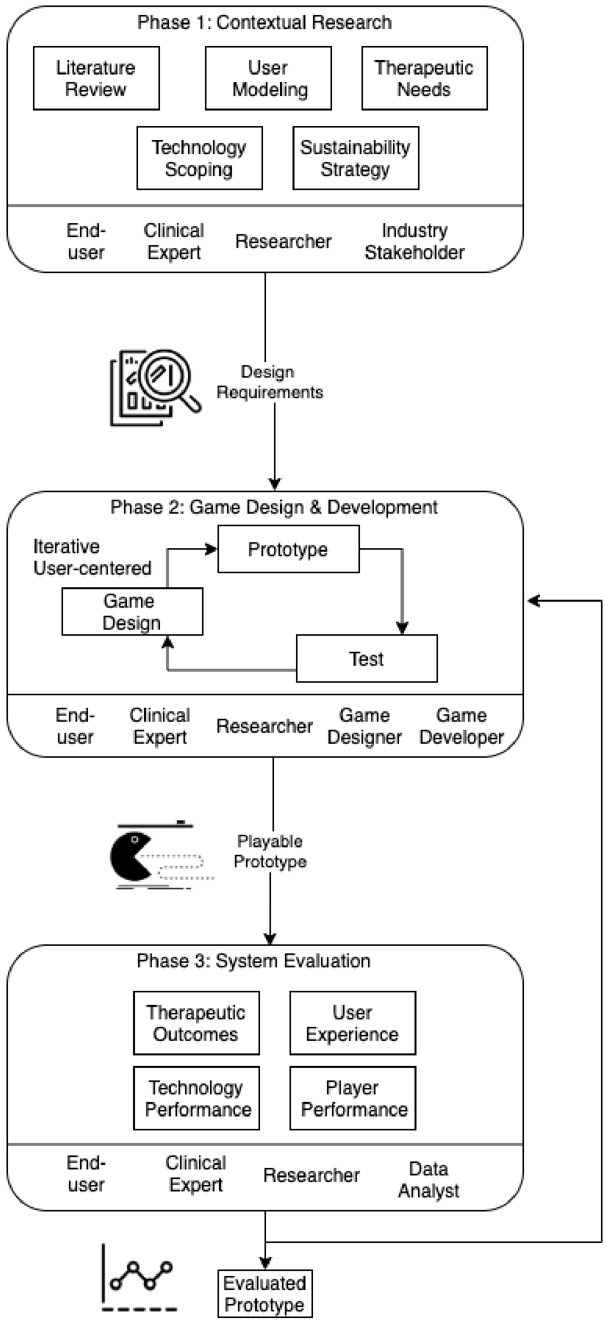


Figure 3.2: Overview of the MIDE framework, adapted from [6].

- **Phase 1: Contextual Research:** A holistic review of the problem and potential solutions is carried out in this phase to define the expectations of the proposed solution. Specifically, the problem is refined through multiple literature reviews (in both academia and industry) and discussions with stakeholders, including therapeutic goals and sustainability expectations. The user preferences and needs of the target population are carefully inspected through multi-disciplinary lenses in order to construct user models that could optimize the experience using the final product. The capacity of existing technology and potential of the selected technology intervention are researched and scoped in order to deliver the exergames with proper equipment and artifacts. The output of this phase is a set of design requirements considering the stakeholders' opinions, technology requirements, accessibility recommendations, and clinical potentials.

- **Phase 2: Game Design & Development:** As the core component of the process in creating a tangible solution to the discovered problem, the game design and development cycle should follow user-centered design principles and iterates until a qualifiable playable prototype is ready. This process is usually started with design sessions, such as brainstorming activities with a multi-stakeholder group, to initiate the game design concepts in light of the healthcare requirements and technology feasibility. Iterative prototyping-testing cycles should be performed to validate specific design options or general game design concepts. At the end of all the cycles, a fully functional VR exergames prototype, which reflects the current design requirements and technological capabilities, should be ready for further actions.

- **Phase 3: System Evaluation:** Although the VR exergames prototype from the previous phase can be considered as the final product, the research and development cycle should not end right away. The developed solution should be systematically evaluated to ensure it meets the intended goals set at the beginning of the process. This phase can be performed in an iterative fashion as the result of a continuous feedback loop to revise the existing exergames solution.

3.3.3 Discussion

The MIDE framework provides considerations and guidelines about the process of creating and evaluating HMD-VR exergames for older adults. However, the general process and principles of this framework can be applied to other types of serious games for health and rehabilitation purposes. The MIDE framework emphasizes the valuable contributions of the key representative stakeholders during every phase towards the development of a viable and effective exergames product in complementing the existing exercise programs. It intends to support the process of planning and executing research in HMD-VR exergames for older adults through detailed considerations and strategies for each phase during the process. As the MIDE framework is generalized based on the VR exergames project, other research and real-world development activities are welcomed to validate and improve the framework.

3.4 Chapter summary & key findings

This chapter describes research activities that the author lead organizing (i.e., brainstorming sessions at Schlegel Villages, metrics consultation sessions with YMCA exercise therapist, discussion sessions for MIDE framework) or actively participated in (i.e., initial brainstorming session, playtesting sessions). The main focus of this thesis work is identifying information that can be collected through Exerfarm Valley system to quantify an individual's performance during exergaming sessions. The key contributions of work described in this chapter are:

- Identification of metrics that can be captured quantitatively by Exerfarm Valley and used to support exercise therapy.
- Creation of multidisciplinary iterative design of exergames (MIDE) framework to guide the process of design, development, and evaluation on exergames.

Chapter 4

Development and evaluation of data visualizations

As discussed in section 3.2.2, Exerfarm Valley system can collect a variety of metrics that represent the player's performance during exergaming sessions. The objective information collected through Exerfarm Valley can be used to help exercise therapists manage or administer the exercise programs, review a client's current and past status, and communicate with the clients on their progress through appropriate data representation methods. The primary objective of this thesis work is to develop new ways of presenting information about player's performance and exergaming sessions using visualization techniques to support exercise therapy delivery. In this chapter, the process of data visualization creation and the evaluation of proposed visualizations are presented.

The design and evaluation process of data visualizations was done through three phases, which are described in the sub-sections that follow:

- Phase 1: Brainstorming workshop and initial data visualizations creation
- Phase 2: Focus group and refinement of data visualizations
- Phase 3: Evaluation of data visualizations through an online questionnaire

4.1 Phase 1: Brainstorming workshop and initial data visualizations creation

To explore the ways therapists use metrics in practice as well as what new metrics might be helpful, a brainstorming workshop was hosted. Brainstorming is a technique that is used to foster group creativity in generating ideas and solving problems [151]. Its applications have expanded from the original use for supporting creativity enhancement in the corporate setting to various fields and settings, including collaborative design with stakeholders and end-users [152, 153, 154]. In the context of this work, the brainstorming workshop was used to collaboratively explore and define potential data visualizations exercise therapists could use in reviewing and analyzing the quantitative data collected from HMD-VR exergames for the identified metrics.

4.1.1 Methodology

Due to limited access to exercise professionals from industry partners during the COVID-19 outbreak, additional exercise therapists were recruited from local community exercise programs as research team members to develop data visualizations collaboratively. The session started with an introduction using videos of the Exerfarm Valley game, and resulting data was given to explain the kinematic data that can be collected from HMD-VR technology and recap the measures that could be used to represent the player's performance during an exergaming session. Based on metrics identified in Table 3.2 and consultations with game developers, a list of game metrics that can be collected using Exerfarm Valley system (see Appendix C.3) was prepared to guide the brainstorming discussions. Using rated importance of the metrics in Table 3.2 as a reference, the valuable information (i.e., measures rated as crucial or important) to visualize in exercise therapy was settled for data visualization brainstorming discussions. In particular, sample data visualizations (see Appendix D.1) of the metrics using simple techniques (bar chart, table, line chart, etc.) were created to provide examples of potential ways in visualizing the information and facilitating the brainstorming process to develop potential ideas for data visualizations. During collaborative brainstorming activities, expectations of the data visualizations and information needed to understand the exergaming sessions were specified and transcribed. The proposed data visualization ideas and metrics information from the brainstorming discussions were analyzed and summarized using concept mapping. A conceptual map generated by concept mapping is a network-like visual representation of information relations and knowledge structures [155]. Conceptual maps have been used in similar ways by other researchers to inform reports of a brainstorming workshop [156] and the design guidelines of a system [157] by illustrating the considerations and their relationships.

The goals of the brainstorming workshop were:

1. gain a better understanding of the preferences and expectations of exercise therapists with respect to different data visualization techniques and metrics
2. collect ideas to generate initial data visualizations for plausible metrics

4.1.2 Results

The participants of the brainstorming workshop were:

- four exercise professionals from the local YMCA associations (3 female, 1 male;2 kinesiologists, 1 business manager, and 1 program supervisor)
- three University of Waterloo researchers from the field of Kinesiology (1 associate professor and 2 PhD candidates)
- two engineer researchers from the University of Waterloo with experience in data visualizations (1 postdoctoral fellow and 1 MASc candidate)

The potential data visualization techniques and the representing information were analyzed and summarized using a conceptual map. The conceptual map of data visualization ideas generated in the brainstorming workshop, including feasible metrics and expected features, is shown in Figure 4.1. Seven data visualization ideas on five different metrics were generated during the brainstorming sessions:

- **Performance score:** The performance score of a game can be displayed in two ways: 1) player performance evaluated as a number in percentage or out of a fixed maximum value; 2) game score calculated based on specific game event (e.g, hit a target, catch a fish, hold a ball). Depending on the specific variable to be collected and its type, the unit and range of the performance score vary. For example, the performance score can be expressed numerically, ranging from 0 to 100% or 0 to 15 (number of a specific game event or value of the game performance score). Different data visualization techniques will be used in visualizing the two types of performance scores:

  - A pie chart could be used to illustrate the player's performance out of a maximum value by highlighting specific sections of the circle.
  - Bar graphs could be used to compare the performance scores between different sessions or events of the game.

- **Reaction time:** Reaction time may be captured multiple times during the game by measuring the time (milliseconds) player takes responding to specific game events/clues (e.g., controller vibration, audio notification). An averaged reaction time for different sessions could be displayed using a bar graph with variance within and between sessions.

- **Distance rowed (kilometers or meters):** Distance rowed could not only reflect the player performance during a rowing game but also indicate the overall intensity of the session. A bar graph could be used to visualize the distance rowed of rowing game, allowing comparisons between different sessions.

- **Heart rate:** A color-coded line graph could be used to show the heart rate responses (beats per minutes) of a client during the game. Stroke rate (revolution per minutes) could also be integrated as a secondary intensity indicator.

- **Range of motion:** A client's range of motion (RoM) can be evaluated through the movements performed. Two data visualization ideas were generated:
  - Expected movement range (centimeters or inches) could be compared with the client's actual movement using a radar chart.
  - All movements during the game could be visualized using a 3D graph to review the exergaming session. The outlier movements can be detected and noted in the 3D graph.

4.1.3 Initial data visualizations creation

Four measures were selected to generate data visualizations for further refinement based on the data visualization ideas generated in the brainstorming workshop:

- **Distance rowed:** an estimation of how far a player would have rowed in real life if he/she was in a rowboat during the rowing game in an Exerfarm Valley exergaming session.

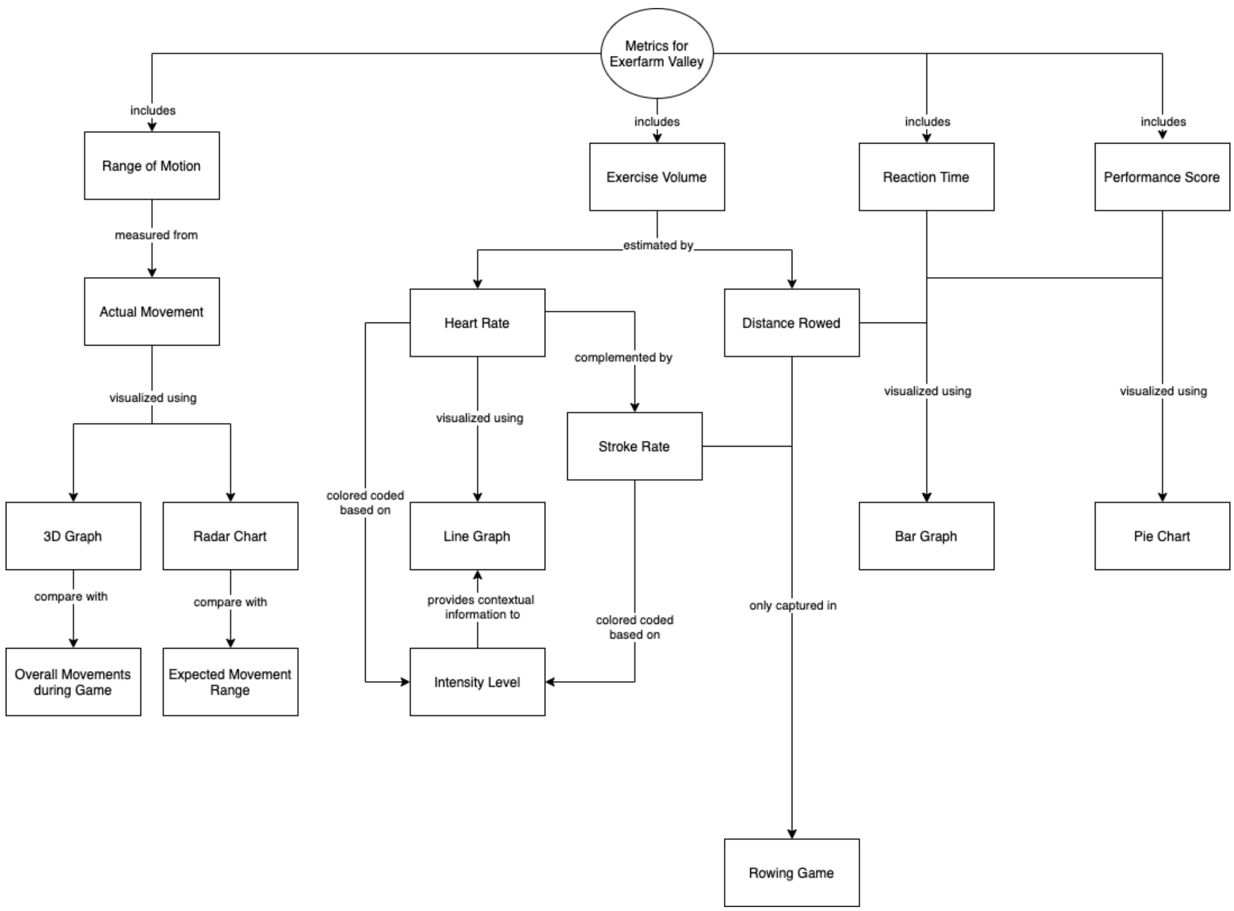


Figure 4.1: The conceptual map of potential data visualization techniques and represented information summarized from the data visualization brainstorming workshop.

- **Heart rate and (arm movement) stroke rate:** the physiological responses of a player and physical movements derived information during the rowing game in an Exerfarm Valley exergaming session.
- **Functional reach:** a client's RoM status by describing how far a person can reach in a seated position.
- **Motion trajectory during gameplay:** the physical locations a player's hands went, extracted from the HMD-VR hand controllers, during the Exerfarm Valley exergaming session.

Distanced rowed - Bar graph

When presented the distance rowed with a short table of related data and a line graph (Figure D.1 in Appendix D.1) in the brainstorming workshop, exercise therapists expressed that a bar graph would be more suitable for visualizing discrete measurements analogous to distance rowed and reaction time. Compared with the line graph, therapists indicated that it would be "more intuitive to just see the bars or just the numbers" while bar graph could also provide some additional information as a line graph, such as trend lines, without introducing biases or assumptions about the changes between different sessions. Thus, a **bar graph** was identified as the preferred way to visualize distance rowed for the rowing game. In Figure 4.2, a mock-up of the weekly record for a client playing the Exerfarm Valley rowing game daily was displayed using the proposed data visualization technique for distance rowed. Weekly and monthly averaged distances for the client were also calculated and presented in the data visualization to give more contextual information about an overall client's performance.

Heart rate and (arm movement) stroke rate - Line graph

In brainstorming the appropriate ways of visualizing heart rate information, exercise therapists built upon the presented idea of the line graph and indicated that contextual information in the background on a secondary y-axis would be helpful. Specifically, stroke rate, which can be derived from arm movements during the rowing game, was proposed as a complementary intensity measure for possible useful information. As a result, visualizing both heart rate and stroke rate in a **line graph** was considered the appropriate way to deliver exercise intensity information about the rowing exergaming sessions. As shown in Figure 4.3, three different alternatives were proposed to visualize heart rate and

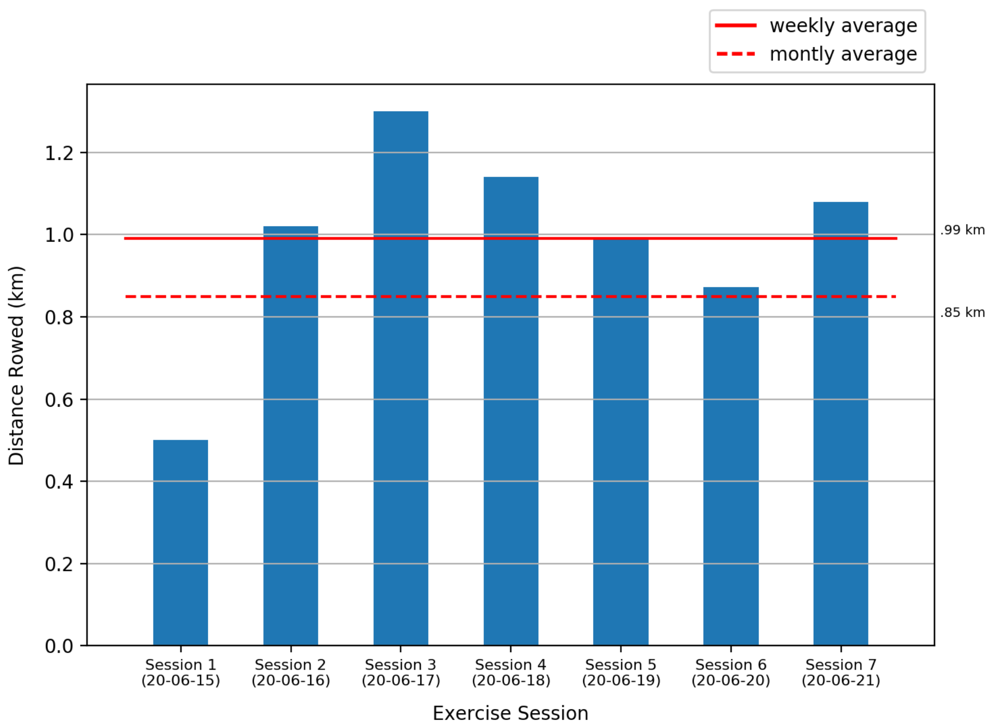


Figure 4.2: Distance rowed - initial data visualization

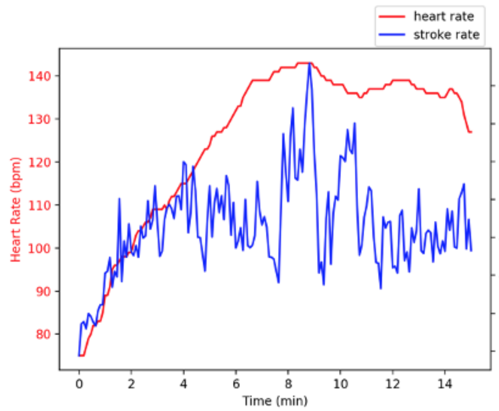
(arm movement) stroke rate. Figure 4.3a presented the information using a double-axes line graph; the colored axis legends reinforced the relationships between the line and the corresponding axis. As exercise therapists mentioned the potential of color-coded information in supporting "understanding at a glance", heart rate zones were masked in specific industry-chosen colors on the data visualization to indicate the corresponding level of intensity [158]. Additional intensity zones, which are calculated based on the maximum heart rate of an individual [158], were added to the double-axes line graph to provide additional context information in understanding the data visualization, as shown in Figure 4.3b. In Figure 4.3c, heart rate and stroke rate were visualized using two different line graphs with the aligned x-axis. All five heart rate zones were displayed on the heart rate line graph, allowing therapists to understand the exergaming session quickly without diving into exact numbers.

Functional reach - Radar chart

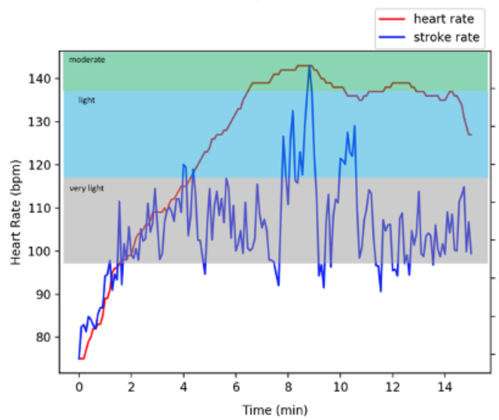
Exercise therapists thought the radar chart could be useful in showing the client's RoM during the brainstorming workshop. The expected RoM was requested by exercise therapists as the contextual information in assessing client's status. Hence, the functional reach of a client in both frontal and lateral directions were visualized using a **radar chart**. Figure 4.4 contrasted the specific client's results with the normative data of the population, such as normal person RoM or averaged clients' RoM, through different colors.

Motion trajectory during gameplay - 3D graph and 2D projected graph

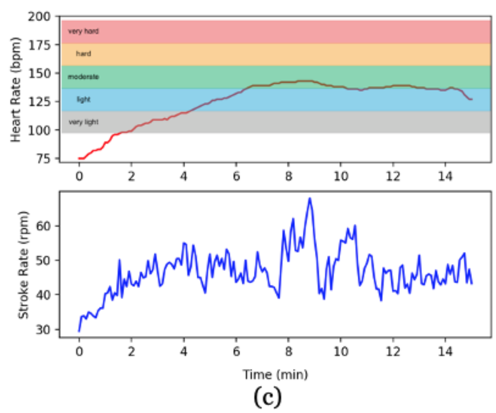
Motion trajectory during gameplay displayed using **3D graph** was considered helpful in providing accurate movement information of a client during an exergaming session in the real world. Exercise therapists thought the data visualization could potentially help with reviewing the exergaming sessions by annotating the motion trajectory and the position of the client. Figure 4.5a explored the data visualization idea with an avatar figure representing the position and the posture of the client during gameplay. The physical locations of the client's hands over time, recorded through HMD-VR hand controllers, were plotted in the 3D space, indicating the motion trajectory during the game. Besides, 2D planar view of the motion trajectory was considered helpful in evaluating the client's movements. Hence, the motion trajectory during gameplay was projected onto the frontal plane, transverse plane, and sagittal plane (see Figure 4.5b, c, and d). Considering the nature of repetitive movements during the game, exercise therapists emphasized the importance of showing



(a)



(b)



(c)

Figure 4.3: Heart rate and (arm movement) stroke rate - initial data visualization

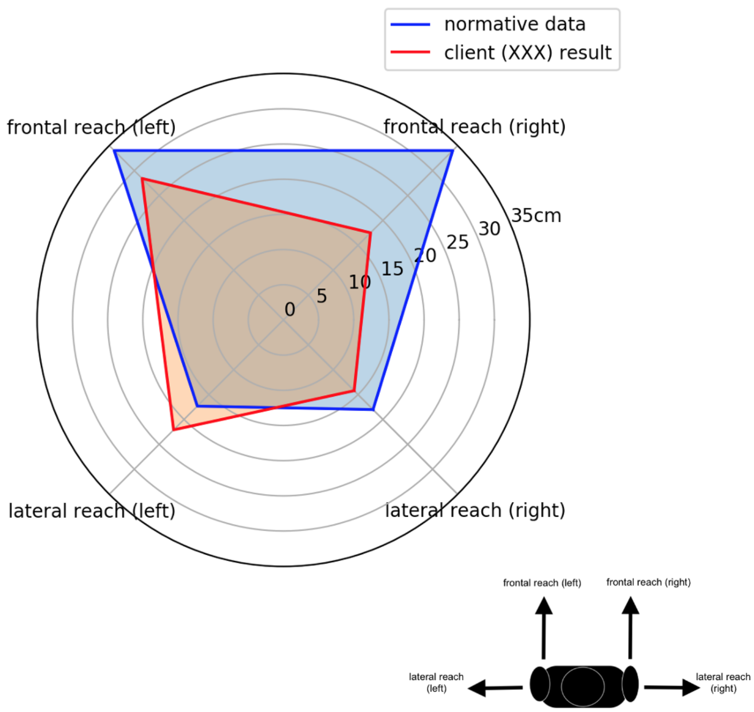


Figure 4.4: Functional reach - initial data visualization

the abnormal movements and the corresponding time such movement happens. The time and location features of the motion trajectory were examined in Figure 4.5e and f.

4.2 Phase 2: Focus group and refinement of data visualizations

Focus groups are forms of qualitative interviews that allows researchers to gather information through interactive group discussions [159, 160]. Focus groups have been used in different fields of study to collect insights of participants on the specific subject (i.e., product, topic, issue) [160, 161], and have been adopted by data visualization researchers in identifying the design requirements and exploring ideas for data visualizations [162, 163, 164]. In this thesis work, the focus group was use to evaluate the appropriateness of the techniques used in the proposed data visualizations, uncover detailed design preferences in visualizing the information, and foster creation of novel data visualizations.

4.2.1 Methods

The same exercise professionals from the local YMCA associations in the previous brainstorming workshop were invited to a semi-structured focus group to review the proposed data visualizations. The focus group was carried out as a design workshop where the presented data visualizations aimed to foster the discussions of novel data visualizations creation, if possible. Specifically, the workshop can be separated into three sections:

- Introduction: Demo the rowing game of Exerfarm Valley and review the metrics to be used in the session
- Exploratory activity: Exercise therapists present the way they would visualize the proposed metrics and sample data
- Data visualizations discussions: The four data visualizations created in the previous phase (see Section 4.1.2) were presented one at a time to promote discussions through the semi-structured questions shown in Appendix D.2

The design ideas from exploratory activity and the feedback on initial data visualizations were analyzed and categorized into different themes using an affinity diagram.

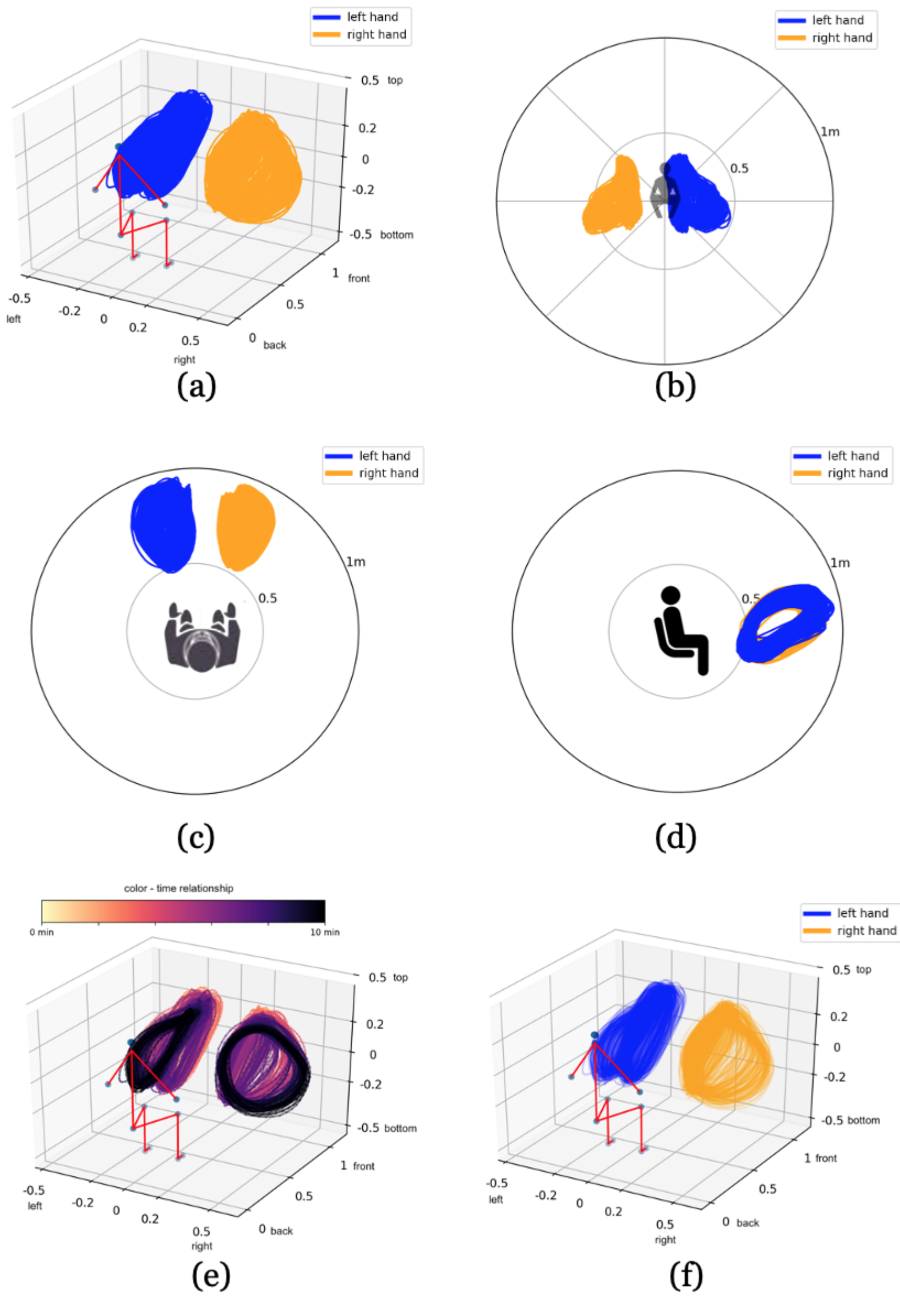


Figure 4.5: Motion trajectory during gameplay - initial data visualization

Affinity diagramming was initially developed by Jiro Kawakita in the field of anthropology to synthesize observations of fieldwork raw data and find new hypothesis [165]. Affinity diagramming is used to organize large amount of unstructured qualitative data based on their natural relationships, and has been used as a systematic approach to problem solving and solution evaluation in the field of human computer interaction and user experience[166, 167].

The objectives of the focus group were:

1. identify data visualization techniques to be used for the proposed information
2. discover the design preferences of the data visualization elements
3. collect novel design ideas for the data visualization concepts

4.2.2 Results

Data visualization ideas inspired by initial data visualizations were condensed from constructive discussions. Feedback and suggestions were extracted from the video recordings and session notes for further categorization. An affinity diagram (see Appendix E.2.1) was used to identify themes by clustering feedback of the data visualizations based on the type of information presented. Insights from the focus group are summarized in Table 4.1.

4.2.3 Refinement of data visualizations

The author used insights from the focus group to iteratively refine the data visualizations through three additional consultation sessions with research team members from the University of Waterloo.

Distanced rowed - Bar graph

Adopting the suggestion of using graphical representations, icons were added at the end of each horizontal bar in Figure 4.6 to visually represent the movements player perform in achieving the estimated distance during the rowing game. The distance rowed of the sessions were displayed on the top at the end of each horizontal bar for detailed client performance. As suggested by exercise therapists, the dates of the exercise sessions could not only show the time difference between sessions but also allow them to refer back to a

Table 4.1: Feedback, suggestions, and perceived usefulness of the initial data visualizations from data visualization revision focus group

Visualization	Feedback on Visualizations	Design Suggestions	Potential Use
Distance rowed (Figure 4.2)	• The data visualization is clear and intuitive. • Date of the session is useful.	• Use intuitive graphical representations at the end of horizontal lines/bars. • Insert footnotes to record conditions that may inversely affect client performance (e.g., lack of sleep, persistent pain). • Highlight the best session and the positive information.	Show to client or use in the end of program report
Heart rate and (arm movement) stroke rate (Figure 4.3)	• Option (c) is preferred. • Heart rate and stroke rate presented is clear and easy to correlate. • Heart rate zone provides helpful contextual information.	• The heart rate zone can be automatically calculated by entered the age of the population. • The time client spent in each heart rate zone would be helpful. • The value of peak heart rate during the session would be nice to have.	Show to client
Functional reach (Figure 4.4)	• The data visualization is intuitive. • Asymmetric information can be detected easily. • The normative data is helpful.	• Overhead reach is useful to see. • The data visualization could be used to compare the range of motion before and after an exercise program.	Show to client
Motion trajectory during gameplay (Figure 4.5)	• Time feature is needed to understand the movements during the exergaming session. • Option (d) is not useful with overlapped motion trajectory.	• Averaged motion trajectory would be helpful. • Maximum value for range of motion could be displayed.	Not in the current practice, could be useful for someone working with specific individuals

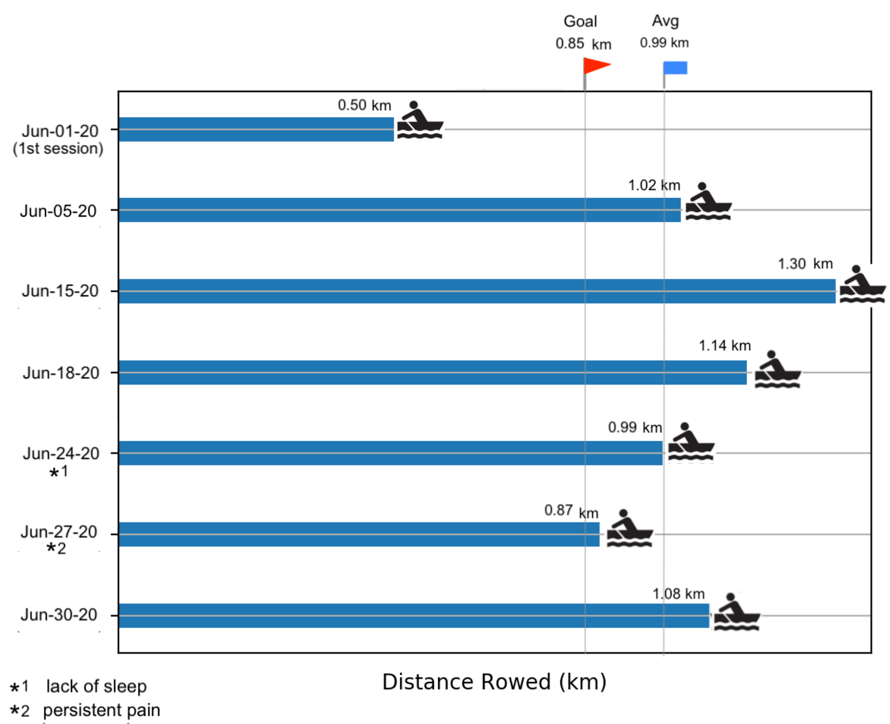


Figure 4.6: Distance rowed - revised data visualization

specific exercise session journal if needed. Hence, only dates were used on the vertical axis to indicate the exergaming sessions. A preset goal and averaged (e.g, weekly, monthly, average of all clients) distance rowed were available as well, depicting the contextual information for evaluating the performance of a client. In understanding the client's performance and the changes between different sessions, the condition of a client or special sessions that may affect the client's performance in an exergaming session were clarified per the request of exercise therapists. Additional qualitative information about a client obtained through conversations or observations, such as lack of sleep and persistent pain, were recorded as footnotes about the specific sessions.

Heart rate and (arm movement) stroke rate - Line graph and table

Preferred by all exercise therapists in the focus group over other alternatives, a separated line graph with an aligned x-axis was chosen to visualize time-series information during an exergaming session. Since stroke rate is specific to the rowing game, the stroke rate in

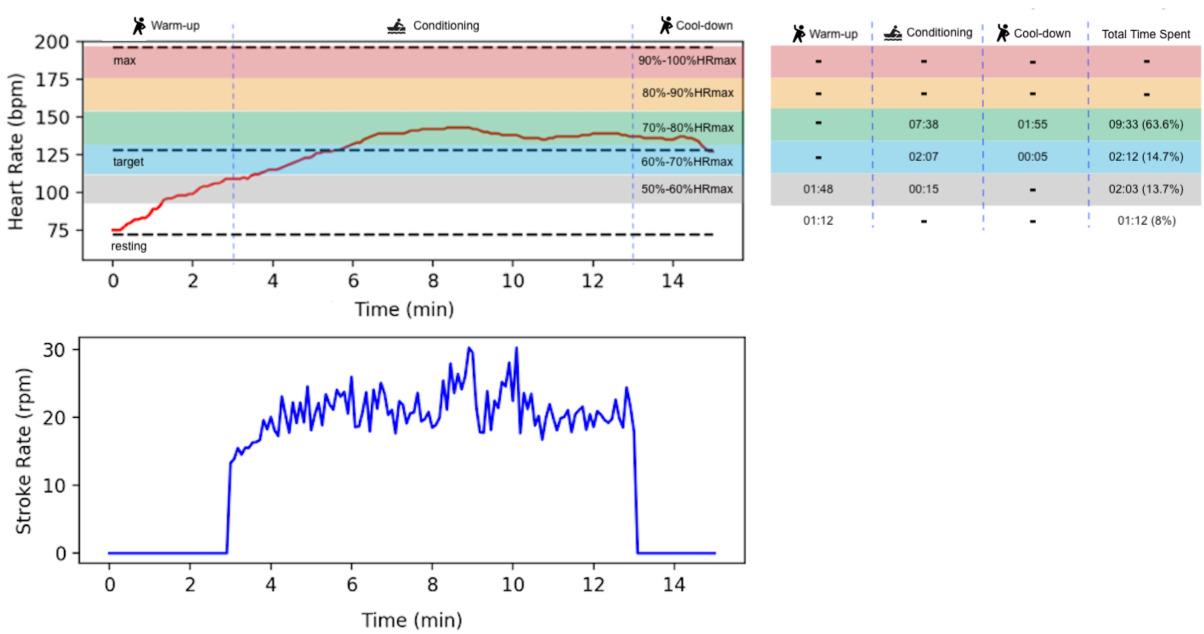


Figure 4.7: Heart rate and (arm movement) stroke rate - revised data Visualization

the warm-up and cool-down stages were considered to be zero. Time spent in each heart rate zone was requested by exercise therapists as useful information in communicating with their clients. In Figure 4.7, time spent in different heart rate zones was calculated for each stage and the whole exergaming session. Different stages were indicated at the top of the data visualization for reference information about an exergaming session over time. As indicated by exercise therapists, heart rate zones provide reference information about exercise intensity. During the focus group and internal consultation sessions, exercise professionals expressed the concern of possible confusion between heart rate intensity zones and intensity zones derived from other measures, such as movements or rating of perceived exertion (RPE). As a result, the heart rate zones were labelled according to the percentage of an individual's maximum heart rate. Additional reference information about the exercise intensity and a client's status can be extracted from the lines of maximum heart rate, target heart rate, and resting heart rate.

Functional reach and overhead reach - Radar chart

Based on the exercise therapists' feedback from the focus group, overhead reach was added to the radar chart to compare a client's RoM with population normative data (see Figure

Figure 4.8: Functional reach and overhead reach - revised data visualization

4.8). The functional reach and overhead reach results were distributed symmetrically along the vertical axis to enable visual comparisons between a client's left hand and right hand. In case a client's RoM is close to the population normative data, a half-circle would be used so that both the markers from the client and population norm are visible.

Motion trajectory during gameplay - 3D graph and 2D projected graph

As mentioned by exercise therapists in the focus group several times, the motion trajectory should be color-coded with time to distinguish movement trajectory over time and detect changes of movement during an exergaming session. In Figure 4.9, motion trajectory

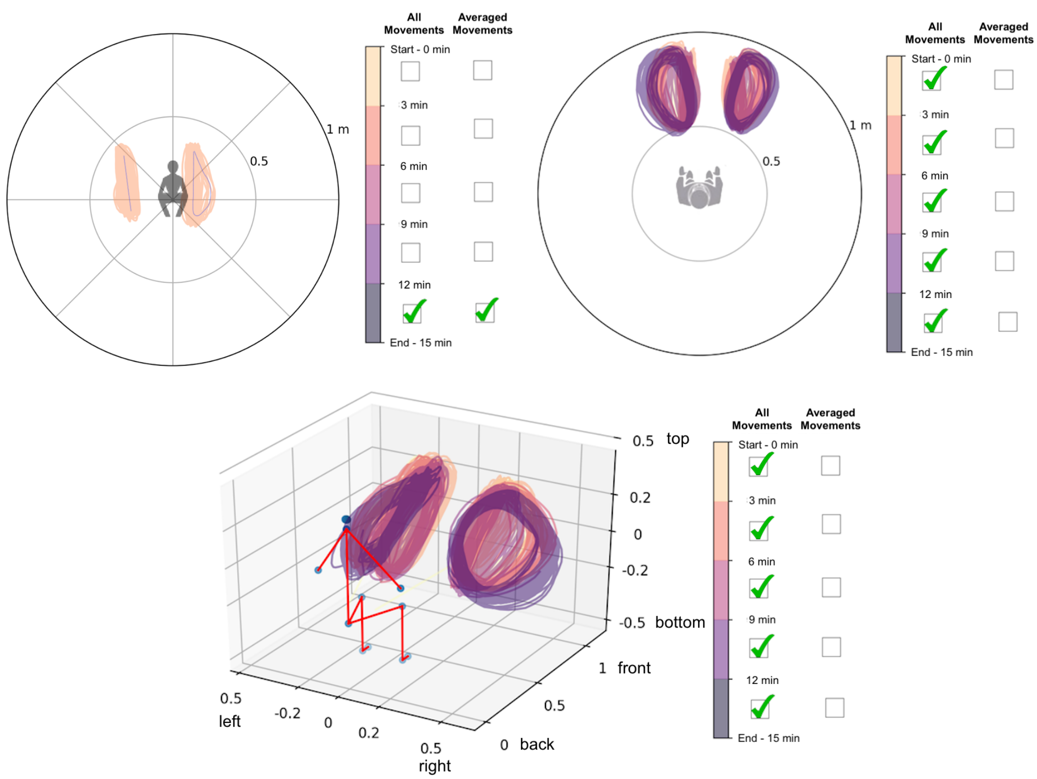


Figure 4.9: Motion trajectory during gameplay - revised data visualization

during gameplay was segmented into multiple equal-length sections based on time, which allows exercise therapists to inspect a specific period during the exergaming session. An averaged motion trajectory for the individual section was also calculated and displayed since exercise therapists considered an averaged motion trajectory to be helpful. As exercise therapists reported the motion trajectory projected onto the sagittal plane not useful at all for evaluating a client's movement, 2D projected graphs of motion trajectory onto the frontal plane and transverse plane were used in the revised data visualization.

4.3 Phase 3: Evaluation of data visualizations through an online questionnaire

After in-depth discussions with recruited YMCA exercise therapists on how to visualize information collected from Exerfarm Valley, the proposed data visualizations should be explored with other exercise professionals for further evaluation and refinement. Questionnaires have been used to collect subjective evaluations of data visualizations and the associated user experience [168, 169, 170]. In order to reach potential participants with a variety of background regardless of the physical location restrictions, the potential of the data visualizations in complementing exercise therapy practice was evaluated through an online questionnaire, which has been employed as a method of evaluating and validating data visualizations [110].

4.3.1 Methodology

An online questionnaire (Appendix B) was developed to collect quantitative and qualitative information. The questionnaire is hosted through the University of Waterloo Qualtrics platform and was distributed via an anonymous link.

Informed consent was obtained at the beginning of the questionnaire by asking potential participants to read through a description of study and indicate their agreement, or not, to participate in this study by selecting the appropriate radio and then clicking on the "next" button. Demographic information about the participants was collected and a demo video of the rowing game was shown to provide detailed contextual information about the study. Distance rowed data visualization (DR, Figure 4.6) was presented at the first to quickly bring the participants into rowing game metrics. As another data visualization delivering information about exercise intensity for the exergaming session, heart rate and (arm movement) stroke rate data visualization (HRSR, Figure 4.7) was evaluated based on the same quantitative questions and some specific qualitative questions. The motion trajectory during gameplay data visualization (MTDG, Figure 4.9) lined up as the next evaluation item in order to collect as many information as possible about the novel data visualization considering the potential withdrawal in the middle of the questionnaire. After evaluating the functional reach and overhead reach data visualization (FROR, Figure 4.8), participants were directed to a separate survey to indicate if they want to receive further publication(s) update and/or a digital gift card as an appreciation of their time and input.

A convenience sample of 25 participants was considered a good target to obtain sufficient information [171]; similar studies have had 5 - 15 participants [172, 27, 173]. The survey was distributed through different networks (e.g., Schlegel-UW Research Institute for Aging [1], AGE-WELL [2], YMCA Canada local associations [3], Ontario Physiotherapy Association [4]) and potential participants were invited through emails to participate in this study as long as they satisfy the following inclusion/exclusion criteria:

- Be an exercise therapist or have other related expertise.
- Have experience with managing or administering exercise therapy.
- Be able to provide informed consent.
- Be able to communicate fluently in English.

The participants were asked to share their candid opinions and thoughts about the data visualizations. The questionnaire consists a set of likert-scale questions to quantitatively analyze the user experience of the data visualizations as well as several qualitative questions to elicit discussions on the specific data visualization [170]. The qualitative questions aim to explore the potential of each data visualization in the practice and identify gaps between the data visualizations and the expectations of exercise therapists. There are also slider-scale rating questions asking exercise therapists' impression about the data visualizations on four different aspects [174]:

- Usefulness: How useful do you find the data visualization?
- Completeness: How comprehensive is the information presented in the data visualization?
- Intuitiveness/perceptibility: How clear is the information in data visualization?
- Appropriateness: How appropriate is the data or data visualization elements that are included in the data visualization?

Mean and standard deviations were calculated for the quantitative responses to analyze the dispersion of exercise therapists' judgements over the data visualizations. The qualitative information inquiring about the improvement and usage of the data visualizations were thematically analyzed using affinity diagrams in order to identify themes and organize feedback regarding the data visualizations. One affinity diagram was created for each data visualization.

[1] https://the-ria.ca/
[2] https://agewell-nce.ca/
[3] https://ymca.ca/
[4] https://opa.on.ca/

4.3.2 Results

The demographic information of the respondents is summarized in Table 4.2.

Table 4.2: Demographic information for the online questionnaire respondents (n=24).

Characteristic	Value
Age (Years)	
Min	22
Max	43
Average	29.9
Gender	
Female	20
Male	4
Occupation[a]	
Kinesiologist	13
Exercise Therapist	6
Facilitator or Management Position	4
Recreational Therapist	3
Other	1 [b]
Setting of Working Environment [a]	
Long-term/retirement care	21
Community Program	3
Private Practice	1
Work Experience (Years)	
Min	1
Max	20
Average	7
Region	
Canada, Ontario	24

[a] Respondent may report multiple if applicable
[b] Personal trainer

Figure 4.10 and Figure 4.11 present quantitative responses from the exercise professionals regarding the data visualizations; detailed values can be found in Appendix E.1. Qualitative responses were analyzed using affinity diagrams (Appendix E.2.2) and the main insights are summarized based on different themes for each data visualization as follows:

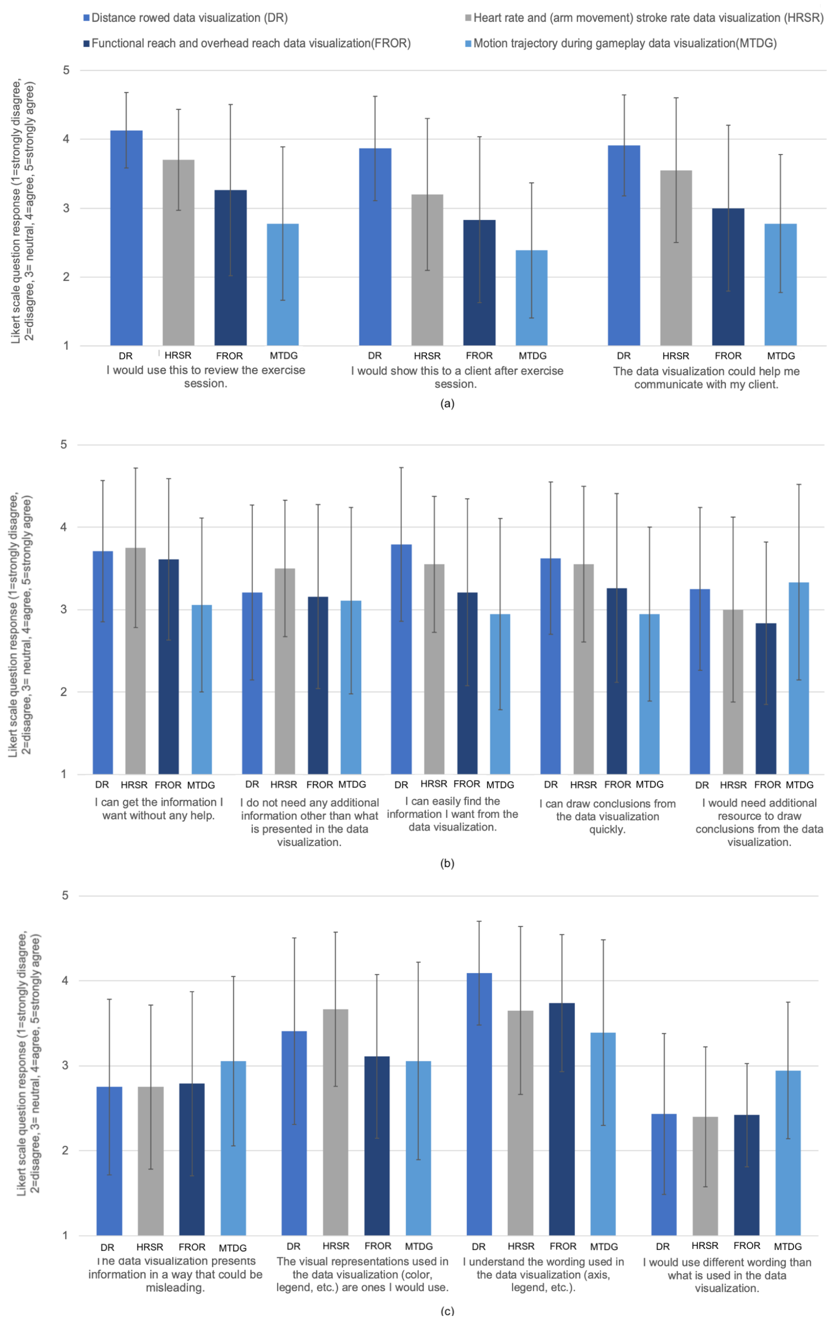


Figure 4.10: Qualitative responses on likert-scale questions (1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5=strongly agree), categorized based on different themes: (a) perceived usefulness, (b) information delivery, (c) visual representation; error bars represents the standard deviation of each response.

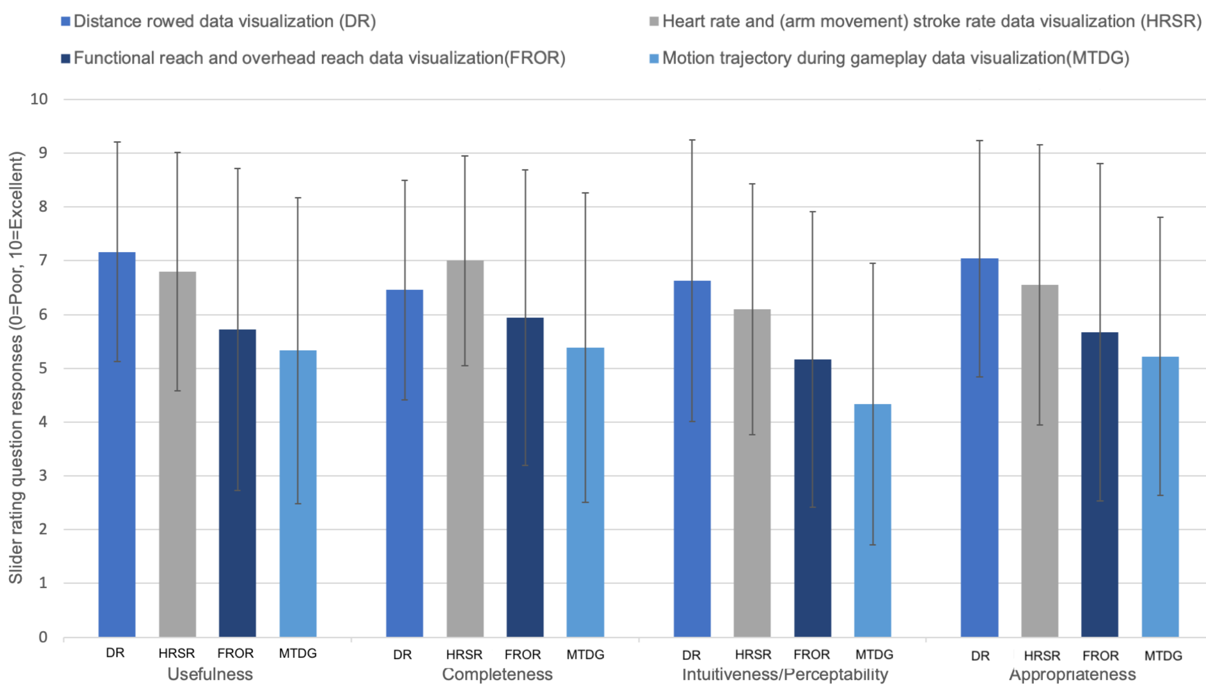


Figure 4.11: Qualitative responses on slider rating questions (0=poor, 10=excellent); error bars represents the standard deviation of each response.

Distanced rowed - Bar graph (n=23; 18 complete responses, 5 partial responses)

In envisioning the **potential use** of DR, respondents reported different scenarios in delivering exercise therapy practice:

- *Communication (n=17):* DR was perceived as a useful tool to facilitate the communications between exercise therapists and the clients or their family members as a progress report of client's performance during the exercise program. Showing the progress and performance, DR could prompt further discussions between exercise therapists and the client, particularly for motivation. Five respondents mentioned that goal setting with the clients could be easier with DR.

- *Administration/management (n=7):* When administering the exercise program, DR was envisioned to be useful in tracking progress of a client. Comparing the progress with other information (e.g., journals, rating of perceived exertion (RPE)), DR could be used to check well-being/health/safety of a client and adjust goals if needed. DR was seen as a potential way to coordinate the program across multiple clients in creating group goals or competitions. One exercise therapist mentioned that DR could be used to advertise the program.

- *Not useful (n=5):* Three exercise therapists reported that DR not applicable to their clients. Two respondents were concerned about the applicability of the exercise intervention to their clients.

Other applications that could employ bar chart in visualizing the information from an exercise session, as reported by exercise therapists, are:

- *Distance related activities (n=16):* Respondents nominated activities that are distance based like walking, biking, swimming, hiking, etc.

- *Training programs (n=3):* Applying the same concept but different metrics, exercise therapists reported that they would modify DR for programs such as gait training, strength training, and balance training. Instead of distance rowed, the metrics to be represented in the data visualization could be time duration on each side for gait and balance training or weight used in strengthening programs.

- *Repetitive movement activities (n=2):* Therapists reported activities that require repetitive movements or events could use the concept of DR. Example activities include object stacking, object lifting, apple picking, and basketball shooting.

- *Object projectile activities (n=1):* Since the performance of the player in an object projectile activity can be calculated by the distance the object travels, DR could be applied to any activities that creates a projectile (e.g., object throwing).

- *Other activities (n=2):* In general, outdoor activities or recreational activities could use this data visualization. However, respondents were not able to name specific activities.

When asked about **representing the sessions** in DR, eight respondents wanted to keep the existing design that uses only date to label exercise sessions while 12 respondents indicated they would like to see both session number and date. In response to the design of DR, exercise therapists provided several **design suggestions**: 1) include the total time player used in achieving the distance rowed (n=4); 2) optimize the design for visually impaired populations by increasing the font and using high contrast colors (n=3); 3) color-code the session with special conditions and add corresponding legend (n=1); 4) include more information about the exercise session or client's performance (n=6), such as range of motion (RoM), movement efforts, heart rate, "a scale for how they felt about the session", and some other details about a single session. Other **feedback on the visualization** from the respondents includes: 1) make the goal and average more obvious in DR for an easier comparison between the bars representing distance rowed (n=1); 2) use color to differentiate different sessions (n=2); 3) put the footnote explanation closer to the specific sessions (n=1); 4) average distance rowed should be removed (n=1); 5) use vertical bar graph instead of the existing horizontal bar graph (n=1); 6) "well done", "great tool", etc. (n=4).

Heart rate and (arm movement) stroke rate - Line graph and table (n=20 responses; 14 complete responses, 6 partial responses)

The **potential use** of HRSR can be categorized as follows:

- *Communication (n=9):* HRSR was perceived as a complementary information to facilitate the discussions with clients in goal setting, motivation, and progress/performance review.

- *Administration (n=7):* With the heart rate and stroke rate being tracked throughout the session, exercise therapists reported that they would use HRSR to review the exercise sessions and monitor client's responses, ensuring the delivery of exercise therapy at an appropriate pace or level.

- *Not useful (n=6):* Three respondents considered heart rate as less important and useless information since the heart rate responses could vary a lot between people and sessions. Three therapists indicated that HRSR might cause confusion as "it's too much for the resident to comprehend".

As the **secondary intensity indicator**, 10 respondents considered stroke rate useful in understanding the exercise intensity, to understand a client's maximum performance and identify potential mobility challenges, quantify fatigue, and to gauge improvements in endurance. However, other exercise therapists (n=5) expressed concerns of using stroke rate due to confusion and lack of validity. As an alternative, two exercise therapists suggested to use an exertion scale (e.g., RPE). Another potential intensity indicator could be the force applied to controller during a stroke, as nominated by one exercise therapist. In addition, six respondents indicated that a secondary intensity indicator (i.e., stroke rate) for warm-up and cool-down stage would be helpful while three exercise therapists preferred the existing data visualization. Exercise therapists also provided **feedback on the visualization**: 1) use heart rate reserve to calculate heart rate ranges (n=1); 2) the table in HRSR was confusing (n=2); 3) the heart rate zone colors, in particular green and blue, were hard to tell apart (n=1). Additional information, such as "how the participant feels throughout the sessions" and oxygen uptake, were requested as **design suggestions**. Five respondents liked the HRSR.

Functional reach and overhead reach - Radar chart (n=20 responses; 13 complete responses, 7 partial responses)

Considering the **potential use** of FROR, nine therapists indicated that *administration* of the exercise program could be benefited. Specifically, four exercise therapists indicated that they could review range of motion information through visual comparison to the target value; five respondents would use FROR to understand the client's RoM in order to deliver or adjust exercise therapy. On the other hand, FROR was considered to be *not useful* by other respondents (n=8) mainly because FROR was confusing to them and hard to explain to their clients (n=3). Three respondents indicated that the information presented was not valuable.

When asked about the **comparative information** to be used in FROR if there were no normative data for the population that could be used, eight exercise therapists commented that they would compare the performance of same individual over time (e.g., initial assessments, average of previous measurement results). Respondents (n=5) also indicated that group means calculated based on records from the population in community or long-term care facilities or from healthy population were acceptable, as long as general characteristics (e.g., gender, age, etc.) are matched. In the category of **feedback on the visualization**, five respondents reported the FROR was not self-explanatory and confusing while a respondent was concerned about potential frustration in clients brought by the comparison with norm. **Design suggestions** for the FROR were: 1) create a table or leader board (n=2); 2) have two radar charts representing the actual plane and location of the direction an individual performed during a reach test (n=2).

Motion trajectory during gameplay - 3D graph and 2D projected graph (n=20 responses; 15 complete responses, 5 partial responses)

The **potential use** of MTDG in exercise therapy practice are:

- *Not useful (n=10):* Respondents reported that they would not use MTDG in the practice. Reasons include: 1) the data visualization is complicated and confusing; 2) the information presented in MTDG does not provide useful information about the client or exercise sessions; 3) the data visualization and exercise intervention are not applicable to all clients.
- *Movement evaluation (n=9):* Respondents indicated that MTDG allows them to evaluate movements and posture of a client during the game. By identifying potential hazardous posture or movement issues, exercise therapists would be able to instruct clients the appropriate movements/posture to avoid further injuries.
- *Identify trend (n=9):* Through comparisons of the movements in different hands and between repetitions, exercise therapists mentioned they could use MTDG to identify trends of a client's movements. Examples of things they could use the MTDG for include identifying dominant side of a client, spotting potential weakness, and identifying restrictions in movements.

For the **graph(s) to be included** in MTDG: Nine respondents preferred to have both 3D graph and 2D projected graph; six people thought 2D projected graph is easier to understand; two exercise therapists liked 3D graph only; and two exercise therapists would like an additional sagittal plane 2D projected graph. Regarding **feedback on the visualization**, two respondents reported that MTDG is confusing while two exercise therapists suggested that the motion trajectory of different colors should not overlap with each other. The **design suggestions** of the data visualization are: 1) label the 2D projected views for people with different backgrounds (n=1); 2) add explanations to MTDG (e.g., checkmark for sectioned motion trajectory, meanings of different colors) (n=3).

4.4 Discussion

While all four data visualizations explored in this thesis research were new to therapists, the 3D graph (MTDG) and radar chart (FROR) are more novel compared to the bar graph (DR) and line graph (HRSR). As such, exercise therapists may require more time in understanding the more novel proposed visualizations as well as envisioning the potential use of them, as discussed during both the data visualization brainstorming workshop and the revision focus group. Results obtained in the online questionnaire support this view as responses showed greater difficulties in comprehension and envisioned use; the slider ratings for MTDG and FROR are one or more points less for MTDG and FROR than for DR or HRSR in all aspects (i.e., usefulness, completeness, intuitiveness, appropriateness). In the qualitative responses, more exercise therapists wrote “I don’t understand” or similar comments for the MTDG or FROR in comparison with the other two data visualizations. One respondent suggested the need to “educate the person operating on how to read” the MTDG as it’s not “easily interpretable”. Between the two novel data visualizations, FROR slightly outperforms MTDG in every statement for the quantitative questions and more respondents find MTDG not useful or confusing. However, as no statistical analysis were done, it cannot be stated if there were significant differences.

Among all four data visualizations, DR is rated as most useful, intuitive, and appropriate. Distance rowed, as a measurement, can be used to represent player’s performance during an exergaming session regardless of an individual’s cardiovascular status. According to three exercise therapists working with seniors from the online questionnaire, heart rate is not the most important metrics and some individual’s heart rate responses during exergaming sessions are meaningless due to atrial fibrillation or other heart conditions. While HRSR is most complete in the information presenting. Exercise therapists need “more details from a single session” in order to evaluate the client performance and managing exercise therapy. DR provides an overview of multiple exercise sessions but lacks detailed information about a specific exergaming session.

Respondents indicated that DR and HRSR could be implemented to help exercise therapists administering the exercise therapy programs. The other two data visualizations, on the other hand, need to be further refined in order to deliver meaningful information to exercise therapists using appropriate data visualization elements. Based on the responses, the most common theme for perceived usefulness of the data visualizations presenting exercise intensity (i.e., DR, HRSR) related information is communication with clients, especially for goal setting or motivational purposes. Although almost half of the respondents considered FROR and MTDG not useful (i.e., “I would not use this”, “this would not help me”), the data visualizations show promise. Specifically, FROR could be used to understand the client's status of RoM with respect to others or previous assessments; MTDG could help monitor client's movements during exergaming sessions to deliver appropriate and effective exercise therapy instructions.

Interactivity in the interface that helps exercise therapists understanding data visualizations is necessary in order to facilitate understanding and the decision making process during exercise therapy. Specifically, small tips or a help icon should be included to instruct exercise therapists on how to interact or find specific information, especially for novel data visualizations such as MTDG and FROR. Additionally, the ability of data visualizations in switching between different views based on exercise therapists' needs and preferences would be useful in integrating the tools to their daily practice. For instance, DR should allow exercise therapists choose between having both date and session number or date only in representing the exercise session since a consensus was not reached between respondents from a similar setting. As for FROR, the potential stigma and frustration brought by the comparison between client's performance with population normative data should be noted, even though it could help exercise therapist understand the client's status with respect to a population standard. Hence, another mode of FROR that compares an individual's performance overtime, which also allows exercise therapists to evaluate the effectiveness of the intervention and adjust exercise programs if necessary, should be implemented.

Taking a broader look at the evaluation responses of the online questionnaire on the proposed data visualizations, DR has the most complete responses in both quantitative questions and qualitative questions; however, this could be because it was the first data visualization shown. After completing the questions regarding DR, respondents would have a feeling for what the study was asking them to do; some respondents may choose to withdrawal from the study in middle by leaving the questionnaire unfinished. Except for DR, many respondents typed "no" in questions that asked for their impressions or suggestions on how to improve data visualization elements. Without further context, it is not possible to extract the meaning of "no" to these types questions.

Regarding the feasibility and validity of measures, sixteen out of twenty-three respondents nominated walking and biking as other potential activities DR can be generalized to. As most of the respondents work in long-term/retirement care settings, this result indicates an important future direction to be considered for VR exergames development in promoting physical activity among older adults in long-term care facilities. Stroke rate, which was rated as the most appropriate secondary intensity indicator during rowing game, still lacks validity and may cause confusion or false reading. Further validation and research should be performed in order to find the appropriate secondary intensity information for all stages in Exerfarm Valley. Furthermore, significance of the difference in a comparison should be carefully evaluated and highlighted to help exercise therapists identify important milestones/outcomes during exercise program. Specifically, a significant increase/decline in distance rowed or performance during the game should be noted in order to facilitate discussions with clients for further adjustments in exercise programs or investigations. The significance could also be used as an effectiveness indicator of the exercise intervention, which would be used as the evidence when exercise therapists select the appropriate interventions for an exercise program.

Data visualization considerations

One important property of the data visualizations is that they are self-explanatory, aligning with the phrase "make sense" exercise therapists commonly use to comment about the proposed data visualizations during the data visualization brainstorming workshop and revision focus group. Additional relevant contextual information presented properly may improve the performance of a data visualization although it also adds complexities. During the data visualisation revision focus group, exercise therapists considered Figure 4.3b as clearer and more intuitive compared to Figure 4.3a even though the colored heart rate zone made the data visualization busier. Comparing the 2D projected graphs in Figure 4.9a, b, and c to the color coded 3D graph in Figure 4.9e, the information presented is more intuitive with the color of motion trajectory changing over time in the 3D graph even though the data visualization technique seems to be more complex and novel, as commented by exercise therapists during data visualization revision workshop. For objective information such as distance rowed, additional qualitative information about the client was requested by exercise therapists in order to obtain a complete picture of the exergaming sessions and player status. For example, exercise therapists preferred Figure 4.7c over Figure 4.7b because the it is easier to find associated time mark of a specific heart rate or stroke rate.

Color seems to be one of the most common data visualization elements exercise professionals use in highlighting or differentiating information. During the data visualization brainstorming workshop and exploratory activity in data visualization revision focus group, exercise therapists suggested multiple times to color-code the changes for distance rowed and functional reach results of an individual between sessions. From the online questionnaire, exercise therapists also suggested: 1) using colored bars to differentiate different sessions; 2) color-code the average/goal to emphasize the values; 3) color the date of the session with situations like pain to highlight specific conditions that might affect user's performance during an exergaming session. However, the color should be carefully chosen and the design should be optimized so that the data visualizations are accessible to visually impaired individuals or in the case of gray-scale display (e.g., data visualization printed using monochrome printer). Other aspects about the accessibility of data visualization (e.g., font size, legends) should also be carefully addressed such that visually impaired individuals can derive the same conclusions as the healthy population [175].

Limitations and Methodological Considerations

In the process of co-creating data visualizations, four exercise therapists from the community programs were recruited. As such, the sample may not represent the opinions of the general population of physiotherapists or exercise therapists. A representative sample from different environment settings (e.g., long-term/retirement care, community programs, private practice) should be recruited for data visualization brainstorming workshop and revision focus groups. With remote workshop and focus group sessions (as required because of COVID-19 outbreak), the ability to engage in group tasks was limited. Actual hands-on drawings of possible ways for data visualizations by exercise professionals could be more intuitive for many people and in-person discussions may foster more in-depth lines of thought. Recruitment of the potential participants for the online questionnaire based heavily on physiotherapists associations and long-term care/community programs in Ontario and the majority of current responses are from Schlegel Village staffs (speculated based on the recruitment network). Therefore, the opinions of the respondents are likely biased by geography and profession. A variety of participants from different geographical locations and work settings would be optimal in evaluating the potential of data visualizations to complement the delivery of exercise therapy.

Further interviews should be carried out in order to understand the ambiguous answers from the online questionnaire. Another key attribute of the data visualization that should be evaluated (in addition to usefulness, completeness, intuitiveness, and appropriateness) is memorability - how well does a viewer retain the information delivered in the data visualization [176]. As an important complementary tool in reviewing the exercise sessions and player's performance, exercise therapists should be able to remember the information presented in the data visualizations so that they may integrate with other information, if necessary, to evaluate the status of a client. However, the evaluation of memorability requires evaluation through an actual memorization task, thus could not be tested in the online questionnaire. In addition to questionnaires, the intuitiveness of data visualizations could be validated through tasks. For example, participants could be asked to draw conclusions from the data visualizations (e.g., read value of a specific variable, compare values of different variables). The time people spent deriving the conclusions and the accuracy of the conclusions may give insight as to the intuitiveness of the data visualizations.

Although there are other data visualization design ideas, the data visualizations in the questionnaire were not compared with alternative options or existing data visualization techniques. All the data visualisations were evaluated through conjecture as exercise therapists were imagining the meaning of data visualizations and how the data visualizations could work in practice. To understand the performance of the data visualizations in real life, the data visualizations should be implemented with the exergames, which need to be integrated as clinical practice. By obtaining the actual data about exergaming sessions, exercise therapists would be able to evaluate the appropriateness of data visualizations and provide constructive feedback on refining data visualizations through their experience working with the clients and the exergames. The frequency, scenario, and total time exercise therapists spend with the data visualizations could be used to understand the actual usage and potential of data visualizations in clinical practice. This, in turn, could be compared with results from the online questionnaire and validate the effectiveness of data visualizations as a complementary tool for exercise therapy. Comparisons between the performance exercise therapists in clinical practice with and without additional explanations/training, as well as before and after a period of adoption, could reveal the intuitiveness and the sustainability of the proposed data visualizations in delivering useful information during administration/management process of exercise programs.

4.5 Chapter summary & key findings

This chapter describes the exploration and preliminary evaluation process of four novel data visualizations for the selected metrics were presented and discussed. The key contributions of this research in this chapter are:

- A multidisciplinary collaborative development process for creating data visualisations was established.
- Four novel data visualizations were created for conveying physical activity in a rowing head-mounted display virtual reality (HMD-VR) exergames game.
- Distance rowed data visualization (DR, Figure 4.6) and heart rate and (stroke rate) data visualization (HRSR, Figure 4.6) could complement the delivery of exercise therapy, especially for communication purposes.
- Functional reach and overhead reach data visualization (FROR, Figure 4.8) and motion trajectory during gameplay data visualization (MTDG, Figure 4.9) could be used internally within exercise therapists to facilitate evaluation of clients' performance in exercise programs.

- Novel data visualizations require more design iterations in order to present useful information to exercise therapists intuitively.

Chapter 5

Conclusions

The goal of this thesis is to explore the potential of data visualizations in supporting the delivery of HMD-VR exergames-based exercise therapy for older adults. This thesis presents research in developing novel data visualizations using information collected through HMD-VR exergames system to represent player's performance and exergaming sessions. In the collaborative development of HMD-VR exergames as a way to support exercise therapy, the thesis work identifies information that can be captured from Exerfarm Valley, proposes novel data visualizations to deliver information to complement exercise therapy practice, and evaluates the data visualizations with exercise therapists. While future work is needed to implement and evaluate the data visualizations in practice, the results of this work demonstrate promising potential of collaboratively designed data visualizations to support and advance exercise therapists' work in managing and administering exercise therapy.

5.1 Key findings

This thesis work contributes to the field of design and development of HMD-VR exergames through the following key contributions:

1. The metrics in Table 3.2 can be extracted from exergames to represent a client's abilities and player's performance during HMD-VR exergaming session.
2. Four data visualizations delivering physical activity and player performance information during a rowing HMD-VR exergame were collaboratively designed with exercise professionals:

- Distance rowed data visualization (DR) - Figure 4.6
- Heart rate and (arm movement) stroke rate data visualization (HRSR) - Figure 4.7
- Functional reach and overhead reach data visualization (FROR) - Figure 4.8
- Motion trajectory during gameplay data visualization (MTDG) - Figure 4.9

All four data visualizations show potential to support the communication and administration process of exercise therapy delivering through HMD-VR exergames. Exercise therapists stated they could envision using DR and HRSR in reviewing the exercise sessions as well as using them to facilitate communications with their clients. The FROR and MTDG need further exploration and refinement if they are going to be intuitively useful to exercise therapists.

3. The multidisciplinary iterative design of exergames (MIDE) framework created during this thesis research provides guidance on the process of designing, developing, and evaluating exergames for older adults. To author's knowledge, it is the first comprehensive framework that supports the planning and execution of research activities in exergames and serious games for health in general.

5.2 Future work

The results in this thesis represent the first analysis of the questionnaire data (see Section 4.3.2). The questionnaire will be kept open until 40 complete responses are collected or two weeks after the last response. A more extensive analysis on the complete data from the questionnaire will be completed and disseminated in a future publication.

While this research demonstrated good potential of the four data visualizations, additional iterations of refinements are needed, especially for the MTDG and FROR. For example, MTDG should include additional sagittal plane projected view and labels that explains the data visualization elements. For FROR, some exercise therapists reported the current design was not intuitive because the overhead reach results are at the bottom of the radar chart, which does not match with the real world representation. Two different radar charts could be employed to represent the frontal body view (lateral reach and overhead reach) as well as transverse body view (lateral reach and frontal reach) for clearer representations. Additional focus groups or workshops should be carried out to evaluate the updated data visualizations and investigate appropriate data visualization designs.

Furthermore, the data visualizations should be implemented in the Exerfarm Valley system and validated through a feasibility study that employs therapists and older adults. This research is planned for Summer 2021 and the information collected through Exerfarm Valley system during the feasibility study will support an understanding of the four data visualizations in actual exercise therapy delivery.

The exercise therapists recruited for the data visualizations development and evaluation process in this thesis work are from Ontario, Canada. However, exercise practices and therapeutic goals may differ in different geographical locations depending on the clinical settings (e.g., community program, private practice, long-term/retirement care institutions). Thus, additional larger scale online questionnaire evaluation study should be carried out to validate the potential of the data visualizations with exercise professionals from different work settings across various geographical locations worldwide. Furthermore, subjective evaluations through questionnaires of the data visualizations should be validated by exercise therapists through VR exergames programs for older adults in the real world. The data visualizations proposed in this thesis work only demonstrated the potential of design concepts and should be validated through real-world scenarios.

This thesis work proposes an initial set of data visualizations that consist of a sub-set of metrics from Table 3.2; the other metrics should be explored using appropriate exergames and data visualization techniques. The interactivity of the data visualizations should be collaboratively designed and evaluated with exercise therapists through interactive prototypes. For example, HRSR should be able to allow zoom in/out over a period of time and provide the specific time mark reading of a point when exercise therapists need. Therapists should be able to rotate the 3D graph of MTDG to provide different views of the motion trajectory within the 3D space. Through the potential integration with clinical data and patient information management system, a data visualization dashboard could be autonomously modulated to better support the exercise therapy practice. The data visualization dashboard could be a way to unify access to client information and client's performance during the exercise program for exercise therapists. A data visualization dashboard module could also be integrated with other exergames system or updated independently if needed. Generalization of the data visualization to other VR exergames or activities in the existing exercise programs could be implemented to validate the potential of novel data visualizations in supporting the delivery of exercise therapy.

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APPENDICES

Appendix A

Related publications from the VR exergames project

A.1 Multidisciplinary Iterative Design of Exergames (MIDE): A Framework for Supporting the Design, Development, and Evaluation of Exergames for Health [6]

Abstract
Exercise video games (exergames) are increasingly being employed as a complementary intervention to promote physical activity engagement in response to the need for creating sustainable strategies for supporting health. While exergames have shown that they can have comparable effects to conventional human-guided training programs in certain situations, its adoption in healthcare applications are still limited. This is in part because of a disconnection between the technology/content producers, healthcare providers, and end-users. Many design frameworks have been proposed to guide the process of creating games for health, however, what is missing is an integrated and multifaceted approach that includes the preliminary research and evaluation stages that are needed to create plausible solutions for exergames. Furthermore, relevant stakeholders are often not included throughout the entire process, neglecting the importance of transdisciplinary collaborations when creating exergames for health. This paper presents the Multidisciplinary Iterative Design of Exergames (MIDE) framework as a comprehensive, integrative, and specific framework for exergame design, development, and evaluation following different research methods,

techniques and tools. The MIDE framework is intended to support researchers, healthcare professionals, and industrial experts in identifying the stages, processes, techniques, and key roles needed to create novel exergames for exercise promotion. As older adults are a key user group, applicability of the framework is illustrated using considerations for older adults and immersive experiences (e.g., virtual reality). A specific use case is presented at the end of the paper to illustrate the use of the MIDE framework in the context of a project of using virtual reality exergames for promoting exercise in people living with dementia.

About this paper

- **Conference:** HCI International 2020 (http://2020.hci.international/)
- **DOI:** https://doi.org/10.1007/978-3-030-50164-8_9
- **Publisher:** Springer, Cham

A.2 Immersive Virtual Reality Exergames for People Living with Dementia: A Co-Creation Design by a Multi-Stakeholder Team of End-Users, Researchers, and Industry [7]

Abstract
Advancements in personalized healthcare using virtual reality (VR) has created opportunities to use immersive games to support a healthy lifestyle for people living with dementia (PLWD) and mild cognitive impairment (MCI). Collaboratively designing exercise-video games (exergames) as a multi-stakeholder team is fundamental to creating games that are attractive, effective, and accessible. In this paper, we explore the use of participatory design methods that involve PLWD in long-term care facilitates, exercise professionals, content developers, game designers, and researchers in the creation of VR exergames targeting physical activity promotion for PLWD/MCI. We present the conceptualization, collaborative design, and playtesting activities carried out to design VR exergames to engage PLWD in exercises to promote upper-limb flexibility, strength and aerobic endurance. We demonstrate how different stakeholders contribute to the design of VR exergames that consider/complement complex needs, preferences, and motivators of an underrepresented group of end-users as well as game design elements that reflect feedback for therapists and researchers.

About this paper

- Anonymous submission

Appendix B

Online questionnaire for evaluating the data visualizations

Demo questionnaire can be accessed at https://uwaterloo.ca1.qualtrics.com/jfe/form/SV_24RvgkDiGK5J6G9; demo video in the introduction section of the questionnaire can be accessed at https://youtu.be/U7f5ZESVPQQ.

Consent

The use of computer games to engage people in physical activity is a growing area of interest. As more games for exercise (i.e., exergames) become available, research is being done into how data from gameplay, such as how a player is moving while playing a game, can be used to understand more about the impact and appropriate use of exergames.

The purpose of this study is to gather the opinions of professionals with exercise therapy or related expertise give their feedback on data visualizations that we have created.
The goal of the data visualizations is to provide information regarding clients' physical performance during virtual reality (VR) exergames in a way that supports therapists in the understanding and development of exercise therapy.

The questionnaire will take about 20 minutes to complete. You can continue answer the questionnaire within 24hrs of your last activity by leaving your browser window open, however, you will not be able to resume your session if you close the browser window.

All responses collected in this study will remain anonymous and will only be accessed by the University of Waterloo research team. Anonymized quotes may be shared for dissemination and teaching purposes. Participation in this study is voluntary and you are free to withdraw at any time during the study; you may leave the questionnaire unfinished and close your browser window should you wish to end your participation.

NOTE: Partially completed responses be collected and be used for data analysis in the study. You can request your data be removed from the study up until Dec 13th, 2020, after which it is not possible to withdraw your data as publications will have been submitted to publishers. If you wish to withdraw your information from the study, please contact Yirou Li at yirou.li@uwaterloo.ca.

The questionnaire is operated by Qualtrics, which is a questionnaire system supported by the University of Waterloo. Qualtrics temporarily collects your contributor ID and computer IP address to avoid duplicate responses in the dataset but will not collect information that could identify you personally. A copy of the responses will be stored to the secure lab server of the Principle Investigator (Dr. Jennifer Boger). The lab server is managed and maintained by University of Waterloo with restricted access to research team members. When information is transmitted over the internet privacy cannot be guaranteed. There is always a risk your responses may be intercepted by a third party (e.g., government agencies, hackers).

This study is part of an MASc research thesis. Should you have any questions, please contact the student research Yirou Li at yirou.li@uwaterloo.ca.

In appreciation for your help with our research you will receive a $15 Amazon or Starbucks digital gift card. To receive this gift card you must enter your email address at the end of the survey, select the gift card type, and submit the survey. Email addresses will not be linked to your answers. If you would like to withdraw from the study and still receive the gift card, you must click through to the end of the questionnaire. The amount received is taxable. It is your responsibility to report this amount for income tax purposes.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee ORE #42573. Should you wish to contact the Office of Research Ethics, you may do so at 1-519-888-4567 ext. 36005 or ore-ceo@uwaterloo.ca.

Do you agree to participate in this study?

- ◯ I have read the information above and agree to proceed with the questionnaire
- ◯ I do not agree

Demographics

Exergames are videogames that encourage the player to do guided exercises in a way that is fun, engaging, and challenging. We are interested in your thoughts and opinions regarding data visualizations – ways of visually presenting data – for VR exergames.

We ask that you share your honest thoughts - your answers will be used to revise data visualizations that may be included in VR exergames in the future.

To get started, please tell us a bit about yourself:

What is your age?

What is your gender?

- ○ Male
- ○ Female
- ○ Prefer to specify
- ○ Prefer not to say

What is your occupation?

- ☐ Exercise Therapist
- ☐ Recreational Therapist
- ☐ Facilitator or Management position
- ☐ Kinesiologist
- ☐ Other, please indicate

What is the setting(s) of your working environment?

- ☐ Long-term/retirement care
- ☐ Community program
- ☐ Private practices
- ☐ Other, please indicate

What is your geographic region (Country, province/state)?

How many years of experience do you have working in a field related to exercise therapy?

Introduction

Now let's get familiar with the rowing exercise that we're going to use as an example.

Please watch the following short video:

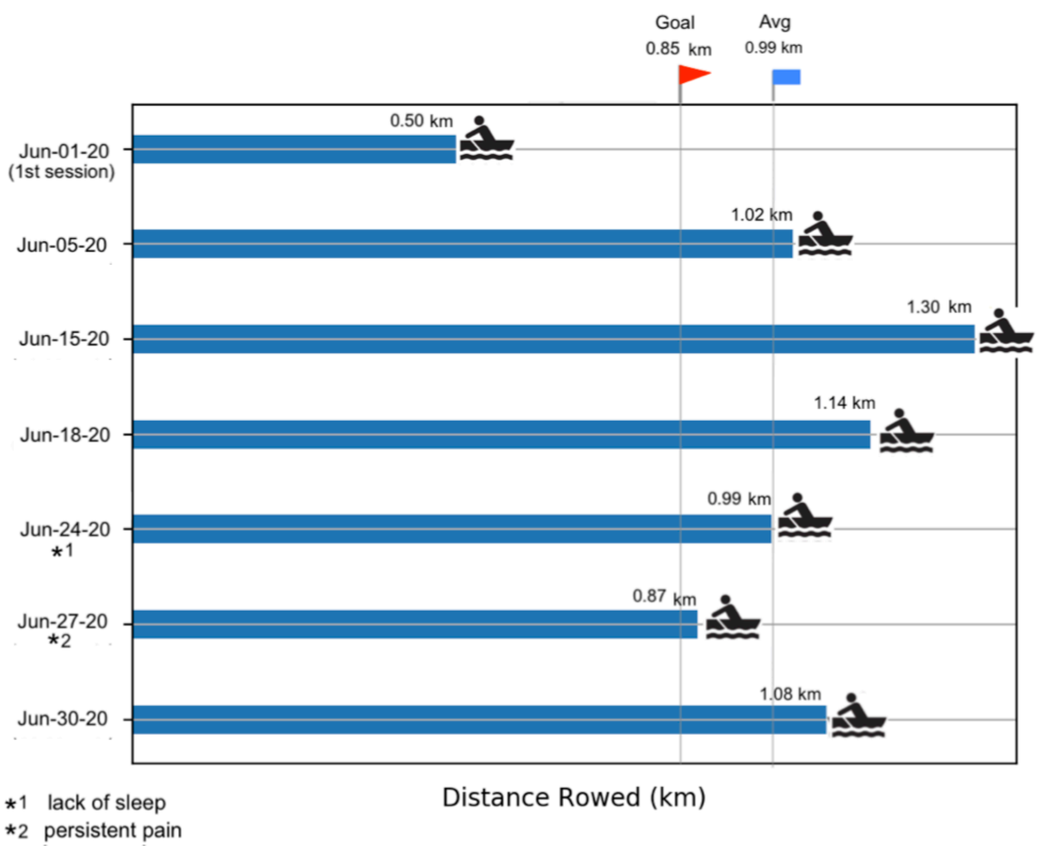
Now we would like you to share your thoughts about four (4) different ways we can look at data from the rowing activity.

Please read questions carefully and let us know what you think. There are no right or wrong answers – we are interested in your honest opinions.

Distance Rowed

Distance rowed - Data visualization 1 of 4

Distance rowed is an estimate of how far someone would have rowed in real life if they were in a rowboat. Distance rowed can be used as an indicator of the overall session activity. Click on image to enlarge/zoom in.



Q1 of 7: Please rate the following on a scale of 1-5 where 1 means "strongly disagree" and 5 means "strongly agree".

1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I would use this to review the exercise session	○	○	○	○	○
I can get the information I want without any help	○	○	○	○	○
I do not need any additional information other than what is presented in the data visualization	○	○	○	○	○
I can easily find the information I want from the data visualization	○	○	○	○	○

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I can draw conclusions from the data visualization quickly	○	○	○	○	○
I would need additional resource to draw conclusions from the data visualization	○	○	○	○	○
The data visualization presents information in a way that could be misleading	○	○	○	○	○
The visual representations used in the data visualization (color, legend, etc.) are ones I would use	○	○	○	○	○

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I understand the wording used in the data visualization (axis, legend, etc.)	○	○	○	○	○
I would use different wording than what is used in the data visualization	○	○	○	○	○
I would show this to a client after exercise session	○	○	○	○	○
The data visualization could help me communicate with my client	○	○	○	○	○

Q2 of 7: Data visualizations can be evaluated on four aspects:

usefulness: How useful do you find the data visualization?
completeness: How comprehensive is the information presented in the data visualization?
intuitiveness/perceptibility: How clear is the information in data visualization?
appropriateness: How appropriate is that data that is included in the visualization?

Please use the sliders to rate the **distance rowed** data visualization for each of these aspects from “Poor” to “Excellent”.

	Poor							Excellent			
	0	1	2	3	4	5	6	7	8	9	10
Usefulness											
Completeness											
Intuitiveness											
Appropriateness											

Q3 of 7: How do you envision using this visualization in your practice? If you would not use this, please say "I would not use this" and tell us why.

Q4 of 7: How would you like the visualization to refer to each specific exercise session? Would you like to see date (as shown in y-axis of the visualization), session number, both, or something different? Why?

Q5 of 7: Is there anything you would like to see added or changed? If so, what and why? If you have ideas of what you would like to see instead, please include them.

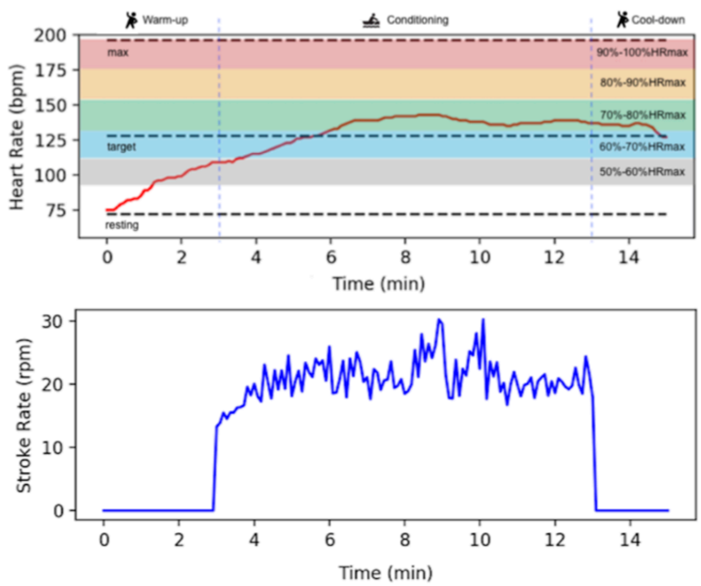
Q6 of 7: Can you envision using the same concept (bar chart) for any other activities? If so, what.

Q7 of 7: Are there any other thoughts you wish to share regarding the **distance rowed** data visualization?

HR

Heart rate and (arm movement) stroke rate - Data visualization 2 of 4

Heart rate and (arm movement) stroke rate can be used as an indicator of the exercise intensity during a session. [Click on image to enlarge/zoom in.]



Warm-up	Conditioning	Cool-down	Total Time Spent
-	-	-	-
-	-	-	-
-	07:38	01:55	09:33 (63.6%)
-	02:07	00:05	02:12 (14.7%)
01:48	00:15	-	02:03 (13.7%)
01:12	-	-	01:12 (8%)

Q1 of 7: Please rate the following on a scale of 1-5 where 1 means "strongly disagree" and 5 means "strongly agree".

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I would use this to review the exercise session					

1 (strongly disagree)	**2 (disagree)**	**3 (neutral)**	**4 (agree)**	**5 (strongly agree)**

I can get the information I want without any help

I do not need any additional information other than what is presented in the data visualization

I can easily find the information I want from the data visualization

1 (strongly disagree)	**2 (disagree)**	**3 (neutral)**	**4 (agree)**	**5 (strongly agree)**

I can draw conclusions from the data visualization quickly

I would need additional resource to draw conclusions from the data visualization

The data visualization presents information in a way that could be misleading

The visual representations used in the data visualization (color, legend, etc.) are ones I would use

1 (strongly disagree)	**2 (disagree)**	**3 (neutral)**	**4 (agree)**	**5 (strongly agree)**

I understand the wording used in the data visualization (axis, legend, etc.)

I would use different wording than what is used in the data visualization

I would show this to a client after exercise session

The data visualization could help me communicate with my client

Q2 of 7: Data visualizations can be evaluated on four aspects:

usefulness: How useful do you find the data visualization?
completeness: How comprehensive is the information presented in the data visualization?
intuitiveness/perceptibility: How clear is the information in data visualization?
appropriateness: How appropriate is that data that is included in the visualization?

Please use the sliders to rate the **heart rate and (arm movement) stroke rate**data visualization for each of these aspects from “Poor” to “Excellent”.

Poor **Excellent**

0 1 2 3 4 5 6 7 8 9 10

Usefulness

Completeness

Intuitiveness

Appropriateness

Q3 of 7: How do you envision using this visualization in your practice? If you would not use this, please say "I would not use this" and tell us why.

Q4 of 7: In order to compliment heart rate information with an intensity indicator of the rowing game, we chose stroke rate. Would you choose a different intensity indicator for rowing? If so, what would you choose? If not, how might you use stroke rate information (if you don’t think this is useful, please say so)?

Q5 of 7: Would you like to see intensity indicator for the warm-up and cool-down periods? If so, what information about intensity would you like to see?

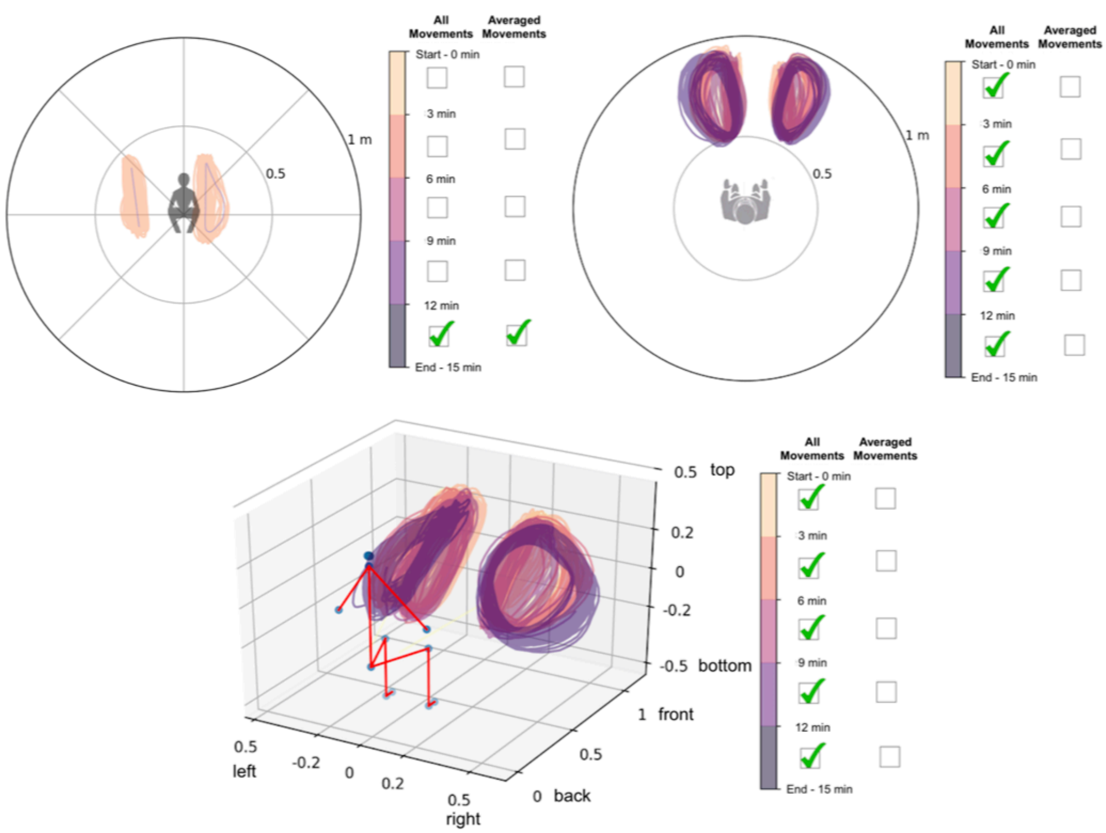
Q6 of 7: Is there anything you would like to see added or changed? If so, what and why? If you have ideas of what you would like to see instead, please include them.

Q7 of 7: Are there any other thoughts you wish to share regarding the **heart rate and (arm movement) stroke rate** data visualizations?

3D

Motion trajectory - Data visualization 3 of 4

Motion trajectory during gameplay can be extracted from the hand-held controllers and is a representation of the physical locations a player's hands went during the game. Click on image to enlarge/zoom in.



Q1 of 8: Please rate the following on a scale of 1-5 where 1 means "strongly disagree" and 5 means "strongly agree"

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I would use this to review the exercise session	○	○	○	○	○
I can get the information I want without any help	○	○	○	○	○
I do not need any additional information other than what is presented in the data visualization	○	○	○	○	○
I can easily find the information I want from the data visualization	○	○	○	○	○
	1 (strongly disagree)	**2 (disagree)**	**3 (neutral)**	**4 (agree)**	**5 (strongly agree)**
I can draw conclusions from the data visualization quickly	○	○	○	○	○
I would need additional resource to draw conclusions from the data visualization	○	○	○	○	○
The data visualization presents information in a way that could be misleading	○	○	○	○	○
The visual representations used in the data visualization (color, legend, etc.) are ones I would use	○	○	○	○	○
	1 (strongly disagree)	**2 (disagree)**	**3 (neutral)**	**4 (agree)**	**5 (strongly agree)**
I understand the wording used in the data visualization (axis, legend, etc.)	○	○	○	○	○
I would use different wording than what is used in the data visualization	○	○	○	○	○
I would show this to a client after exercise session	○	○	○	○	○
The data visualization could help me communicate with my client	○	○	○	○	○

Q2 of 8: Data visualizations can be evaluated on four aspects:

usefulness: How useful do you find the data visualization?

completeness: How comprehensive is the information presented in the data visualization?
intuitiveness/perceptibility: How clear is the information in data visualization?
appropriateness: How appropriate is that data that is included in the visualization?

Please use the sliders to rate the **motion trajectory** data visualization for each of these aspects from “Poor” to “Excellent”.

	Poor							Excellent			
	0	1	2	3	4	5	6	7	8	9	10
Usefulness											
Completeness											
Intuitiveness											
Appropriateness											

Q3 of 8: How do you envision using this visualization in your practice? If you would not use this, please say "I would not use this" and tell us why.

Q4 of 8: How might the motion trajectory visualization could help you understand your clients and their session? If you cannot think of a way this would help you, please say "This would not help me" and tell us why.

Q5 of 8: Would you like to see only the 2D view (top), 3D view (bottom), or both?

Q6 of 8: How would you like to spatially order the 3D graphic and two 2D projected planar graphics? Would you like to see an additional sagittal plane view of the 3D graphic in the visualization?

Q7 of 8: Is there anything you would like to see added or changed? If so, what and why? If you have ideas of what you would like to see instead, please include them.

Q8 of 8: Are there any other thoughts you wish to share regarding the **motion trajectory** data visualization?

ROM

Functional reach and overhead reach - Data visualization 4 of 4

Functional reach and overhead reach can be used to describe how far a person has reached with their arms while in a seated position. Click on image to enlarge/zoom in.

Q1 of 6: Please rate the following on a scale of 1-5 where 1 means "strongly disagree" and 5 means "strongly agree"

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I would use this to review the exercise session	○	○	○	○	○
I can get the information I want without any help	○	○	○	○	○
I do not need any additional information other than what is presented in the data visualization	○	○	○	○	○
I can easily find the information I want from the data visualization	○	○	○	○	○
	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I can draw conclusions from the data visualization quickly	○	○	○	○	○
I would need additional resource to draw conclusions from the data visualization	○	○	○	○	○
The data visualization presents information in a way that could be misleading	○	○	○	○	○
The visual representations used in the data visualization (color, legend, etc.) are ones I would use	○	○	○	○	○

	1 (strongly disagree)	2 (disagree)	3 (neutral)	4 (agree)	5 (strongly agree)
I understand the wording used in the data visualization (axis, legend, etc.)	○	○	○	○	○
I would use different wording than what is used in the data visualization	○	○	○	○	○
I would show this to a client after exercise session	○	○	○	○	○
The data visualization could help me communicate with my client	○	○	○	○	○

Q2 of 6: Data visualizations can be evaluated on four aspects:

usefulness: How useful do you find the data visualization?
completeness: How comprehensive is the information presented in the data visualization?
intuitiveness/perceptibility: How clear is the information in data visualization?
appropriateness: How appropriate is that data that is included in the visualization?

Please use the sliders to rate the **functional reach and overhead reach** data visualization for each of these aspects from "Poor" to "Excellent".

	Poor						Excellent				
	0	1	2	3	4	5	6	7	8	9	10
Usefulness											

Poor **Excellent**

0 1 2 3 4 5 6 7 8 9 10

Completeness

Intuitiveness

Appropriateness

Q3 of 6: How do you envision using this visualization in your practice? If you would not use this, please say "I would not use this" and tell us why.

Q4 of 6: If there was no population norm data available, is there anything else you would like to compare to? If so, what and how?

Q5 of 6: Is there anything you would like to see added or changed? If so, what and why? If you have ideas of what you would like to see instead, please include them.

Q6 of 6: Are there any other thoughts you wish to share regarding the **functional reach and overhead reach** data visualization?

Comments

Are there any additional questions or thoughts you would like to share with us?

Exit

Thank you for participating in our study "Evaluation of novel data representations for virtual reality exergames to promote physical activity in older adults living with dementia"!
– we appreciate you sharing your time and knowledge with us!

Dear Participant,

Thank you for your participation in our study. Your responses to the questionnaire will be used to create better data visualizations to support exercise using virtual reality.

Please remember that your responses are anonymous. A summary of the project can be accessed on the project's website at: https://uwaterloo.ca/intelligent-technologies-wellness-independent-living/projects/virtual-reality-games-promoting-exercise-people-living.

If you are interested in receiving more information regarding the results of this project or if you have any questions or concerns, please contact one of us at the email address below at any time. A copy of any publication(s) resulting from the study will be sent to you if you provided your email to us in the last question of this questionnaire.

Many thanks for your participation!

Sincerely,

Yirou Li (University of Waterloo)
Email: yirou.li@uwaterloo.ca

Dr. Jennifer Boger (University of Waterloo)
Email: jboger@uwaterloo.ca
Phone: 519-888-4567 x38328

(you will be redirected)

Appendix C

Metrics for Exerfarm Valley

C.1 Identified feasible metrics

Domain	Outcome Measures	Measures	Application	Crucial	Important	Good to have	how would you measure this metric
	Time Played	Total time per session	Exercise volume				
	Repetitions	Number of rowing strokes	Exercise volume				
		Heart rate	Exercise intensity				
		Time in HR zones	Exercise intensity				
Physical (Fitness)	Intensity	Energy Expenditure (METs)	Exercise Volume				
	Reaction Time	Time after reactive cue(controller vibration/visual object present)	Balance, fall risk (reaction time is a predictor); simple processing/attention				
	Task Switching (executive function)	Can change goals correctly	Balance, fall risk (task twitching is a predictor); executive function				
Cognitive	Head position	Head position tracking	Attention, visual processing				
Physical (Kinematic)	Postural Balance (seated)	Trunk acceleration, range of motion	Balance, fall risk				
Cardiovascular health	Heart Rate Variability	Time and frequency domain features	Cardiac risk/adaptability				
Physical (Kinematic)	Range of Motion (RoM)	Wrist movements	Flexibility + RoM				
		Neck movements	Flexibility + RoM				
		Elbow/Shoulder movements	Flexibility - Postural control + RoM				
Physical (Kinematic)	Smoothness	Number of sudden changes in speed					
		Change in accelerations(shaking of hand/wrist while moving)					

C.2 Potential metrics

Possible Metric(s)	**Type of Data**	**Category**
Elicited movement after controller vibration	In-game	Data logs
TBD, time lag after switching? error due to switching?	In-game	Data logs
Head position tracking (raycast from the center of the field of view)	In-game	Data logs
Total time per session	In-game	Data logs
Points (Rowing distance + Fishes Caught)	In-game	Data logs
Number of Rowing, Line Throwing	In-game	Data logs
Steps/Repetitions	Sensor	Actigraphy
Steps/repetitions per time		
Energy Expenditure (METs)	Sensor	Actigraphy
Light-to-Moderate PA	Sensor	Actigraphy
Wrist movements (X, Y, Z) (e.g., maximal vertical position)	Sensor (linear)	VR equipment (IMUs)
Wrist Flexion/Extension, Deviations (Ulnar and Radial)	Sensor (angular)	VR equipment (IMUs)
Neck movements (X, Y, Z)	Sensor (linear)	VR equipment (IMUs)
Neck Flexion/Extension, Lateral Bending	Sensor (angular)	VR equipment (IMUs)
Elbow/Shoulder movements (X, Y, Z)	Sensor (linear): Inverse Kinematic	VR equipment (IMUs)
Elbow Flexion/Extension, Pronation/Supination	Sensor (angular): Inverse Kinematic	VR equipment (IMUs)
Shoulder Flexion/Extension, Adduction/Abduction, Rotation	Sensor (angular): Inverse Kinematic	VR equipment (IMUs)
Wrist peak velocity and acceleration	Sensor (linear)	VR equipment (IMUs)
Elbow/Shoulder peak velocity and acceleration	Sensor (linear): Inverse Kinematic	VR equipment (IMUs)
Number of velocity peaks	Sensor	VR equipment (IMUs)
Normalized Jerk	Sensor	VR equipment (IMUs)
Spectral arc lenght	Sensor	VR equipment (IMUs)
Trunk movements (X, Y, Z)	Sensor: Inverse Kinematic or External	
Trunk speed and acceleration	Sensor: Inverse Kinematic or External	
Non-exercise/exercise posture (monitoring change session to session)		
Time people spent in their target HR levels	Sensor	Chest Strap
Time domain features (SDNN, RMSSD)	Sensor	Chest Strap
Frequency domain features (HF, LF, VLF)	Sensor	Chest Strap

C.3 Collectable game metrics

Scenario	**Game Metrics**	**Outcome Measures**	Application
Rowing	Total time rowing	Exercise duration	Exercise Volume
	Number of rowing strokes	Repetitions	Exercise Volume
	Energy expended (strokes * energy/stroke)	Energy expenditure	Exercise Volume
	Time to react after a fish/dolphin appears	Reaction Time (ms)	Cognition (reaction time), Balance
	Points collected	Game standing	Game Play
	Distance covered	Game standing	Game Play
	Time spent in heart rate zones	Exercise intensity	Exercise intensity
	Range of motion		Balance, Risk of Fall
Fishing	Total time in fishing scenario	Exercise duration	Exercise Volume
	Number of times line thrown (both hands)	Repetitions	Exercise Volume
	Energy expended (line throws * energy/throw)	Energy expenditure	Exercise Volume
	Time to react after controller vibration (fishes biting)	Reaction Time (ms)	Cognition (reaction time)
	Number of times the rod does not move after controller vibration	Accuracy	Cognition (attention)
	Points collected	Game standing	Game Play
	Fishes caught	Game standing	Game Play
Task X			
Total	Total Time	Exercise duration	
	Points total	Game standing	
	Energy expended (repetitions rowing* estimated energy/rep + line throwing * estimated energy/rep)	Energy expended	
	Reaction time in rowing		
	Reaction time in fishing		

Appendix D

Materials for data visualization development

D.1 Sample data visualizations used in the data visualization brainstorming workshop

Distance Rowed(km)	10

Distance Rowed Last Session(km)	Distance Rowed(km)
8.3	**10**

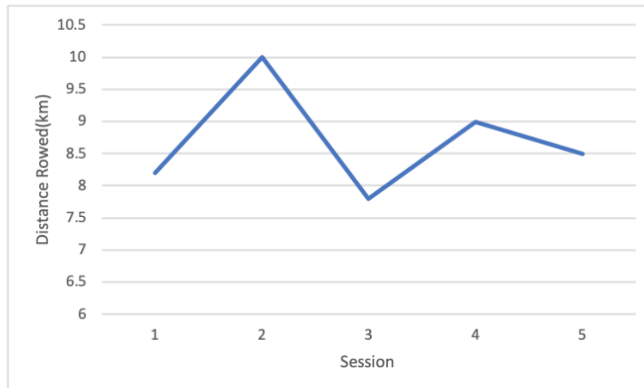


Figure D.1: Distance rowed - sample data visualization

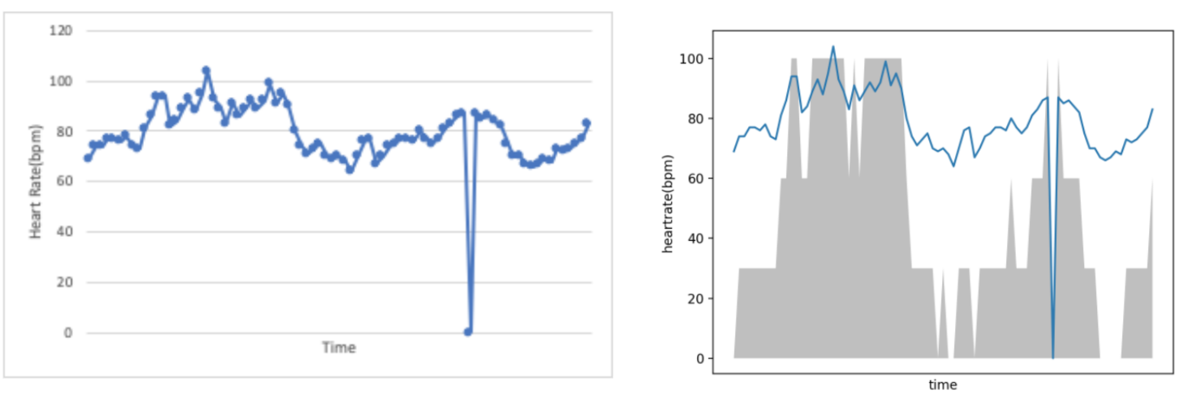


Figure D.2: Heart rate - sample data visualization

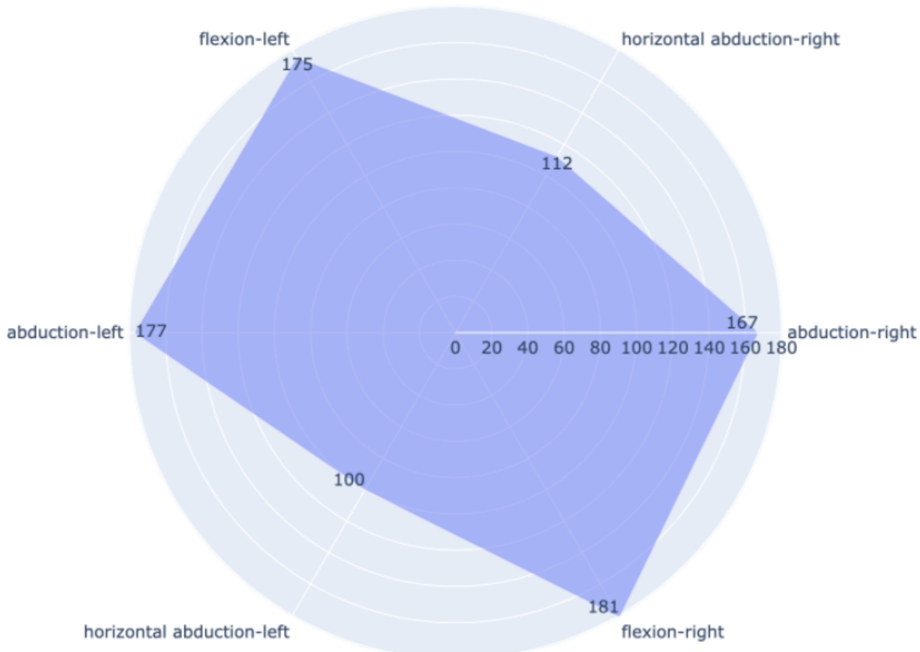


Figure D.3: Functional reach - sample data visualization

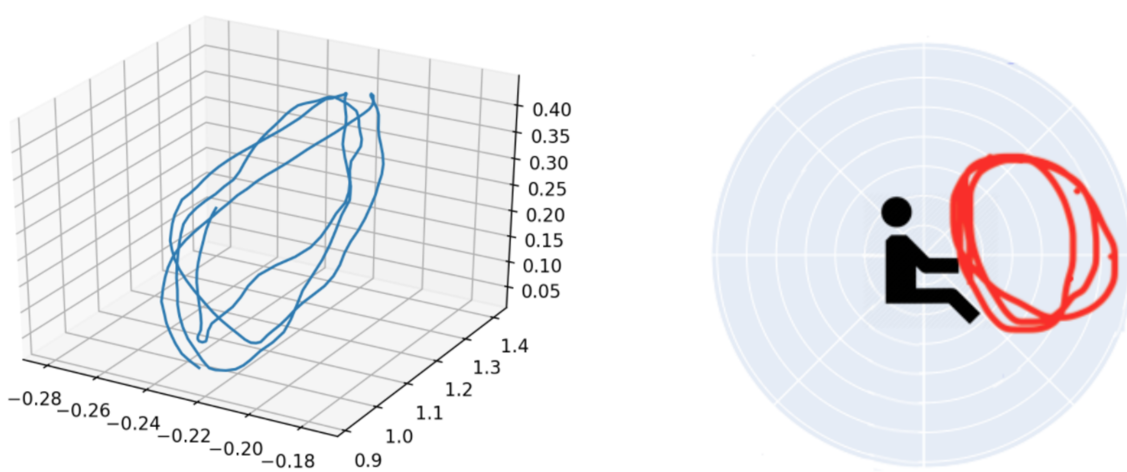


Figure D.4: Motion trajectory during gameplay - sample data visualization

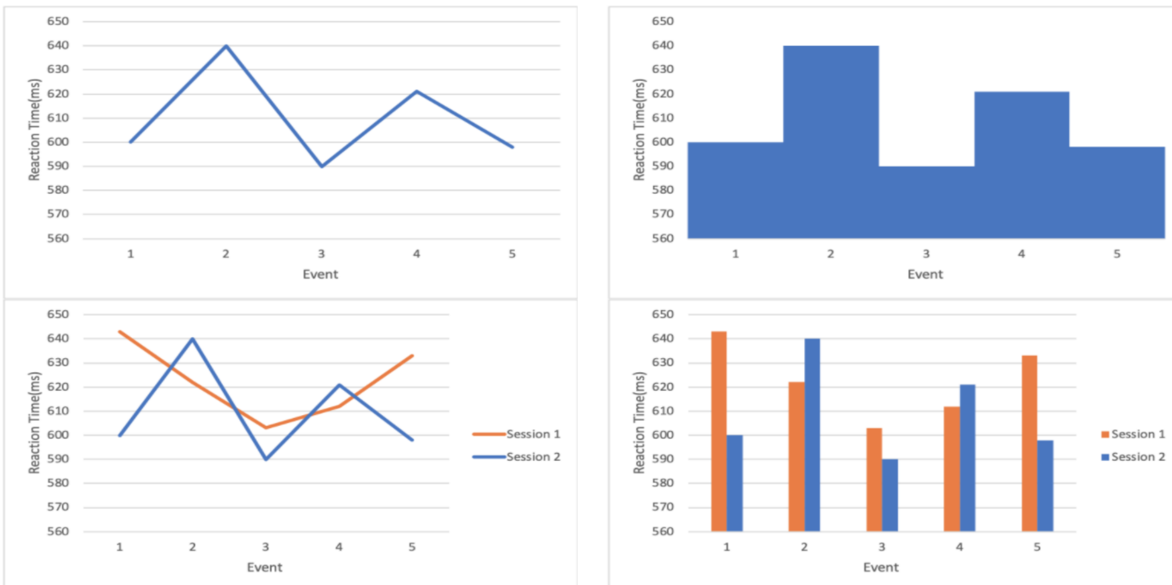


Figure D.5: Reaction time - sample data visualization

Session	Target Hit	Target Missed	Total Score
#1	**43**	7	86
#2	47	3	94
Average	**45**	5	**90**

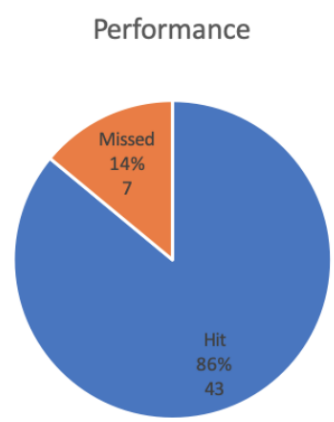


Figure D.6: Game score - sample data visualization

D.2 Semi-structured interview script for the data visualization focus group

Beginning:

Hello everyone, welcome to the second session of data visualization, in this session we'll be looking into details about each type of graphics and corresponding features/information to be used in the graphics.

Before we officially start the session, I want to mention once again that this session is video and audio recorded, with your consent. Please raise your hand if you're okay with it.

I hope everyone enjoy this session and have fun brainstorming different visualizations – we're going to collaboratively design the data visualization that best fit your need.

Exploratory activity: ***at least 10 min, max 25 min***

(Play video) Just a recap on our rowing exergame and the movements that we've used to identify the metrics and will be used here for different data visualizations. Although we've prepared some sample visualizations, we do want to do a small fun activity using the sample data we sent you before. As you may remember, we've asked you to try some data visualizations using the sample data and now we would like you to present the idea.

If you haven't done it, that's also fine, we'll do this activity all together in this session.

Have you guys checked the data & scenario? Is there any problem with the information?

Imagine that those are the data you get from a rowing exercise session; how would you visualize and compare the data? It could be table/bar chart/line chart/any other type of thing you would do. Anyone wants to start?

[discussion]

Start with the sheet by order. Would you use table/chart to see it? How would you do it?

Would you use any color or specific arrangement to highlight some information?

Call out names to engage 😊

Metrics: ***max 5 min***

So yah, that was a nice activity. As we've discussed before, following are some of the metrics that will be useful about exercise sessions. Although for rowing specifically, reaction time might not be applicable. Any thoughts here? Are other metrics you can think of that we haven't cover here? [optional discussion]

Bar chart(slide 6):

Right now we'll be looking at "distance rowed".

Slide 6: ***max 5min***

1. **Would this plot be useful?**
2. **What would you name this plot?**
3. **What would you change about this plot?**
4. **What would you add to this plot?**
5. Would you show this to participants? Anything you would change if showing to participants?
6. **For x-axis, would you use "session#" or just date? Or you prefer both?**
7. Would you compare multiple sessions (more than 2 or only 2) or just a session with its average?

8. **Would you like to see the average?**
9. Would you like different colors or line styles for monthly/weekly average?

Hear rate(slide 7-9):
Right now we'll be looking at "heart rate & stroke rate".
Slide 7: ***max 5min***

1. **Would this plot be useful?**
2. **What would you name this plot?**
3. **What would you change about this plot?**
4. **What would you add to this plot?**
5. Would you show this to participants? Anything you would change if showing to participants?
6. **Would you prefer axis value color black or corresponds to line? What about axis title?**

Slide 8: ***max 2min***

1. **Would you prefer this plot or the one before?**
2. **What would you change about this plot?**
3. **What would you add to this plot?**
4. **Does heart rate zone add any additional information here?**

Slide 9: ***max 2min***

1. **Would you prefer this plot or the one before?**
2. **What would you change about this plot?**
3. **What would you add to this plot?**

****Radar plot(slide10): 10-15*min***
Right now we'll be looking at "modified functional reach tests results & maximum reach".

1. **What would you like to name this plot?**
2. **What would you change about this plot?**
3. **What would you add to this plot?**
4. Would you show this to participants? Anything you would change if showing to participants?
5. **In addition to having information on reaching front and lateral, would the results of reaching up add any value to this plot?**
6. What if we plot the maximum reach in front/lateral/up direction?
7. **What if we then incorporate additional kinematic values to show the reaching range of certain motions during the game? For rowing, we can then see what's the comfort rowing range vs. the max reach.**
8. **In that case, would you like to see min/max/ave/others?**

****3D plot(slide11 & 12):**
Right now we'll be looking at "movements during the game". These are data extracted directly from controllers.

Slide 11: ***5min***

1. **What would you like to name this plot?**
2. **What would you change about this plot?**
3. **What would you add to this plot?**
4. Would you show this to participants? Anything you would change if showing to participants?
5. **Would you like to have different colors for trajectories of different hand?**
6. **Would you like to have the axis values?**

Slide 12: ***5-7min***

Here we're adding some more features to the trajectories. The color of the trajectory will gets darker if the participant passes the locations more in the left plot, and the color in the right plot gets darker as time passes .

1. **What do you think about the added information ?**
2. Would you prefer any of these plots over the ones in the previous slide?

2D plot(slide13 - 15):

Continuing with "movements during the game", we'll be looking on some other arrangements.

Slide 13: **5-7*min***

1. **What would you like to name this plot?**
2. **What would you change about this plot?**
3. **What would you add to this plot?**
4. Would you show this to participants? Anything you would change if showing to participants?
5. How would you like to have the axis values for distances?
6. **Would you like to have some angular information about the participant's range of motion?**
7. **Would you like to have different colors for trajectories of different hand?**

Slide 14: ***max 5min***

1. **What would you change about this plot?**
2. **What would you add to this plot?**
3. What do you think about this compared to a 3D plot?
4. **Would you prefer to see them all, or 2 of them or only 1 specific?**
5. **Would you prefer to see them in a specific (spatial) order?**

Slide 15: ***max 5min***

1. **What would you change about this plot?**
2. **What would you add to this plot?**
3. Would you prefer this over 3D and others we've shown?
4. **Would you prefer see them in a specific (spatial) order?**

Appendix E

Results for data visualization development and evaluation

E.1 Quantitative results of the online questionnaire

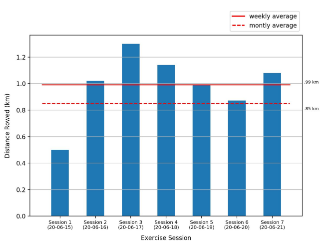
Table E.1: Quantitative evaluation results from the online questionnaire (n=24); values presented are the mean value with standard deviation in parentheses.

Question	DR [a]	HRSR [b]	MTDG [c]	FROR [d]
Likert scale questions; 1 - "strongly disagree", 2 - "disagree", 3 - "neutral", 4 - "agree", 5 - "strongly agree".				
I would use this to review the exercise session.	4.13 (0.55) [e]	3.70 (0.73) [f]	2.78 (1.11) [i]	3.26 (1.24) [g]
I can get the information I want without any help.	3.71 (0.86)	3.75 (0.97) [f]	3.05 (1.06) [i]	3.61 (0.98) [i]
I do not need any additional information other than what is presented in the data visualization.	3.21 (1.06)	3.50 (0.83) [g]	3.11 (1.13) [i]	3.16 (1.12) [g]
I can easily find the information I want from the data visualization.	3.79 (0.93)	3.55 (0.83) [f]	2.94 (1.16) [i]	3.21 (1.13) [g]
I can draw conclusions from the data visualization quickly.	3.63 (0.92)	3.55 (0.94) [f]	2.94 (1.06) [i]	3.26 (1.15) [g]
I would need additional resource to draw conclusions from the data visualization.	3.25 (0.99)	3.00 (1.13) [f]	3.33 (1.19) [i]	2.83 (0.99) [i]
The data visualization presents information in a way that could be misleading.	2.75 (1.03)	2.75 (0.97) [f]	3.06 (1.16) [i]	2.79 (1.08) [g]
The visual representations used in the data visualization (color, legend, etc.) are ones I would use.	3.41 (1.10) [h]	3.67 (0.91) [i]	3.06 (1.16) [i]	3.11 (0.96) [i]
I understand the wording used in the data visualization (axis, legend, etc.).	4.09 (0.61) [h]	3.65 (0.99) [f]	3.29 (1.09) [i]	3.74 (0.81) [g]
I would use different wording than what is used in the data visualization.	2.43 (0.95) [e]	2.40 (0.82) [f]	2.94 (0.80) [i]	2.42 (0.61) [g]
I would show this to a client after exercise session.	3.87 (0.76) [e]	3.20 (1.10) [f]	2.39 (0.98) [i]	2.83 (1.20) [i]
The data visualization could help me communicate with my client.	3.91 (0.73) [e]	3.55 (1.05) [f]	2.78 (1.00) [i]	3.00 (1.20) [g]
Slider rating question; min = 0 (Poor), max = 10 (Excellent).				
Please rate the data visualization for its usefulness.	7.12 (2.04)	6.80 (2.32) [f]	5.33 (3.99) [i]	5.94 (2.88) [i]
Please rate the data visualization for its completeness.	6.46 (2.04)	7.00 (1.95) [f]	5.39 (2.75) [i]	5.94 (2.88) [i]
Please rate the data visualization for its intuitiveness.	6.63 (2.62)	6.10 (2.34) [f]	4.33 (2.74) [i]	5.17 (2.62) [i]
Please rate the data visualization for its appropriateness.	7.04 (2.20)	6.55 (2.61) [f]	5.22 (3.14) [i]	5.67 (2.59) [i]

[a] Distance rowed data visualization, Figure 4.6
[b] Heart rate and (arm movement) stroke rate data visualization, Figure 4.7
[c] Motion trajectory during gample data visualization, Figure 4.9
[d] Functional reach and overhead reach data visualization, Figure 4.8
[e] N=23
[f] N=20
[g] N=19
[h] N=22
[i] N=18

E.2 Affinity diagrams

E.2.1 Focus group and refinement of data visualizations



Feedback on Visualizations

The data viz makes sense

I like the visual of bar graph

Give it a good 4 for intuitiveness

Including date helps to know the distance between sessions

I like using both session# and date

With the date, it'll be easier to circle back to detailed journal for more info

Design Suggestion

If shown to client, Graphical representation, boats lined up and easier compare with each session. "Oh, i went further"

Highlight best numbers and just good things

Great point, it's just good to see the outlier, add a bit more context

Relate to the journal? Add insight to client performance in the session

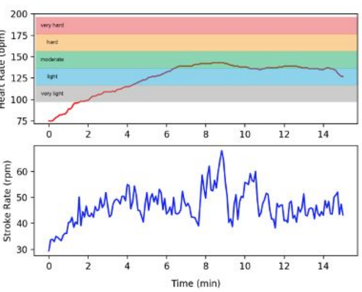
Increase pain/lack of sleep, one of condition

Potential Use

We don't really measure between sessions, we usually do pre-, post- and highlight the positive

A comparison between first, last, best day, different accomplished. In end of report and show to client

Statistical difference between session distance rowed



Design Feedback

HR intensity given by shading could be confused with movement intensity

Much easier to see when separated, time mark can be easier to find

Much easier to see when separated, time mark can be easier to find

Average stroke rate, how long they spent in the zone, top&bottom, when does the change happen, fatigue, etc.

Design Suggestion

Concern: is the scale shifted based on age?

Could someone enter age and the data adjusted to the population?

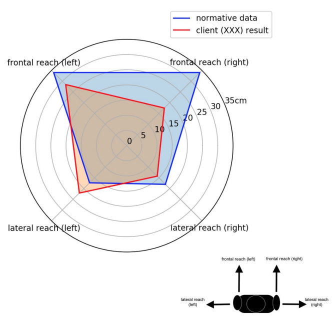
Value of peak HR would be helpful

Enter target hr, and show how long they spent in the zone

HR intensity given by shading could be confused with movement intensity

Potential Use

good to show to client



Design Feedback

Never seen anything like this, quite interesting. Easy to see where the normative data lies. Neat visual

I like it, i'll give it a 4 of 5

I agree, it works really well

Quite like showing the norm, it'll be good to enter the age/sex and just get the norm to compare

Shows asymmetric information

Design Suggestion

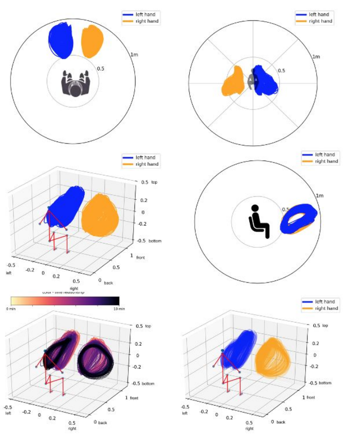
Overhead reach is useful

Potential Use

Client would be interested, Motivational with positive changes

Show the difference and color coding, good to use for report/communicate with client

Good way to show client, convincing them to other disciplines collaboration



Design Feedback

Time feature makes it clearer to see the motion changes over time

Like the color coded information, to know how the movement changes over time

Without time color, no useful info

Side view overlap with each other, hard to see

I like the top and front, kinda see movement pattern and irregular movements, not the side view

Design Suggestion

A table on the side say the actual number, ave/max useful

Have just maximum and average distance reached in each direction

Value of max reach would be useful

Kinematics information would be helpful in knowing the body movement for coaching

Potential Use

Not useful for client but probs for ppl working with specific individual

The whole graph is interesting to look at, but don't know how important to practice

I too see it interesting, but don't see it useful in program/with client

I don't see how I would use this in my practice

E.2.2 Evaluation of data visualizations through an online questionnaire

Distance Rowed Data Visualization

Potential Use

Communication

P8: It would be for the resident to see

P12: I would envision using this visualization daily after each session to give residents a visual for their performance that day.

P12: I would use it to show my clients in an easily presented form

P13: showing residents progression or regression

P24: It is easy to show clients how much they rowed and to get the average of the distance rowed.

P4: reporting progress,

P21: provide feedback on progression.

P7: Good visual feedback for the resident. They would be able to keep a copy if they wanted to,

P8: or to share a report with their family.

P7: could share with their family

P5: This could be used in care conferences with families to show which exercises are working and which cause more pain.

P19: I would use it in a way that would show the resident their progress after they complete the activity. By tracking it each time, the resident can see how far they are going vs. the last session. We can also explain to the resident reasons as to why they may have gone either further or less distance based on how they were feeling.

P15: It would be beneficial to use this visualization in some instances for residents to show them how far they have improved.

P6: You can also compare it to other times to show them any improvements or changes in technique they may want to consider

P3: I would use the information to show the client and allow for some discussion into the reasons for the differences.

P6: If you can show them how far they rowed before, they can push themselves to go farther the next time.

P4: participant/patient motivation,

P2: I can see us showing clients this graph to hopefully motivate them on their progress.

P7: Great motivation tool as progress is displayed clearly.

P7: or use it as a motivation tool.

p20: The horizontal bar graph creates the visual picture of a distance race between trials and would be encouraging with clients

p20:I would use this with clients that are unable to row and could therefore feel the satisfaction of knowing how far they'd have if could

P21: It would depend on the resident using the platform. I could envision using the visualization to motivate and

P10: I could see this being a good way to get those who do not typically participate in exercise regimes to want to try (doesn't feel like you are "exercising").

P6: It would be good for goal setting for residents.

P6: It is good for goal setting to give them a minimum distance to row

P4: Goal-setting,

P14: It would allow residents to see their goals and see visually see how short or ahead they may have been that day but also allow them to connect it with how they felt after their exercise session.

P22: we could use it as a goal for each of the residents.

Management

P9: It would be a good visualization to track progress

P7: Could use it to advertise the program because results are simple and clear.

P5: Also, a great quick reference tool.

P4: as well as safety/health/ well-being check (ie: compare performance to self-reported rate of perceived exertion).

P24: It would be helpful to determine if the goal is needed to be changed.

P7: I would be able to use the data to create rowing competition or group goal, having multiple residents collaborate on a common shared goal.

P8: It could be a tool for contests/challenges between residents.

P22: we could make it a program the most distance rowed wins a prize

P9: and use in comparison to other days and across other participants

Not Useful

P9: it would not be a great visual to display for the participates to show them there progress.

P15: As well as I work mostly with dementia patients, which means that they would not conceptualize or understand what this charting means or even remember previosu sessions done.

P18: I would not use this. It does not give the residents meaningful data. It would not resonate with them.

P9: it would not be a good visual to analyze other factors that influenced the distance rowed in a specific session,

P17: I would not use this as I feel long term care resident's would not understand what is being asked, or not be okay with wearing the VR over their eyes.

P23: I would not use this as a primary exercise session method in long term care because I find that only a few residents find it beneficial to track their progress. The cost vs benefit would probably not be most effective in this setting.

P16: I would not use this, as rowing would become only an upper body stimulus based on this video. It could be used with some residents for sure but I would prefer to incorporate the whole body into the exercise.

Other Applications

P22: yes for contests, walking challenges.
P3: Walking, cycling,
P16: tons of activities, pole walking distances, cyber cycle distance,
p23:Yes, this could be used for cycling or walking distances.
P14: cycling, treadmill
P12: I could use this concept for walking and stationary biking distances
P17: Yes, for resident's on the walking program,
P11: Anything distance related like walking, Nustep, biking
P8: Yes for walking programs or using a Nustep bike. All activities which track distance.
P10: I could see the same concept used for biking, walking,

P15: Perhaps steps walked on a treadmill or during a walk just to track it. I have done this before in a challenge for my independent living residents and I conceptualized how far they had walked (using a pedometer) to distances in KM to walk to in Canada. Ex. you walked all the way to Toronto
P19: Yes - on the NuStep or sit to stand machine.
p5:NuStep bikes,
P21: Can swimming activities be used given the arm movements?
P2: A VR hiking activity
P20: Other distance based simulations/observations especially regarding exercise or sport.

P16: gait balance test but instead of distance it would be time duration on each foot.
p17: or balance program
P5: gait training programs, weight used for strengthening programs

P3: other games/tasks (ie: object stacking/lifting or projectile use).
P13: different types of games, amount of apples picked, basketballs shot, etc

P10: or really any activity that relates to a outdoor activity.
P4: Yes! For recreation activities. This would be a great tool to use. Showing the number of times they participated in each domain (social, intellectual etc.)

Representing the Sessions

P3: Date and session number for sure
P5: I think the more data included in the legend, the better. However, more data could be captured in progress notes, assessments and care plans.
P7: Date and exercise session makes sense. I would like to see a timeline of effort. Did they pause for a rest, how engaged were they.
p11:I would like to see the date and session number
P12: I would like to see both date and session number

P8: Date is required so yes it should be in there as part of regular documentation standards.
Session number - good to see initial session. If there are too many to count then every 10 sessions can be marked.
P10: I think both the session number and date would be helpful. Session number or date on their own may not give a good idea as to how hard a person is working to see progress, where as both together gives us a good indication of how dedicated someone is and how many sessions they are participating in regularly.
P17: Date and time would be beneficial
P13: yeah date and time will be useful
p24:I would like date and session number because there might be gaps if they are unable to make a session due to circumstances.

P23: Having date and session number would be helpful because of the amount of time between sessions - for example, some are 3 days, and one is 10 days. Indicating that there wasn't a session missed in that period would be helpful at ensuring the data was more clear with little room for misinterpretation.

P2: Date is helpful to see how many exercise sessions they attended each week. It could also be useful if there was a decline to see if it was after a long gap of inactivity.
P4: Date is helpful, as it facilitates activity tracking more easily than "session number", which may not capture time between sessions.
p19:. I like how the visualization works now.
P22: I like it just how it is

P6: I think the date would be good because you can see how their abilities change over time, and you can monitor their condition (health, energy, injuries) better with the dates available
P14: I would like to see the data as it was shown, this allows the resident to remember what they did the session before or to say next time I want to improve past this point.
P15: I like the way it is set up with the dates then the distances, it is easy to understand and explain.

P21: The date on the y-axis works. This way you can see frequency per week if applicable.

P9: specific to amount of weeks the sessions were performed in to give time data a variable

P20: Session number would better show if there was a progression but with the 2 "*" the date seems like a good y-axis

P16: no they are fine

Distance Rowed Data Visualization

Design Suggestions

p2: I would suggest having time to accomplish on there as well. That way we could see if the distance accomplished was due to extra minutes at the activity or from extra effort.
P7: Time. I would like to know how long it took them to row a distance or their pace. A line graph of exertion during the session. Did they start slow and speed up near the end. Was their effort consistent. Being able to pair it with a HR monitor.
P9: I would add the time it took for a participant to row a certain distance, in this visual it shows the session and distance travelled but does not display anything about the time it took to achieve that distance, the sessions should have been described as 10 minutes or another value to portray this information as well.
P12: I would also like to see time of session (how long it took to row the distance)

P17: More detail about body mechanics (ex: reaching full ROM, having partial ROM, necessary cueing, etc.) to compare progress across sessions.

P7: visualization is a good summary of many sessions, it would be great to have more detail from a single session.

P15: But I work with some resident's who are visually impaired and would not benefit.
P4: Have design/colour/font been optimized to be accessible for those with limited colour perception or visual acuity?
p13:maybe use contrasting colours to make it easier for visually impaired residents

P3: with the possibility of some other notes to highlight the reason for the differences (pain, lack of sleep, etc.)
P3: I would like to see some opportunity for qualitative data too.

P14: add a scale for how they felt about the session

P16: I would include a metric for HR monitor and some kind of time domain.

p21:Also, is there any information which could be captured related to cadence? It would be great to know effort, not just distance. Is it a slow movement over long period of time....or quick movements over short period of time which equate to the distance? Also, is there any way to determine the range of motion used for the activity? Understanding if there is progression with amount of movement per activity would be helpful.

Feedback on the Visualization

P9: I would have put the session numbers on the x axis and distance travelled on the y axis- then I would have the x axis
P11: Info from the asterisks would preferably be right below the date/session

P13: make the bars a bit thicker,
P15: Maybe change the colour between sessions so it does not seem like all of the same since some seniors with cognitive difficulties may not be able to differentiate between sessions since they are all the same colour
P15: Maybe use different colours for different sessions though.

p24¨I would make the line for goal and average stand out more because it is hard to compare.
p4:I would suggest colour-coding or emphasizing the "Goal" and "Average" vertical bars.

P19: I would not list the average as the distance can be different each time and the lines may discourage the resident. I would keep a goal value to give the resident a feeling of accomplishment
p10:Maybe find the mean avg across all sessions for just the one participant and not each session so then you can factor a larger number over time to see how the participant is doing independently

P2: Looks great. Well Done!P5: Great tool.
p21:Not at this time - this is a great start.
p23:I like the current format. The visuals of using the blue to represent water and the rowboat figure is easy to understand when presenting the data. I also find it is well laid out, and not too cluttered or confusing.
P18: I don't understand the purpose of what you are trying to accomplish

Other Considerations

p21:I am curious how the distance is calculated?

p13:do you need to row with both hands or one?

P9: I don't think I would use a bar chart for most activities, I could see myself using it mainly to track a participants progress in repetitions for exercises, for example having each time displayed and how many repetitions were achieved that session, but I would go more in depth to factor in age and any other physical factors that could influence each session

p15:Seems interesting but I do not think many resident's or seniors would feel 100% confident using technology to get the data. As well as many seniors start to have worst mobility, either from previous injuries or worsening medical conditions and rowing may not be the most appropriate measure for each person. As well as many resident's have some type of chronic illness and may struggle with rigidness and tremors making data not valid.

Heart Rate and (arm movment) Stroke Rate Data Visualization

Potential Use

Communication

p2:It could also be useful as a base line and with goal setting for the individual.
p16:I would use this with initial client assessments creating a baseline and periodic testing to see difference.

p16:I would use this with initial client assessments creating a baseline and periodic testing to see difference.
p7:Really great, would definitely use this. I think the residents would like to see the exertion/HR graph

p6:After a session, I could show residents the level of effort that they used during exercise, and push them to work harder and harder to reach their full potential and show them just what they are capable fof
p21The heart rate shows how hard they are working and if they need to be working harder.
P11: After each session to encourage

p14:It would help to show a resident what their hear rate was like during the session and to understand what it feels like at certain percentages.
p13:show them how much their activity levels increased over time

Administration

P2: I might use this to reinforce working at an appropriate pace.
p4:Monitor training response over time. Facilitate exercise progression. Monitor changes in skill acquisition/learning.

p19:This is great - it helps to understand the intensity of the activity which is useful as a kinesiologist.
p12:I would use this info for my own review, it would be too complex to present to my client base
p9:I would use this because it visually demonstrates the changes occurring over time during the sessions, if I were to gather multiple sessions then I can overlap them and find an average of how the participant is doing as well
p5: But this is useful to see the degree to which an exercise is completed.

p8:I would use this periodically.
I don't think it is something the resident is interested in seeing particularily. It would be a tool to track effectiveness of intervention or monitor drastic outcomes.

Not Useful

P10: I would likely not use this as I don't find HR to be the most important method when it comes to working with seniors.
p17:I would not use this as it's too much for the resident to comprehend. It would cause more confusion than focus.
p13:the graph seems a little too hectic for residents to understand

p15:I would use this but for only some resident's since some of them have A. Fib. or heart conditions that may mean their heart rate is all over the place. A lot of the resident's either have extremely high or extremely low HR so their exercise HR may react irrationally and may make data invalid.

p18:I would not use this as every session is very different with the resident's. Some days we do more exercise than others and sometimes there is no reason why. Typically, you get a good sense of the resident's current health status and how they are doing throughout the session. This graph is fairly confusing and I would not show it to a resident as it may overwhelm them.

p20I would not use this - same reason as for prior visualization.

Design Suggestions

p9:Heart rate is a good indicator of how the participant is physically doing throughout the rowing session, It could also be good to record oxygen uptake throughout the session to compliment the heart rate indicator- I could use this stroke rate information to see at what point in the session the participant is working there hardest (by intensity of HR) and compare it across time to analyze whether cardiovascular endurance has increase or identify any physical problems that may be occurring during the sessions,

p15:I would like to know how they are doing the HR readings and what the relation of error is with movement. (is it a HR monitor or an ECG)

P5: I prefer the bar graph with legend.

p9:I would like to see a verbal indicator of how the participant feels throughout the sessions as well, some sort of mental factor as well to factor into the physical data.

P4: Perhaps a light or pop-up in the game user interface advising participants to "Slow Down" or "Speed Up" at various times (including during the warm-up, cool-down and "workout" phase).

Heart Rate and (arm movment) Stroke Rate Data Visualization

Secondary Intensity Indicator

p7I would pick the stroke rate. I find that information very helpful
p5:This is very useful and I would keep as presented.
p8:Makes sense.p21Stroke rate is fine.
p12:I would also use stroke rate
p19:Stroke rate is helpful for intensity
p10:Stroke rate is likely the best intensity indicator to use.

p14 I would not use the stroke volume as it think it would be confusing for residents.
p20:After one Google search, many studies say that stroke rate in rowing does not equate to intensity or efficiency of the workout. Instead you could use applied force, since stroke rate does not necessarily indicate intensity in which the individual is striking the water.
p11:Heart rate would be sufficient for the cognitive level of my residents. Involving stroke rate would require further education and be confusing in my context.

p4:Stroke rate information would be particularly interesting in determining whether or not participants are able to "smooth the curve" and maintain a consistent stroke rate with practise.
p9:using the stroke rate it also good to view where the participant peaks in ability to have max rows
P3: I might use stroke rate to see if it indicates other potential challenges in mobility.
p2:This can quantify fatigue and the effects of pacing the activity. Also may indicate improvement in endurance.

p15:Stroke rate is probably the most valid way to test movement for rowing, but also the movement of the stroke may bump the HR monitor and give false readings.
p18:I think it is hard to report this data either way. Using stroke rate it may be confusing to other people viewing the graph as it is not a common term. Although, it is the indicator that makes the most sense.
p17:I don't understand

p7:I don't know if I am misunderstanding the question. I would definitely like to see from beginning to the very end of the session all information.

p21How long they are at that intensity and what is their heart rate.

p9:I would like to see the intensity indicator for warm up and cool down period to analyze the resting heart and cool down rate vs the stroke rate, if a participant has a difficult time it would be good to view data across all variables and not exclude and period of participation

p21How long they are at that intensity and what is their heart rate.
p12:Heart rate for w/u and c/d is the only indicator I would need
p11:Not really

p19:Many seniors do not "warm up/ cool down" - might be good to include stroke rate from start to finish
P6: Im not sure

p20Force applied during the stroke would be a good indicator of intensity.

p14:only if the intensity was included for the middle as well so people could see the difference
p20Yes, that would be helpful.
p6:Yes because it is a good comparison to compare to the actual conditioning

P4: I might consider adding a "Rate of Perceived Exertion" measure (such as the Borg Scale).
P4: I would suggest including Rate of Perceived Exertion (perhaps a scale that can be selected in-game).

p14:I would choose an exertion scale, they are often more intuitive for people with little background in physiology

Feedback on the Visualization

P15: For seniors they need a longer warm up and cool down session as well as significant rest between sessions (at least 48 hours between high intensity). I would say 5- 10 minute warm up and 5-10 minute cool down would be appropriate if it was a longer session, but seniors should not have any exercise session longer than an hour. The results only show a few minutes which mean blood may not have sufficiently moved around the body enough to seem warmed up prior.

p13:the term may off put some residents

p21The blue and green colour is a bit similar and would like better contrast in colour.

p9:It is well organized and simple to read
p7:No looks great
p2: I think what you have is great.
p15:Visually very well done
p14:I like that the warm up and cool down are included
p6:Maybe using HR monitors to help ensure accuracy

p20The table on the right hand side is confusing - possibly needs better titles to explain its purpose.
p11:The breakdown chart on the far right is confusing as a graphic for my residents. Just the HR one is sufficient on its own

P4: It may be helpful to remember that many older adults functional heart rate range does not match age-predicted heart rate ranges (ie: 220-age may not accurately reflect max heart rate). Might also be helpful to calculate heart rate range based on Heart Rate Reserve (Karvonen method) rather than Heart Rate max alone.

Motion Trajctory During Gameplay Data Visualization

Potential Use

Movement Evaluation

p17It could help you observe their movements and stability control while they perform the exercise session.

p8:It would let me visually see the trajectory over the course of the session as well as any discrepancies between arms

p12:This would help me evaluate the client's posture and movements throughout the session

p9:This is a great visual representation of the actual movements and ROM the participant is demonstrating during the session, I would use this visual to identify any issues with shoulder/arm range of motion, as well as an education tool to show the participant what they have done

P2: I could see when the clients technique starts to be effected by the exercise.

P4: Would help understand how to cue and provide participant-specific feedback as relates to movement.

p4:Allowing participants/practitioners to evaluate range of motion and movement fluency in detail. Give feedback regarding body position and coordination. May help identifying how individual differences/injuries affect game performance.

P5: This would be good to see where a person's balance is and how to correct it.

p6:I am not very knowledgeable with the type of visualization, the only way I can imagine using it is for helping residents learn appropriate movements and helping improve form

p6If they are doing the movements incorrectly, you can teach better technique

Identify Trend

p7:It would help me to see their reach, the areas they are most comfortable moving in. Possibly their functional reach and max functional reach. It would be good to see over a time period what changes the motion trajectory visualization had.

p7:This information would be more valuable for the clinician, I wouldn't share it with the resident. It is too confusing and not really useful for them to see. I would look at it and then summarize the findings for the resident.

I would use it.

P14 I would use this in practice to show the resident where the majority of their movement occured

p14 we are trying to spot where they have some weakness or may rely heavily on one arm vs the other

P3: It could be helpful when talking to clients to show how their mobility is impacted.

p20It would only be helpful if the client would have weakness in one arm vs the other.

p8:This can help find differences and areas of weakness to target.

P13: it will show where the residents favour one side over the other

P2: I might use this to show a client if they were favoring one side to accomplish the task.

p14it would help if there was a dominants side or to help correct to where the appropriate space for the movement would be

P18 i would use it to help identify restrictions in movement and quality of movements.

p18I would use it, but not frequently. Definitely on first session and then I would choose a frequency to compare changes. If a resident experiences any changes, this could help confirm and we could assess further. For example pain.

P3 Pain levels, endurance.

Not Useful

p16This would not help me. For a healthy population it may be helpful, but for a population that have limited mobility or tremors, would not be helpful.

p15I would not use this because of the variation of movement between injuries and chronic illnesses.

p20This would not help me. I find the other data would be more beneficial.

P10: I would likely not use this as it doesn't seem like a super relevant indicator relating to someone's health.

p14:I also just don't find this information very helpful in an exercise setting unless

p17I would not use this. I find it more beneficial if it were to be on their feet so we could see more of the stability and balance aspect. Here you get to see upper body ROM, but you can see this by observing them. Their lower body however, you can see their postural movements.

p12:I would not use these images, the data presented is too complicated for my client base

p15This would not help me as I do not even know what it's representing

p20I would not use this.

p11This would not help me.

p11I would not use this

p10This would not help me.

p19No - same reason as prior.

Motion Trajctory During Gameplay Data Visualization

Graph(s) to Be Included

p14bothP3: both
p7:Both P11: both p12:both
P9: Both views are great to see the trajectories
p10Both are good visualizers.

P4: 2D view is easier to interpret and explain at a glance. P2: 2 D top
p8:The 2D is much clearer to me and to residents.
p19:2D seems to be more readable.
p20I do not find 3D helpful. I like 2D.
p18I would be more apt to use the 2D view.

p17:3D view.
p13:I prefer the 3d view

p6Im not sure

p10It looks fine as is.

p14I think I would also like to see the sagittal plane version
P7: Not sure, Another graph might be helpful but also might be redundant. I would have to see it and compare it to the other graphs to determine which is most useful.

p17Yes - on lower body as well (y-z axis)

p19:Yes, an additional view in 3D would be helpful.

p12:top then bottom

P4: I would order the 2D graphics as follows:

1) Sagittal plane
2) Transverse plane

3D graphics:

sagittal plane view might be helpful, provided it does not increase complexity.
P9: Ordering the 2D then 3D graphics is a great way to slowly adjust and look into what is being displayed.

p13 I would want to see the 3d first if I was going to see both

Design Suggestions

p17Add another axis on for bottom of feet to understand weight/balance control.

p12:3d diagram of the resident

p3:label the view for individuals who don't have the same background
p13:probably best to educate the person operating on how to read this, the residents might have a big difficulty reading

p4: Also, a legend indicating the purpose of the checkmarks would be helpful.

Feedback on the Visualization

p14:I don't understand what this is showing me

p7:the graphs above aren't easily interpretable. I needed to pause and think about what I was looking at and then what it meant for my resident.

p14I just don't see the validity in this graphic

P9: Having the trajectories split up into the times- so instead of having one visual of the entire time it would be interesting to see the trajectory broken up into separate pieces such as 3 min then 6 mins instead of having the entire trajectory overlapped.
p18I am not sure about the overlapping of colours over time - some information gets lost

P4: More clarity regarding the colour-coding and how the different colours relate to temporal or spatial characteristics of the movement.
P7: no looks good, not a fan of the purple but that's just a preference to look at
P1: It would be better to use different colours on the same graph showing the motion trajectory from all the sessions.

Potential Use

P4: Rapid comparison of participant to norms or group means. Raising participant awareness of movement patterns.

P3: More for my information and to help with bigger picture probably.

P2: I would not use this.

P5: I myself would not be using this type of data, however, I'm in recreation therefore not applicable data.

P16: I would not use this, it is not valuable in my setting

P14: i would not sure this because it would be confusing to explain to the residents

P11: I don't know that I would use this or that having it would enhance the way I could communicate the info to my residents.

P6: I do not think I would use this as I feel it is disheartening to residents to be compared to a already set standard

P19: I would not use this. I can see how far their reach is without this graph and it is confusing to look at and interpret.

P7: I would still use it but not as much as the other graphs

P8: Sharing areas of weakness and comparison to norms/target

P9: This is a great visual to compare the participant over a norm in relation to their upper body movement and distance of reach.

P12: I would use this to evaluate the ROM of my clients upper extremities

P10: This would be a great tool when working on improving ROM in ones shoulders.

P15: to demonstrate their full ROM and compare to norms

P22: I would use this because it shows range of motion.

P21: I would not use this - same as prior.

Comparative Information

P4: Group means/norms.

P7: Gather information based on other residents values or community gathered values.

P8: No just ensure population norm is age matches

P20: It would be important to indicate where the norm values are derived from (based on age, sex, etc.)

P16: well if this is trying to represent seniors, maybe seniors with injuries or healthy seniors or chronic illnesses

P4: Could also compare individuals initial performances to performance after a set duration (likely 8 to 12 weeks) of familiarization/training and practise.

P6: Maybe compare to their movements over time

p20:I would use this to see current reach, but then compare over time.

P9: I would use this data and compare it after each session with the same participant, if there is a strengthening or rehabilitative purpose to the sessions then I could see if both arms are becoming more equal. therefore instead of comparing to a norm, the data would be used to compare the participants sessions over a period of time

P15: previous measurements for improvement

P12: I would like a base line of my client's reach out of the rowing session

P21: You could compare it to your client's initial assessment (i.e. first session).

P22: I would like to be able to compare from different sessions such as first session compared to 12th session to see if there was improvements.

Design Suggestions

P20: I like the view for lateral and frontal reach. I t would be helpful to change the view for overhead reach - from the side, where it would show height above the midline. Right now it looks like it is posterior reach until you look more closely at the labels.

P4: Perhaps a sagittal and transverse body view to clarify ranges of motion.

P4: I would encourage caution putting more than 2 plots together to avoid confusion/clutter.

P9: It would be interesting to see posture movement included as well, it would be interesting to analyze whether the participants posture varies in comparison to the norm and/or over their on sessions over time

P14: maybe a leaderboard instead of this type of graph

P2: I would prefer the data presented in a table format

Functional Reach and Overhead Reach Data Visualization

Feedback on the Visualization

p20:I like the comparative to the population norm

P15: I like this idea
P11: But I don't have any issues with the design

p6:I just wouldn't want a resident to feel like they are not meeting up to a standard, I feel it would be better to compare their own results to eachother

P12: a better graphic

P12: it's kind of confusing having over head reach as the bottom portion of this graphic

P7: It is not self explanatory, I needed to really sit and think about what I was looking at. What it meant for my resident and their progress.

p7:This would be the most challenging of the 4 to use because I don't find the information easy to interpret or read.

P2: It`s a bit tricky to read for me

P17: Sorry, again, I do not have the expertise to know what I am looking at.