# User Interface Design and Validation for the Automated Rehabilitation System

by

Agnes Wen-Kok Lam

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2015

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

In current physical rehabilitation protocols, patients typically perform exercises with intermittent feedback or guidance following the initial demonstrations from the physiotherapist. Although many patient-centered systems have been developed for home rehabilitation, few systems have been developed to aid the physiotherapist as well as patients in the rehabilitation clinic. This thesis designs and validates the user interface of an Automated Rehabilitation System (ARS), tailored for both patients and therapists in the clinical setting. The ARS was designed using an iterative design process, developed with physiotherapists and patients in a knee and hip replacement clinic. ARS consists of body-worn inertial measurement units which are used to continuously estimate the patient's pose. The estimated pose is graphically represented as an animation and overlaid with the instructed motion on a visual display shown to the patient during exercise performance. ARS allows physiotherapists to quantitatively measure patient movement, assess recovery progress, and manage and schedule patient exercise regimens. For patients, ARS provides visual feedback and a novel exercise guidance feature to aid them while exercising.

As an initial "proof of concept", two user studies were conducted with healthy participants to evaluate the usability of the visual guidance tool. Motion data was collected by the inertial measurement unit sensors and used to evaluate quality of motion, comparing user performance with and without visual feedback and with or without exercise guidance. The quantitative and qualitative results of the studies confirmed that performing the exercises with the visual guidance tool promotes more consistent exercise performance and proper technique with healthy participants.

Following the user studies with healthy participants, system requirements and design requirements were derived through a focus group with 13 physiotherapists. The physiotherapists were presented with an early version of ARS and were asked to discuss how they envisioned the system could potentially be used in their current workflow and whether such a system could improve their current protocol. The physiotherapists provided comments on both the physiotherapist and patient interface of the system. The physiotherapists felt the physiotherapist interface would be useful for patient assessment and provided suggestions on how the data could be better displayed to fit their current workflow. The physiotherapists also felt the patient interface would be helpful for patients to learn the exercise motion, but they expressed concerns as to whether the patient population would be able to comprehend the guidance component of the patient interface.

Following adaptations of the interface to incorporate physiotherapist feedback, the patient interface was evaluated in a user study with 26 outpatients in the clinical setting.

Patients were asked to wear the inertial measurement unit sensors during their exercise session and were instructed to use the ARS interface for a subset of the exercises in their exercise regimen. At the end of the exercise session, patients were asked to complete questionnaires and participate in a semi-structured interview where the researchers asked the patients to discuss their experiences using ARS while exercising. The results show that performing the exercises with the visual guidance tool improves the quality of exercise performance and that patients had a positive experience exercising with ARS.

Finally, a pilot study was conducted with two healthy participants to evaluate the effects of different forms of feedback on exercise performance. Participants were instructed to perform four different exercises and were shown a different feedback method for each exercise. The results of this pilot study showed that additional feedback from ARS may improve range of motion and increase consistency in exercise performance, and is worth further investigation in future work.

## Acknowledgements

First and foremost I would like to thank my supervisor, Dr. Dana Kulić, for her continued guidance, suggestions and support throughout this process. I am extremely grateful for all the hours spent in meetings, the advice she provided throughout the progress in the research and for reviewing my papers. I am appreciative of the administrative tasks that she handled which allowed for me to conduct this research without significant roadblocks. I am also thankful for her funding which allowed for me to travel and attend a conference to further my knowledge in the engineering and biomedical field.

I would like to thank the other researchers that contributed to the design of the user interface of the Automated Rehabilitation System, especially in the early phases of development. I would like to thank Yeti Li for his contributions of the initial workflow and wireframes of the user interface, Stefanie Rao for her high-fidelity mock-ups of the system, Michell Fergenbaum for his expertise in the domain of physiotherapy and Danniel Varona-Marin for his contributions in designing and conducting the user studies. I would also like to thank the other members of the Automated Rehabilitation System team, Jonathan Lin, Vladimir Joukov, Roshanak Houmanfar, Michelle Karg and Christopher Thomas, for their contributions to the back-end of the system and insightful discussions and advice during the development process of the system.

I would like to thank Cardon Rehabilitation and the University of Waterloo for funding this research.

A special thanks goes to the staff and patients of St. Joseph's Health Centre Guelph for their time, participation and accommodation for the studies. I would like to thank the physiotherapists for their participation in the focus group and their valuable feedback and input on improving the system. I would also like to thank the patients who participated in the user study, who were willing to use the system and provide feedback on their experience during their exercise session. I would like to especially thank physiotherapist assistant Irene Pica for her valuable assistance and recruitment of participants while we were conducting the user study with patients.

Finally, I would like to thank all my friends, family and loved one. This research and thesis could not have been possible without the help of your continuous support and encouragement throughout the process.

## Dedication

This thesis is dedicated to my parents, Lansie and Wilfred, and my brother Angus. Thank you for your endless support to get me where I am today.

# Table of Contents

# List of Tables

# List of Figures

## Nomenclature

| | |
|---|---|
| ARS | Automated Rehabilitation System |
| EGF | Exercise Guidance Feature |
| IMU | Inertial Measurement Unit |
| MAX | Maximum |
| PT | Physiotherapist |
| PTA | Physiotherapist Assistant |
| REP | Repetition |
| ROM | Range of Motion |
| SIT KNEE EX | Sitting Knee Extension |
| STAND HIP ABD | Standing Hip Abduction |
| STAND HIP EX | Standing Hip Flexion |
| STAND HIP FLEX | Standing Hip Flexion |
| STAND KNEE FLEX | Standing Knee Flexion |
| W EGF | With Exercise Guidance Feature |
| WO EGF | Without Exercise Guidance Feature |

# Chapter 1

# Introduction

During physical rehabilitation, patients who perform rehabilitation exercises under the supervision of a physiotherapist (PT) perform the exercises more correctly and have less pain than patients who learn and complete the exercise from a brochure [7]. Despite the benefits of direct supervision from PTs while patients complete the exercises, PTs are usually supervising multiple patients during an exercise session in the clinical setting. PTs rotate between patients, giving some patients more attention and assistance than others, depending on their recovery progress and ability. Because of this, patients are not given constant feedback on the correctness of their exercise performance. Occasionally, this results in the patients skipping an exercise, performing the wrong exercise, preforming the exercise motion incorrectly, or performing the incorrect number of repetitions while unsupervised. In addition, in current practice PTs do not have the ability to record their patients' exercise motions [21]. If PTs want to assess the progress of patients based on exercise performance, they must rely on their visual and written observations of their patients during the exercise session and use tools such as the goniometer to measure the static range of motion (ROM) of patients [22]. This becomes increasingly difficult as the number of patients a PT supervises increases. PTs are also currently unable to analyze their patients' exercise motions following the exercise sessions because they do not have any form of quantitative data on their patients' movements.

With the advancement of technology, research groups have developed various systems to enhance physiotherapy exercise sessions. The majority of these systems were designed for the home use [1–3,23]; fewer have been designed for the clinical setting [10,20,33]. One of the goals of the rehabilitation systems developed in the literature is to provide patients with guidance and feedback with regards to their exercise performance. Home systems have also focused on increasing compliance and motivation for patients during exercise performance, as they are not under any form of supervision by a PT, but this is less of a concern for systems intended for the clinical use.

The focus of this thesis is to design and validate the user interface of a rehabilitation system targeting PTs and patients following hip or knee replacement surgery. The main goal with this type of rehabilitation is to increase strength and range of motion while minimizing pain so that patients are able to carry out the activities of everyday living. The three main options for rehabilitation are in-patient, out-patient and at-home rehabilitation [24]. Patients that have additional medical conditions or complications post-surgery require additional monitoring at a medical facility and are typically admitted to in-patient care. Patients are typically admitted to in-patient care for seven to 10 days, depending on the severity of their condition, and receive one to two hours or rehabilitation on a daily basis, under the supervision of a physiotherapist (PT) or physiotherapist assistant (PTA).

Patients who do not require additional monitoring following their surgical procedure have the option of either out-patient or at-home rehabilitation. Patients who have a form of transportation to a rehabilitation clinic are admitted to out-patient rehabilitation while patients who lack any form of transportation or are unable to leave their homes receive at-home rehabilitation. Patients who receive at-home rehabilitation are given an exercise program to follow and are expected to preform the exercises at home. A PT may visit the patient at their home to provide treatment and to evaluate the progress of the patient. In out-patient rehabilitation programs, patients attend a rehabilitation clinic twice a week for six weeks where their progress is assessed, and perform exercise programs under the supervision of a PT or PTA. Patients are also given a set of exercises by their PT to do at home on days they do not have an appointment at the clinic.

In clinical rehabilitation, PTs work with the patients to identify their individual goals for rehabilitation, assess the progress of their patients throughout their rehabilitation program and assign exercise regimens tailored towards the functional ability of each patient. PTs modify the exercise regimens on a weekly basis based on their patient's capability, progression and goals for rehabilitation. Modifications made to the exercise regimens by the PT include: exercises to be completed, number of repetitions for each exercise and the amount of ankle weights used during exercise performance. During the exercise session in the clinic, multiple patients perform their exercise routines at various apparatuses around a gym at the same time. In some cases, PTs work one-on-one with patients but in most cases, a PT or PTA is supervising multiple patients simultaneously. Common mistakes made by patients during exercise performance include using the hip or torso for compensation during exercises and performing the exercises at too high of a velocity, resulting in using momentum and/or gravity to perform the motion.

To design a system suitable for clinical use, the system should be beneficial for both patient and PT use. The patient interface should guide patients in performing the correct exercise in the correct manner and provide feedback on their exercise execution while patients are unsupervised by their PT or PTA. Patients should also be able to use the system while operating the various apparatus required for their exercise regimen. The PT interface should allow the PT to create and modify exercise regimens for their patients. The PT interface should also provide PTs with the motion data collected by the system of their patients in such a way that can be easily interpreted by the PTs during their assessment of patient progress.

To improve exercise performance and tracking for both patients and physiotherapists, this research proposes the use of an Automated Rehabilitation System (ARS). ARS is a system specialized for clinical use, consisting of separate user interfaces for the patient and the clinician. ARS utilizes inertial measurement units (IMUs) to track the patient's exercise motion and provides visual cues to guide the patients to perform the proper exercise motion. ARS provides the patient with a visualization of their exercise motion as well as an exemplar motion as guidance to improve the quality of their exercise performance. ARS continuously tracks and measures the hip, knee and torso joint angles, enabling assessment of range of motion, tempo, and compensation. The motion data is stored and can be subsequently reviewed by the PT through the user interface.

## 1.1 Thesis Contributions

This thesis describes the design and validation of the user interface of the Automated Rehabilitation System.

**Design and implementation of the user interface.** The various components of the user interface of the system were designed to aid both PT and patient users in the clinical setting. The patient interface was designed to provide patients with feedback and guidance as they preform rehabilitation exercises in the clinic. While using the patient interface, the system is capable of storing the motion data of the user's exercise performance. Analysis of the motion data reveals that the user's motion is positively influenced while using the system. Using the patient interface causes the user to perform the exercises in a more controlled pace, more correctly, more consistently, to increase range of motion, and to reduce compensatory movement. The system was also positively received by users during exercise execution. The PT interface was designed to allow PTs to create and modify exercise regimens for their patients. The PT interface was also designed to provide PTs with the data of their patents' exercise motions during progress assessment, which was not a focus in previous work. Using the feedback from the studies described below, both the PT and patient interfaces were designed to better satisfy the requirements of the clinical setting.

**Evaluation of the user interface with healthy subjects.** The patient interface was initially evaluated with healthy participants in two user studies. The first study, conducted with 12 participants, considered the effect of exercise guidance compared to using motion feedback alone. The second study was conducted with 10 participants and compared the use of the designed UI with a log sheet typically used in existing clinical protocols. Both studies provided preliminary results indicating that healthy participants modified their motion patterns as a result of feedback and preferred the proposed user interface to motion-only feedback or the log sheet.

**Focus group with physiotherapists.** A focus group was conducted with PTs to elicit system requirements and their feedback on the system. The PTs were walked through a preliminary version of the system to generate discussion of how such a system could be used in the clinical setting. 13 PTs provided their feedback and suggestions on both the PT and patient interface. The PTs provided substantial feedback on clinical requirements and the usability of the system, which were used to improve the user interface design and the design of the patient study.

**Evaluation of the user interface with physiotherapy patients.** The patient interface was then evaluated with rehabilitation patients in the clinical setting. Patients were asked to use the system while preforming a subset of their exercises from their exercise regimen. The IMU sensors capture the motion data of the patients as they performed the exercises. Patients then completed a questionnaire and were interviewed to elaborate on their experiences while using the system. The results of the study showed that the proposed system was able to measure patient movement in real time, including both directed and compensatory movement. Feedback was effective in improving the motion performance of the patients and patients rated the experience of using the system positively.

**Evaluation of feedback mechanisms with healthy subjects.** Based on the results from the healthy participant and patient studies, which indicated the strong influence of feedback on motion performance, and additional pilot study was designed to investigate different feedback mechanisms. Three feedback mechanisms were evaluated in a pilot study with two healthy participants. Participants were asked to perform various exercises while observing the UI with one of the feedback mechanisms. Preliminary results from the pilot study indicate that the type of feedback influences motion performance, and this is an important direction for future work.

## 1.2 Thesis Outline

Chapter 2 provides an overview of the existing research on motion measurement and feedback systems designed for rehabilitation. First, the systems designed for home use are presented. The home-based systems are categorized into guidance systems and exer-gaming systems, and examples of both are provided. Second, the systems designed for clinical use are presented. The clinical systems are again categorized into guidance systems and exer-gaming systems and examples of both are provided. Finally, preliminary research on various feedback methods that can be provided by a rehabilitation system is discussed.

Chapter 3 details the design of the UI of ARS. This chapter first describes the various components of the system and how each component interacts with the user interface. A description of the workflow and functionality of both the patient and PT interface is then provided, where the patient interface focuses on exercise guidance and the PT interface focuses on the creation of exercise regimens and patient assessment. Major design decisions for each interface are also discussed.

Chapter 4 describes the user studies conducted with healthy participants as a "proof of concept" to evaluate ARS. Two studies were conducted with healthy participants. In the first study, participant motion data and subjective evaluations while exercising with and without the system's exercise guidance feature as feedback were compared. In the second study, exercising while using the system and the exercise guidance feature was compared to exercising with a log sheet adopted from the current protocol in a rehabilitation clinic. The results of the studies showed that participants preferred exercising with the proposed system and the exercise guidance feature over the alternatives and were performing the exercises more correctly and with more consistency when using the system and the exercise guidance feature.

Chapter 5 describes the focus group conducted with PTs to evaluate ARS. 13 physiotherapists were asked to evaluate both the PT and patient interface of the system. The PTs believed that the PT interface had potential to be useful for patient assessment and provided recommendations to modify the current interface to better fit the current clinical protocol. The PTs also felt that the patient interface would be helpful for patients to learn the exercises, but were skeptical as to whether patients would comprehend the virtual avatar of the patient interface.

Chapter 6 describes the user study conducted with physiotherapy patients in the clinical setting to evaluate the effectiveness of ARS, as well as to address the concerns raised by the PTs described in Chapter 5. 26 total knee or total hip replacement patients were asked to use the system for a subset of their exercises during their exercise session in the clinic.

Upon completion of the exercises, patients were asked to complete a questionnaire and participate in a semi-structured interview to discuss their experiences using the system while exercising. The results of the study showed that the system was positively received by participants, participants did not have any trouble interpreting the virtual avatar, and using the system positively influenced the exercise motion preformed by the patients.

Chapter 7 describes the pilot study conducted with two healthy participants to evaluate the effects of various feedback methods provided by ARS during exercise execution. Participants were asked for perform four exercises and were given a different feedback method for each exercise. The results of this study show that additional feedback promotes increased range of motion and consistency in exercise performance and is worth investigating in future work.

Chapter 8 summarizes the findings of this thesis and describes directions for future work.

# Chapter 2

# Related Work

Many research groups have designed, developed and evaluated the use of various systems to assist patients and PTs during physiotherapy rehabilitation. Groups have focused on designing systems either for guidance or exer-gaming to increase motivation and compliance among patients when they need to preform physiotherapy exercises. Exer-gaming systems uses gamification concepts to promote exercise performance. Systems have also been designed either for the home and clinical setting. This chapter reviews the various guidance and exer-gaming systems, first for the home environment, and then the clinical environment. This review will highlight the interface designed for patient use, the interface designed for PT assessment and any validation conducted on the system and patient performance, in relation to our targeted application[1].

## 2.1 Guidance Systems for Home Use

Rehabilitation systems designed for home use are very popular in the literature. Since patients do not have access to a PT at home, researchers have designed various systems to provide patients with guidance and feedback as they perform the rehabilitation exercises unsupervised. For example, the Rehabilitation Visualisation System (RVS) is intended for the home environment and utilizes two IMUs to track the exercise motion as users preform knee exercises [2]. Users are provided with real-time feedback on their exercise motion and the correct exercise motion is also demonstrated on a virtual avatar in a separate

[1] An earlier version of this chapter has been accepted for publication in *Human-Computer Interaction* [14].

screen of the user interface. The feedback is provided in the form of a graphical fan with changing colour gradient indicating the range of motion of the knee. Patients are provided with a progress chart indicating the range of motion achieved for each repetition and PTs are able to view this progress chart when communicating remotely with their patients on their progress. RVS was evaluated with knee replacement patients in the acute phase of their post-operative rehabilitation. In this phase of rehabilitation, typically only seated or supine exercises are performed, and recovering range of motion is the primary target of rehabilitation. Tempo is not a focus as patients' ability to regulate motion speed may be impeded due to pain. Because RVS was designed for home use, the emphasis is on patient use and there is little discussion on the PT's interaction with the system. Ayoade and Baillie do not mention whether the system includes the capability of modifying the exercise programs, which is necessary in clinical use. Ayoade, Uzor and Baillie [3] discussed that in designing RVS, they elected to keep the demonstrated motion separate from the user's motion to prevent users in the early stages of recovery from over extending or flexing while trying to keep up with the range of movement and pace. The trade off, however, is that patients can only focus their attention on either the demonstrated motion or their own motion, and do not get the benefits of both the guidance and the feedback simultaneously.

Interactive Virtual Telerehabilitation (IVT) is a similar system also intended for the home environment, which also utilizes two IMUs to track the exercise motion as users preform knee exercises [23]. The interactive application of this system consists of a 3D avatar which demonstrates the exercise to be performed, and waits for the user to reproduce the motion, but it is unclear how this was implemented in the system. Again, IVT has little emphasis on the PT's interaction with the system. IVT includes a web portal for therapists, which allows them to remotely review the data collected by the system and modify the therapy as the rehabilitation evolves, but there is no discussion on what can be modified or if existing exercises can be customized.

PT Vis is a wearable knee brace which uses bend sensors to detect the bend angle of the knee [1]. A wire bar graph on the device gives visual notification of the bend progression as the patient performs the knee extension exercise. The device only provides the user with feedback on how much knee flexion the user achieved but does not provide guidance on how to perform various exercise motions. PT Vis also does not include any interface for the PTs.

All the systems above also only provide feedback for knee movement. Not only does this restrict the systems from including hip exercises, it also precludes the ability to detect and correct any hip compensation while performing the knee exercises. An important factor when performing rehabilitation exercises is minimizing the movement of the compensatory joints and without tracking the motion of the hip, users are not provided with real-time guidance and feedback on this aspect of their exercise motion. The systems above also do not provide patients with any guidance and feedback with respect to the tempo of the exercise motion.

## 2.2 Exer-Gaming Systems for Home Use

Rehabilitation systems have also been designed to help patients increase their compliance and motivation to perform the exercises in the home setting. Research groups have proposed exer-gaming systems to encourage performance of repetitive exercise motions. For example, Uzor and Baillie [32] used the IMU-based system and designed games to be played in the home setting to encourage seniors to perform their exercises at home.

Thera-Network is a system which consists of a knee brace and an online system [12]. The brace tracks the knee angle and Electroluminescent (EL) strips light up as the user increases their range of motion. The online component is based on the buddy system, where patients seek out others who are undergoing similar physiotherapy and use the progress of their online friends as motivation. Although Thera-Network provides patients with feedback on the bend angle of their knee, it does not provide patients with guidance on how to perform different exercise motions. PTs can also track the progress of their patients online through this system, but are only provided with information in the form of the level of EL strips that light up and are not provided any information on the tempo, speed or compensatory movement as patients exercise.

Exer gaming systems are typically designed to increase compliance and motivation, but may lack guidance and feedback with regards to exercise performance.

Recent work in the literature has began to look at detecting compensation during exercise performance. Gesture Therapy is a virtual reality-based system for rehabilitation of the upper limbs [30]. Sucar et al. introduce the idea of detecting compensation in the trunk while users interact with the system, but the compensation component of the system is not further investigated in the analysis of the system.

## 2.3 Guidance Systems for Clinical Use

While there are many systems designed to enhance the various aspects of exercise performance at home, systems designed specifically to satisfy the requirements of the clinical setting are less commonly discussed in the literature, especially systems designed specifically for guidance and feedback. Kinerehab is a system intended for use in the clinic for users with cerebral palsy which utilizes the Kinect to track exercise motions [10]. An interactive interface provides users with step-by-step video instructions and waits for the user to complete the motion before proceeding to the next exercise. However, the users' wheelchairs and walkers interfered with the accuracy of the system as the Kinect identified the aids as an extension to the users' bodies. A similar issue would arise using a camera-based system, such as the Kinect, for motion tracking in the knee and hip rehabilitation clinical setting as some exercises are performed using various apparatuses that would interfere with the camera's detection of the users' bodies. PTs may assist the patient with their movements or correct incorrect movement and the body of the PT would also block the line of sight of a camera-based system. Huang mentions that Kinerehab allows PTs to adjust the rehab program according to the individual needs of patients and provides therapists with a reference to monitor patients' progression, but the interface for PTs is not described in further detail.

TactaPack uses an accelerometer sensor system to detect the movements of the limb as a patient is exercising [20]. If the sensors detect an unsafe motion, where the movement exceeds a certain threshold, the devices will vibrate, notifying the patient through haptic feedback that they have reached an unsafe position. This system aims to prevent unsafe positions, but does not provide the users with guidance in performing the exercise motion correctly. There is also no mention of an interface for PTs in the TactaPack system.

Yeh et al. [33] describe the design process of their system intended for clinical use, which consists of two IMUs and an interactive interface displaying the user's exercise motion, but the system is only validated in a small pilot study consisting of two participants. There is mention that the data collected by the system will be saved to the database to allow the physician or therapist to review the patient's rehabilitation, but there are no details about the type of data to be made available to the PTs and how this data would be displayed.

## 2.4 Exer-gaming and Motivational Systems for Clinical Use

Finally, there are several systems that have been designed to address compliance and motivation in the clinic. RIABLO is intended to be used in both the clinical and home setting, and utilizes five inertia sensors and a board of pressure sensors to capture the movement of the patient [6]. Patients collect rewards for preforming the exercise movements through playing the games designed for RIABLO. Feedback is conveyed to the patients in the form of rewards and penalties in the games. PTs can access the system in the clinic or via a web application where they can create the exercise program for their patients, set the parameters of the exercises in the program and monitor the progress of their patients.

Lange et al. [15] developed an exer-gaming system using a Kinect-like device to train balance. Users are required to touch virtual jewels in a particular order presented around their body, while the Kinect-like device tracks the movements of the patient.

Gockley and Matarić [8] developed a social robot which senses the location of the patient and uses the concept of proxemics and engagement for motivation. With the use of inertia sensors to track the user's motion, the robot executes different levels of proxemics and engagement depending on the motion performed by the user. The focus of this work is the design of a social robot used as an exercise companion to motivate users to exercise for a longer period of time. The system, however, does not provide users with any form of guidance on how to perform the exercises.

The RehabMaster is a task-specific interactive game-based VR system for post-stroke rehabilitation of the upper extremities [27]. The RehabMaster uses a PrimeSense 3D awareness sensor and tracks the patient's upper extremities as they engage in rehabilitation games in the seated position. While this is suitable for upper body rehabilitation, the RehabMaster uses a camera-based system, the use of apparatuses for lower body exercises and assistance from the PT will cause occlusions to the line of sight of the camera. There is mention of an assessment module in the RehabMaster which tracks the patient's rehabilitation progress, but there are no further details on how this component of the system is implemented.

While the systems designed for clinical use have developed approaches for both patient and therapist feedback, none of the systems provide patients with real-time guidance and feedback on their exercise performance. In addition, most of the research described above has not analysed the motion data collected by the system to evaluate how using such a system affects the patient's exercise performance. There is also very little discussion on an interface for PT's to assess their patients. The goal of this thesis is to design a system specifically for clinical use, providing patients with guidance and feedback on their exercise performance for both knee and hip exercises while also providing an interface for PTs to analyze the data collected by the system to aid the assessment of their patients. In evaluating the system, this research also analyses the motion data collected to assess how the use of such a system affects the exercise performance of patients.

## 2.5 Feedback Methods of Rehabilitation Systems

There has also been preliminary work evaluating various guidance methods provided by rehabilitation systems to better guide patients during exercise performance. Physio@Home is a prototype system intended to be used at home to provide patients with proper guidance of exercise execution without the feedback of PTs [31]. The system consists of a "wedge visualization" with four distinct components for different forms of guidance, incorporating both feedback and feedforward guidance. The system was evaluated under four conditions: wedge visualization and video without wedge visualization using the single view and multi view mode. It was shown that participants had the lowest error and greatest range of motion using the wedge visualization in the multi view setting. The additional guidance from the wedge visualization was shown to be the more accurate than using the video without the wedge visualization but because it was evaluated as a whole, it is unknown which of the four components was the most effective form of guidance.

# Chapter 3

# The User Interface of the Automated Rehabilitation System

This chapter details the various components designed for the user interface of the Automated Rehabilitation System (ARS) , for both the patient interface and the PT interface. It provides an overview of the hardware platform and software environment used to develop ARS. The chapter then details the components of the patient interface which were designed to help improve the exercise performance of patients as they perform their rehabilitation exercises in the clinic. The chapter also details the components of the PT interface that were designed to help PTs create exercise regimens for their patients, as well as analyse the motion data of their patients collected by the system[1].

## 3.1 Overview

ARS is a measurement and data visualization system targeted for clinical use in physiotherapy for both PTs and physiotherapy patients. Figure 3.1 provides the workflow of the four major components of ARS. Patients wear IMU sensors which track their movement as they perform rehabilitation exercises. The current configuration of the system uses SHIMMER [4] sensors. The system takes accelerometer and gyroscope data from the IMUs and converts it to joint angles using a pose estimation algorithm [19] and segments the time series data of the exercises online using a segmentation algorithm [18]. Both the motion

[1] An earlier version of this chapter has been accepted for publication in *Human-Computer Interaction* [14].

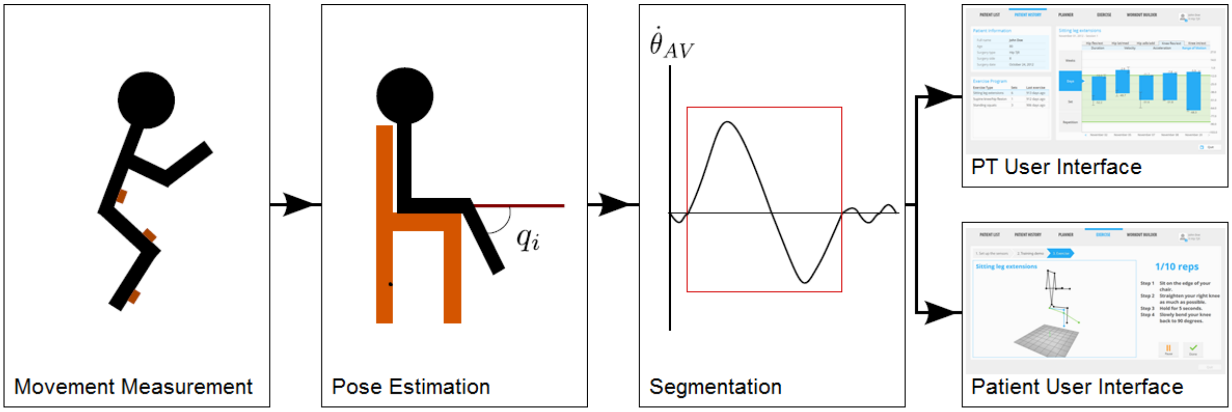


Figure 3.1: Process workflow of the Automated Rehabilitation System. The Movement Measurement component consists of IMUs worn by the patient as they are exercising. The Pose Estimation component estimates the joint angles from the gyroscope and accelerometer data of the IMUs. The Segmentation component segments the time series data of the exercise sequence into individual repetitions. There are two types of user interface: the Patient Interface is observed by the patients as they exercise, providing guidance and feedback to encourage proper exercise motion execution. The PT Interface is used by PTs to review schedule workouts and review patient motion data.

of the hip (3 joint angles) and the motion of the knee (2 joint angles) are simultaneously estimated, allowing the system to be used for any knee or hip exercise. Modelling and displaying the hip joint allows not only the inclusion of hip exercises in the system, but also allows for any compensation performed by the hip joint while performing knee exercises to be measured and identified. The system also tracks torso movement (3 joint angles) to identify compensatory movement in the torso and allow for exercises which require torso movement. The data collected and processed by the system is displayed to the patients via a graphical user interface (UI). Screenshots of the patient interface is shown in Figures 3.2 - 3.5. Along with the patient interface, the UI also consists of a PT interface, where PTs are able to create workout regimens for their patients, schedule the regimens and review the data collected on the patients' exercise movements by the system. Figures 3.7 - 3.10 show screenshots of the PT interface.

The hardware of the system consists of the IMU sensors and a laptop, which executes the software to compute the patient pose, segment the data into individual REPs and displays the UI. This allows for the system to be portable and because the IMU sensors are wireless, users are not restricted to a confined proximity of the laptop. The software

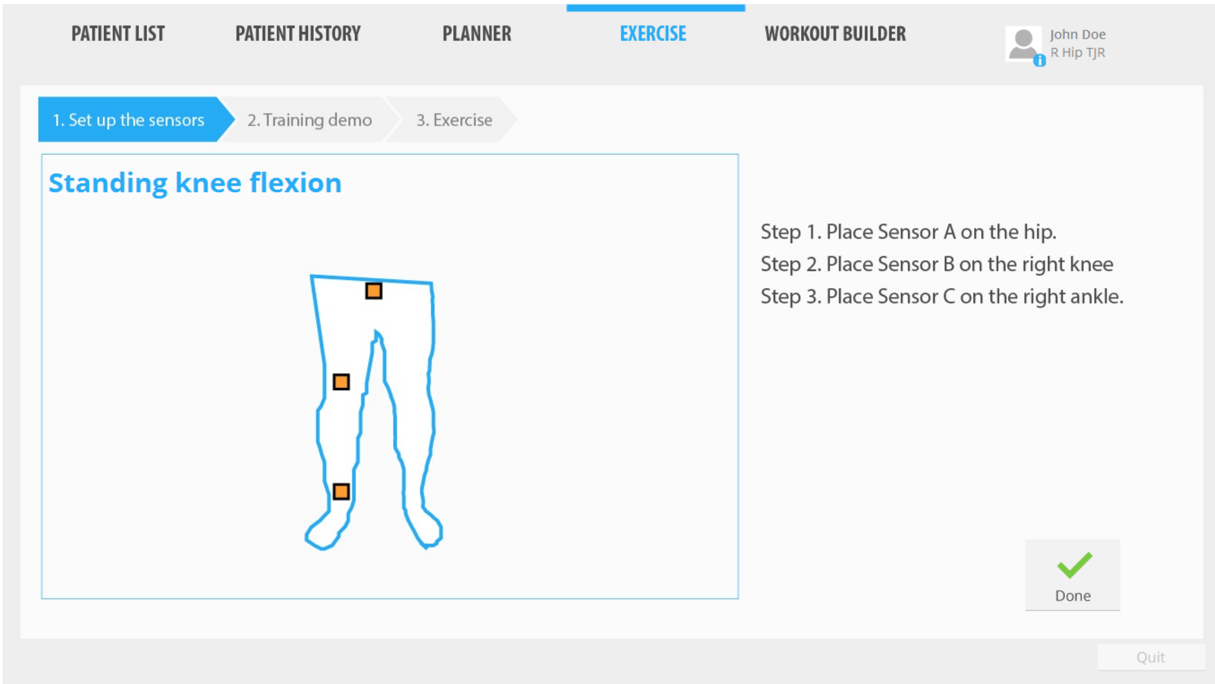


Figure 3.2: Screenshot of the patient interface of the Automated Rehabilitation System showing patients how to place the sensors prior to beginning their exercise session.

is written in JAVA, using libraries from Java Swing and the Processing language for the UI components. The pose estimation algorithms are written in C++ and packaged as a DLL-file to interact with the UI software. The segmentation algorithms are written in MATLAB and packaged as JAR-file using the MATLAB Compiler to interact with the UI software. The ARS software follows the model-view-controller software architectural pattern, where the model consists of the back-end algorithms and data collected by the IMU sensors, the view consists of the UI components, and the controller updates the model and view accordingly.

An initial prototype was designed for ARS and was evaluated as a "proof of concept" in a user study with healthy participants described in Chapter 4 and used to facilitate discussion in the focus group with PTs described in Chapter 5. To design a prototype interface for this complex sociotechnical system, an Ecological Interface Design (EID) [5] was used. The EID approach helped with understanding the domain of physiotherapy and the role of an automated rehabilitation system such as ARS in a clinical setting. Results of a work domain analysis revealed several functions and constraints that led to the initial

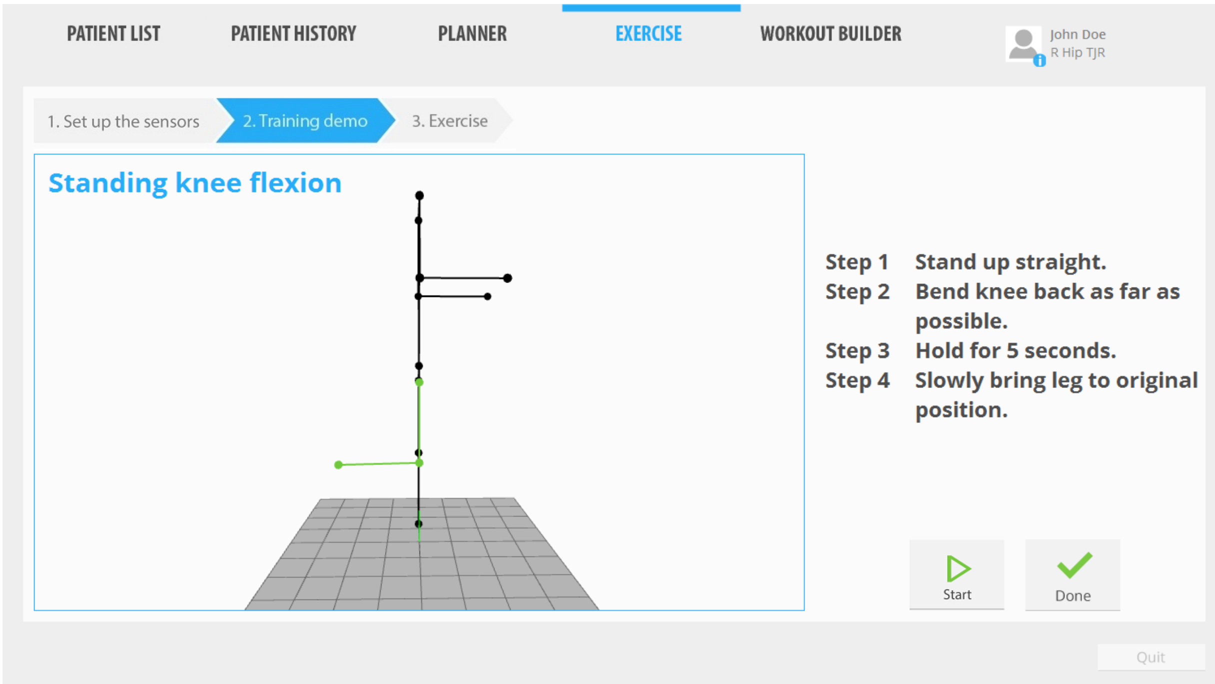


Figure 3.3: Screenshot of the patient interface of the Automated Rehabilitation System during the demonstration of the exercise prior to exercise execution. Before the patient preforms the exercise, the exercise is demonstrated on the virtual avatar to remind the patient of the exercise motion for the exercise to be performed.

requirements for ARS's prototype interface. The development of this prototype interface is described in Li, Burns and Kulić [16]. The workflow of the system was designed by researcher Yeti Li and the high-fidelity wireframes of the initial prototype was designed by Stefanie Rao. Dr. Mitchell Fergenbaum consulted on the understanding in the domain of physiotherapy. Because the concept of using rehabilitation system is still completely novel in the clinical setting, an initial prototype was designed prior to conducting a focus group with the PTs so that it could be used as a starting point to facilitate the discussion of the focus group. The prototype allowed for the PTs to better visualize this new concept of rehabilitation systems used in the clinical setting.

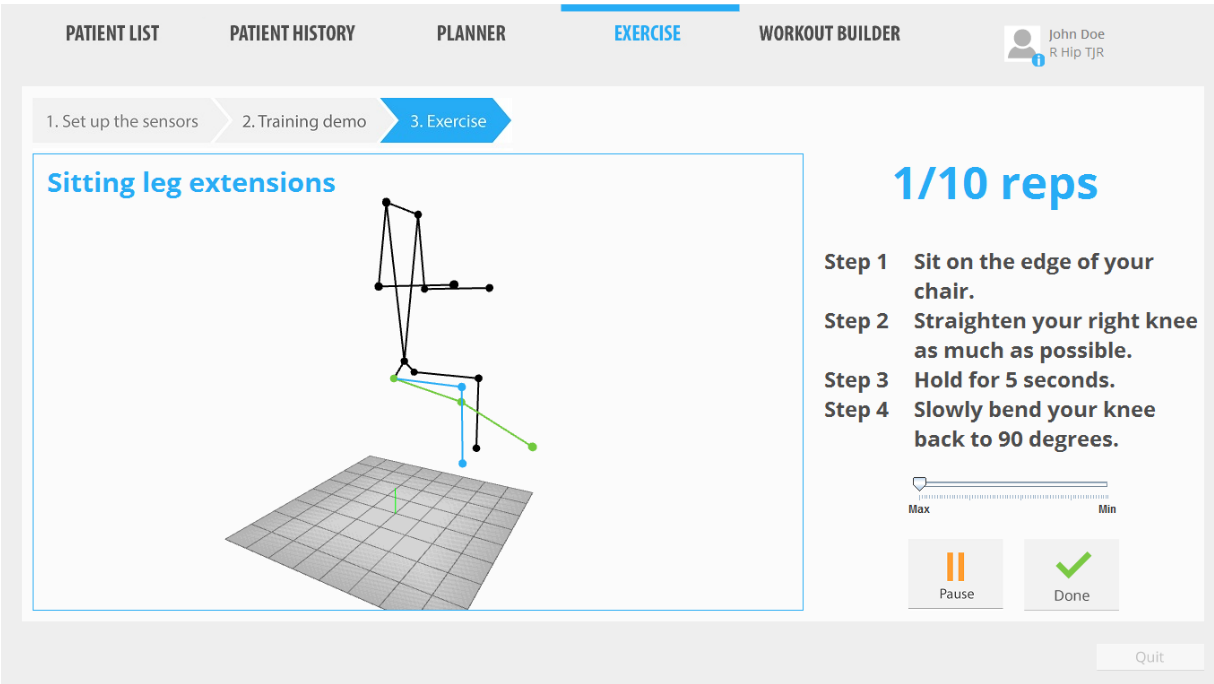


Figure 3.4: Screenshot of the patient interface of the Automated Rehabilitation System during exercise execution. The blue leg of the virtual avatar represents the user's motion and the green leg represents the guidance motion, demonstrating the ideal exercise motion.

## 3.2 Patient Interface

The patient interface first shows the patient where to place the IMU sensors. This screen, shown in Figure 3.2, guides the patient and/or the PT on how to place the sensors on the body. The patient is then shown a demonstration of the exercise to be performed, shown in Figure 3.3. The patient has the option to replay the demonstration, by pressing the play button, if necessary. The replay feature was not in the initial prototype of the system, but was added to the system when both PTs and patients voiced that it would be useful for patients to replay the demonstration in the event that they missed it the first time. The demonstrated motion is the same motion recorded by the PT for the exercise guidance feature, described below.

Once the demonstration is completed, the patient is taken to the exercise execution screen, shown in Figure 3.4. The exercise execution screen includes a virtual avatar which displays the user's exercise movements in real-time as the user is exercising. The system

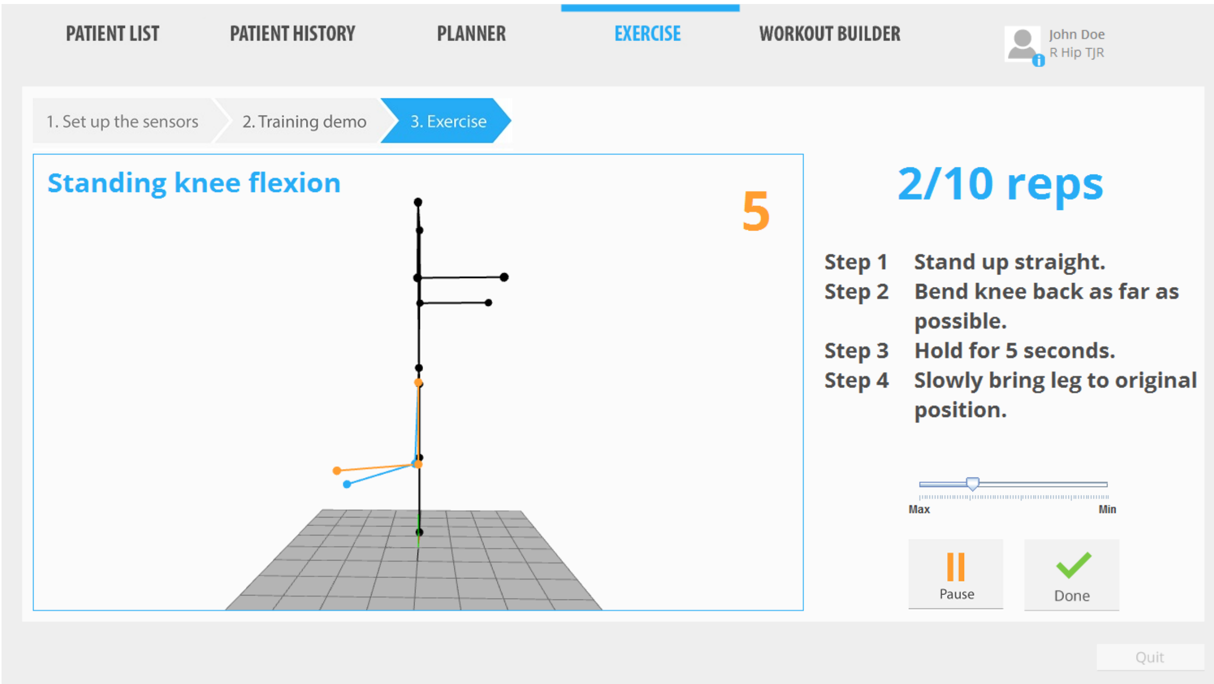


Figure 3.5: Screenshot of the patient interface of the Automated Rehabilitation System when the five second hold feature is activated during exercise execution. The guide leg changes colour from green to orange and a five second countdown appears in the upper, right hand corner in orange.

was implemented to track both hip and knee movement for the user studies described in Chapter 4 & 6, allowing for user to use the system for guidance for both hip and knee exercises. Tracking of the hip movement also allows for patients to detect and correct any hip compensation used while performing knee exercises, as shown in Figure 3.6. The patient UI also provides other information with regards to the exercise set: name of the exercise, list of instructions and number of repetitions (REPs) completed. The initial prototype of the system included a timer which tracked the time elapsed of that exercise set, but was later removed as both PTs and patients expressed that the timer was not useful for completing this type of exercise, in Chapters 5 & 6, respectively. The Quit button is also disabled during exercise execution as PTs expressed they were worried patients may accidentally quit out of the application during their exercise session. Through discussions with the PTA during the user study conducted with patients, it was discovered that reducing compensatory torso movement is also an important factor to performing leg exercises. Torso

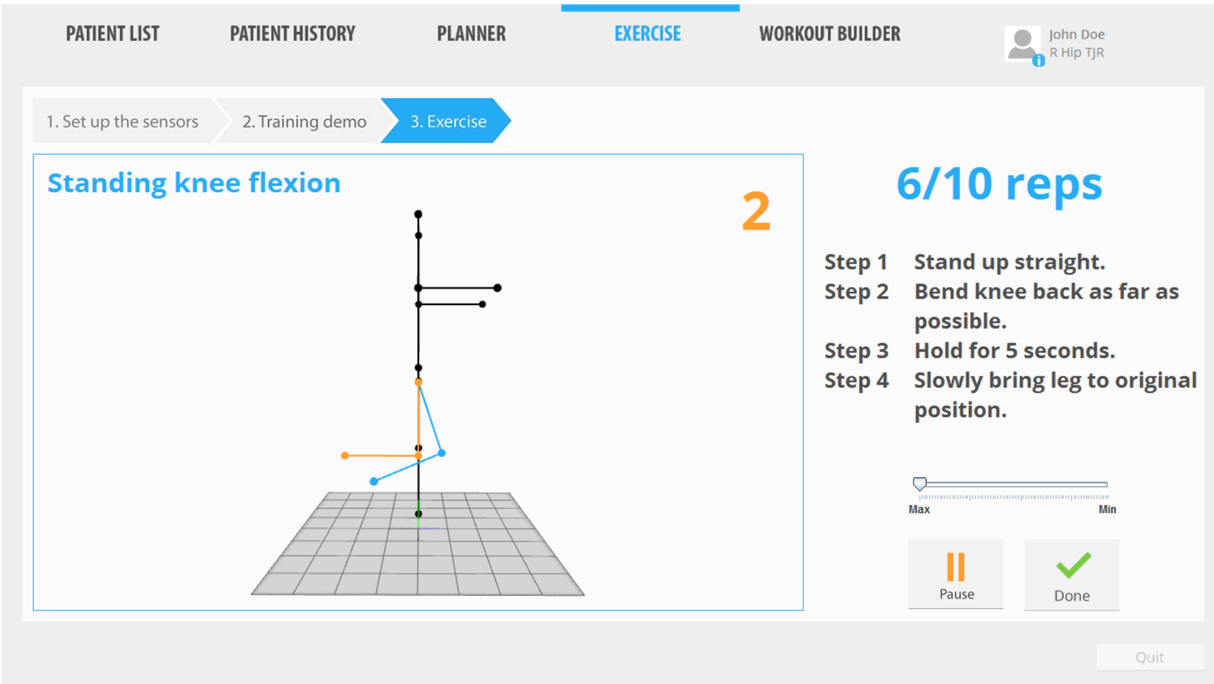


Figure 3.6: Screenshot of the patient interface of the Automated Rehabilitation System displaying an example of compensatory movement in the hip while preforming the standing knee flexion exercise. Patients using the system can detect their compensatory movement by observing how their upper leg is misaligned with the guide leg.

tracking was then added in the system, and evaluated in the feedback study described in Chapter 7.

The exercise guidance feature (EGF) of the exercise execution screen provides continuous visual feedback to the user, displaying the ideal exercise motion in comparison to the user's current motion. The EGF provides real-time guidance and aids users in recalling the exercise to be performed by rendering the first half of an exercise motion overlaid on the real-time motion on the virtual avatar. The system monitors the progress of the users and adjusts the advancement of the guidance based on user progress. When the system detects that the user has performed the instructed motion and achieved the final flexion or extension position by detecting the joint angle of the active joint, the EGF will display the second half of the motion, returning to the rest position. In essence, the user follows the guiding motion of the avatar for each portion of the exercise during flexion and extension. When the system has detected that the patient has returned to the rest position, EGF

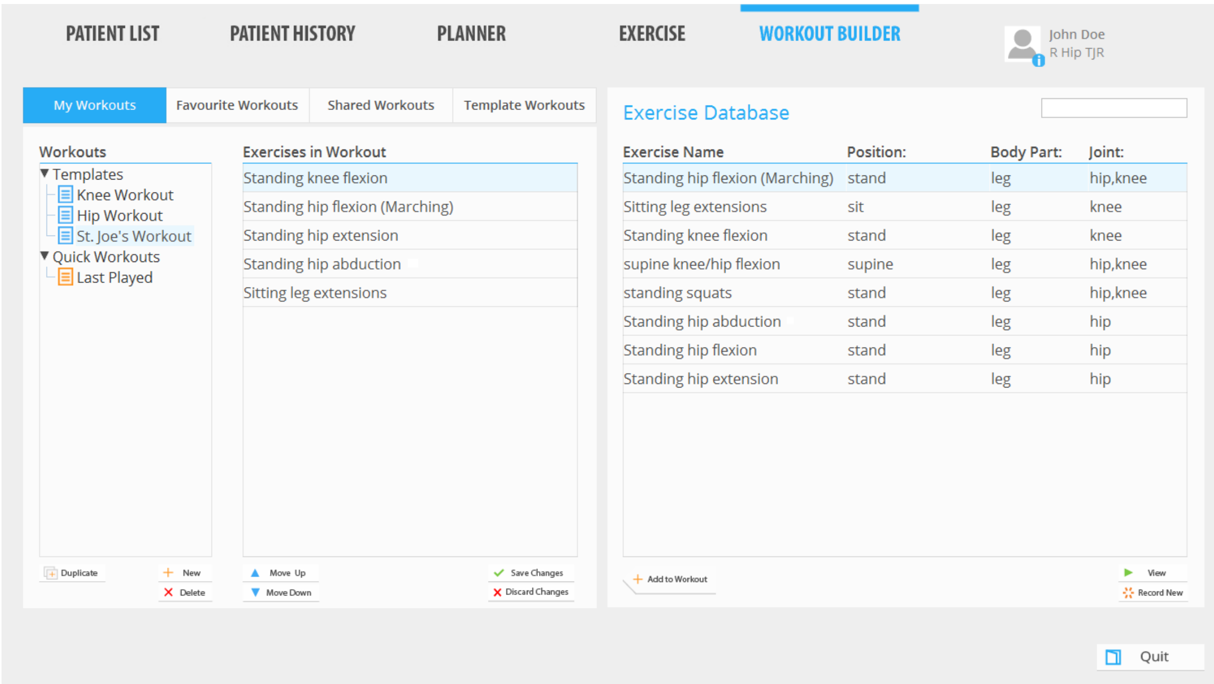


Figure 3.7: Screenshot of the PT interface of the Automated Rehabilitation System showing the Workout Builder screen where PTs create a new or modify an existing exercise regimen and also add or modify exercises in the exercise database.

repeats and renders the first half of the motion again and this is repeated for each REP of the exercise set. By default, EGF is set to hold the flexed or extended position until the user has achieved the same angular position as the demonstrated motion, but this threshold can be lowered such that the EGF will activate the second half of the motion before the user has achieved the full range of motion. The EGF threshold can be lowered by adjusting the slider on the exercise screen. The slider starts in the maximum position, shown in Figure 3.4, where the threshold is set to the final flexion or extension position as demonstrated by EGF. As the slider is moved towards the minimum end, shown in Figure 3.5, the threshold is lowered, activating the second half of the EGF motion when the user's performed the exercise at a reduced range of motion. This allows users with restricted movement to use the system. EGF allows users to compare their exercise motion to the exemplar motion during each REP of their exercise set, allowing users to visually identify errors in their exercise motion and correct their motion to better match the ideal motion. This slider was added during the user study conducted with patients in Chapter 6, where

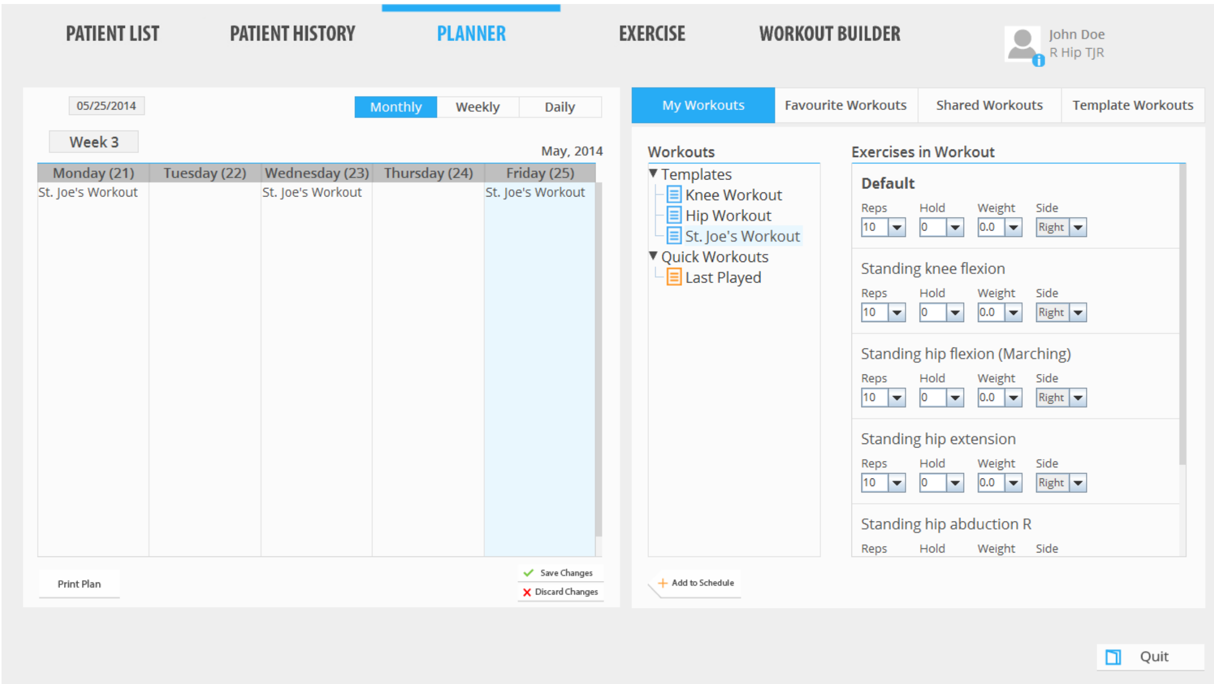


Figure 3.8: Screenshot of the PT interface of the Automated Rehabilitation System showing the Planner screen where PTs schedule exercise regimens for their patients and set the parameters for the exercises.

it became evident that different patients had differing range of motion when performing the exercises for the study.

The system also includes an optional five second hold feature. When the five second hold feature is enabled, the avatar guide leg will change colours, hold for five seconds at the maximal flexion or extension position when the system detects that the user has achieved the EGF threshold, before the guide leg is returned to the rest position. A five second countdown also appears on the screen during the hold portion of the exercise. The five second countdown is activated when the system detects that the user has achieved the joint angle set by the EGF threshold. This threshold can be lowered such that the five second countdown will activate before the user has achieved the full range of motion for users with restricted movement. The five second hold feature is implemented to guide patients who are instructed to hold their pose at the flexed or extended position for a certain amount of time. Figure 3.5 shows a screenshot of ARS when the five second countdown is activated during exercise performance. The five second hold feature was also implemented


Figure 3.9: Screenshot of the PT interface of the Automated Rehabilitation System showing the Patient History screen where PTs track the progress of their patients by reviewing the data collected by the system. The data displayed in this screen shot shows the range of motion of a patient preforming sitting knee extensions over five days. The green area on the plot provides a "healthy range" for PTs to use as reference to compare the patient's data against the healthy population. This range can be changed by the PT or disabled if the PTs prefer not to see it.

following the focus group conducted with PTs, where PTs indicated that they instructed some patients to perform the exercises with a five second hold to promote performing the exercise in a more controlled manner.

Although it was mentioned by Ayoade, Uzor, and Baillie [3] that overlaying an exemplar motion could cause patients in early stages of recovery to over extend or flex trying to keep up with the range of movement and pace which can lead to injury, the ability to modify and customize the range of motion and velocity of the exemplar motion in ARS would prevent this. ARS can record exemplar motions demonstrated by the PTs using the IMU sensors. The recorded motion captures both the range of motion as well as the velocity of the motion demonstrated by the PT and thus, ARS renders the exemplar motion exactly how the PT

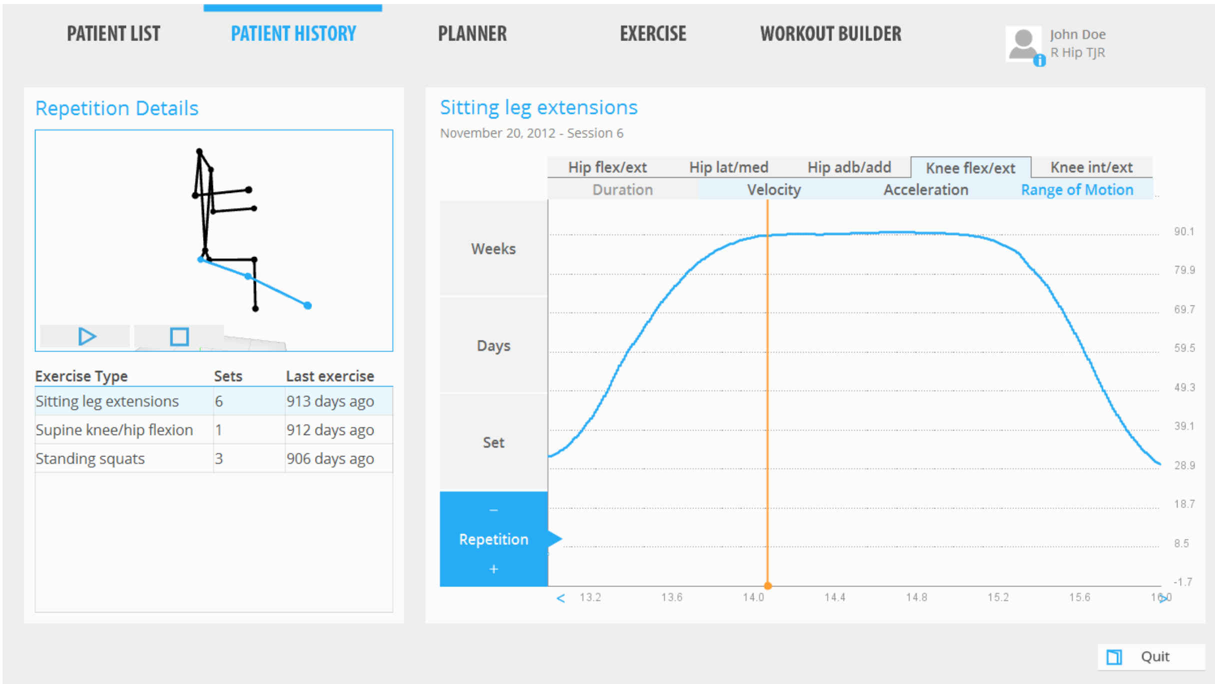


Figure 3.10: Screenshot of the PT user interface of the Automated Rehabilitation System showing the Patient History screen displaying the information for one repetition of an exercise. This screen shows the motion profile of the repetition (right) as well as a replay of the motion on the virtual avatar (left).

performed it. PTs are able to record an exemplar motion with restricted range of motion or reduced velocity for patients in early stages of rehabilitation and/or with limited mobility. Overlaying the exemplar motion on the user's motion as opposed to displaying on separate screens allows the user to benefit from seeing both movements without having to split their attention between two screens. Users are able to directly compare their movements to the exemplar motion, identifying how their exercise performance differs from the ideal motion and allowing users to correct their movement to better match the ideal motion.

## 3.3 Physiotherapist Interface

The PT interface consists of three main modules: the workout builder screen, the planner screen and the patient history screen.

The workout builder screen, shown in Figure 3.7, allows the PT to set up exercise regimens for their patients. PTs can build a workout from scratch or select a pre-existing workout as a template and modify the template to fit the needs of specific patients. PTs can delete exercises, change the order of exercises and add additional exercises from the exercise database to the workout. PTs can also add new exercises or modify existing exercises in the exercise database. To create a new exercise, the exemplar motion for EGF can be recorded by the PT to ensure that the correct motion is demonstrated by the virtual avatar and followed by the patient. To record an exemplar motion, the PT straps on the IMU sensors and the IMU sensors record the motion as the PT performs the exemplar motion. The system utilizes the motion data recorded by the IMU sensors to render the exemplar motion for EGF. This also allows PTs to customize the motion of an existing exercise for patients with a restricted range of motion, so that only the range achievable for the patient is demonstrated by EGF. The workout builder screen did not exist in the initial prototype of the system, but was designed and implemented following the focus group with PTs, described in Chapter 5. The PTs indicated that they commonly customized their patients' exercise regimens either based on their personal preference, or to tailor the regimen to the specific needs and capabilities of their patients.

The planner screen, shown in Figure 3.8, allows PTs to select which workout the patient is assigned on which days. This is where the PT would specify the parameters of the workout: the number of reps, how long to hold the exercise, the weights used and whether to do the exercise on the right or left leg. PTs can enter default values used across all the exercises in the workout or specify specific values for each exercise. The calendar view was inspired by the current method used in the clinic to schedule patients for their next appointment.

The patient history screen, shown in Figure 3.9, displays the data collected from the patient's exercise sessions such that the PT can analyze the characteristics of the patient's movement and track patient progress throughout their rehabilitation program. The patient history screen plots the duration, range of motion, peak velocity and peak acceleration of each repetition for each exercise. The plots provides a "healthy range" for PTs to use as reference to compare the patient's data against the healthy population. This range can be changed by the PT or disabled if the PTs prefer not to see it. The initial prototype of the patient history screen had only plotted the absolute value of range of motion, but it was suggested by the PTs in the focus group described in Chapter 5 that it was more useful to see both the peak maximum and minimum angular values during exercise execution, as shown in Figure 3.9. PTs can view the data grouped by session, days, or weeks, groupings suggested by the PTs during the focus group.

The PT can also look at each repetition individually, shown in Figure 3.10. The screen displays the motion profile of the repetition, as well as a video replay of the motion demonstrated on the virtual avatar. PTs can move and rotate the camera view of the virtual avatar, allowing them to view the motion from different angles to get a full understanding of the motion.

## 3.4 Summary

The ARS user interface and integration with the motion measurement system was designed and implemented to aid both the patients and PTs during physiotherapy in the clinical setting. ARS was designed to provide patients with guidance and feedback during exercise execution to promote correctness in exercise performance. Unlike the majority of previous work, ARS also includes a significant PT-facing component, and was designed for PTs to set up exercise regimens for their patients, as well as allow PTs to review the motion data of their patients collected by the system to aid progress assessment.

Subsequent chapters detail the studies conducted to acquire and refine the system requirements for the ARS UI which led to the final design described above, as well as the evaluation of the ARS UI with both healthy and patient populations.

# Chapter 4

# Validation with Healthy Participants

This chapter describes the two user studies conducted with healthy participants to assess the initial usability of the EGF, along with the rest of the ARS UI. These studies were conducted immediately following the design of the initial prototype of ARS as a "proof of concept" that using such a system may positively influence the motion quality of the user. This chapter first describes the protocol of the two studies, and the two conditions tested for each of the studies. The data from the two studies is presented and analysed and the significant results from the studies are discussed[1].

## 4.1 Protocol

Two user studies were conducted to evaluate the usability of EGF with healthy participants. The first study compared the visualization component alone to the combined visualization and guidance system, while the second study compared the complete user interface (UI) of ARS with a typical current clinical protocol. In current practice, patients are provided with a log sheet listing the exercises and number of REPS to be performed. Figure 4.1 is an example of the log sheet used in current clinical practice, adapted from the St. Joseph's Health Centre Guelph. In both studies, participants were asked to perform two sets of exercises under two test conditions while their motion was recorded using the IMUs of ARS. Before the participant performed each exercise, the exercise was demonstrated once by one of the researchers. Upon completion of the exercises, the participants were

[1]An earlier version of this chapter has been published in *IEEE Engineering in Medicine and Biology Society (EMBS)* [13].

| NAME | | | | ( ) HIP/ ( ) KNEE EXERCISE PROGRAM | | | |
|---|---|---|---|---|---|---|---|
| THERAPIST | | DATE: | DATE: | DATE: | DATE: | DATE: | DATE: |
| 1 | NUSTEP × | | | | | | |
| 2 | BUNGEE WALK × | | | | | | |
| 3 | LUNGE ONTO STEP STRETCH × | | | | | | |
| 4 | STEP TOUCHES × | | | | | | |
| 5 | STEP UPS | | | | | | |
| 6 | A) SITTING KNEE EXTENSION x 10<br>B) STANDING KNEE FLEXION × 10<br>C) BILATERAL HEEL RAISES ×<br>D) STANDING HIP FLEXION × 10<br>E) STANDING HIP EXTENSION ×<br>F) STANDING HIP ABDUCTION × | | | | | | |
| 7 | ICE HEAT | | | | | | |
| 8 | SIT <-> STAND × | | | | | | |

Figure 4.1: An example of the log sheet used in current clinical protocol, that was used for reference as the control condition of Study #2.

asked to complete a questionnaire with regards to the perceived usability of the various test conditions. After completing the questionnaire, the researchers conducted a semi-structured interview with the participants, where they were asked to elaborate on their answers from the questionnaire. Both studies were approved by the University of Waterloo Ethics Board.

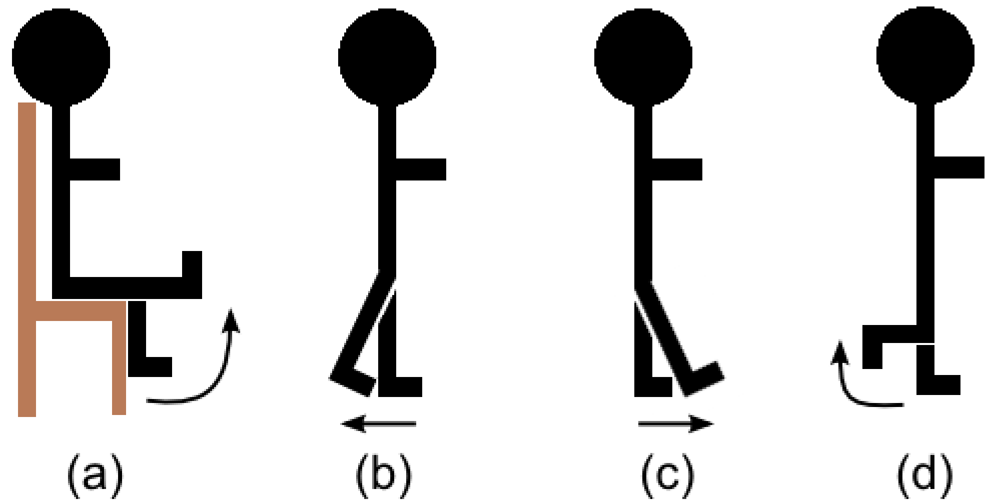


Figure 4.2: The four exercises selected for assessment for the two user studies with healthy participants, where direction of movement is indicated by the arrows: (a) sitting knee extension, (b) standing hip extension, (c) standing hip flexion, (d) standing knee flexion.

### 4.1.1 User Study #1

Participants were required to complete two sets of two leg exercises with the right leg: sitting leg extension (SIT KNEE EX) and standing hip extension (STAND HIP EX). The SIT KNEE EX exercise required participants to sit on a chair, straighten the knee until the leg was parallel to the ground, and then return the leg to starting position. The STAND HIP EX exercise required participants to stand upright, bring their leg back while keeping the knee straight, and then return the leg to starting position. The SIT KNEE EX and STAND HIP EX exercises are demonstrated in Figure 4.2 (a) and (b), respectively. The participants were asked to complete one set of 10 REPS of each exercise using EGF, and the other set of 10 REPS of each exercise while watching their real-time motion in the UI but with the EGF turned off. Participants in Group A performed the exercises first without (WO) EGF, and then with (W) EGF; participants in Group B performed the exercises in the reverse order. The researchers did not specify to participants how the EGF should be used and left it up to the interpretation of the participants. Some participants waited to watch the motion of the guide leg before attempting the motion. Others chose to "chase" the motion, copying the motion of the guide leg as it was moving.

### 4.1.2 User Study #2

Participants were required to complete two sets of three leg exercises with the right leg: SIT KNEE EX, standing knee flexion (STAND KNEE FLEX) and standing hip flexion (STAND HIP FLEX). The STAND KNEE FLEX exercise required participants to stand upright, bend the knee until the leg is at about a 90° angle, and then straighten the knee, returning to starting position. The STAND HIP FLEX exercise required participants to stand upright, bring their leg forward while keeping the knee straight, and then return the leg to starting position. The STAND HIP FLEX and STAND KNEE FLEX exercises are demonstrated in Figure 4.2 (c) and (d), respectively. The participants were asked to complete one set of 10 REPS of each exercise using the log sheet as reference, and the other set of 10 REPS of each exercise using EGF along with the UI of the system. Participants in Group A performed the exercises first with the log sheet, and then with EGF, while participants in Group B performed the exercises in the reverse order. While using EGF, participants were asked to wait for the guide leg motion to complete before executing the motion. This is due to the fact that during study #1, participants who did not wait for the motion to complete and instead performed the motion simultaneously with the guide leg were more likely to find using the EGF confusing.

### 4.1.3 Hypotheses

The expected results of the studies are summarized into the following hypotheses:
**H1:** EGF will improve the consistency of exercise performance and lower the variability between participants
**H2:** EGF will improve correctness of the range of motion in exercise performance
**H3:** Participants will prefer the UI and EGF to the log sheet or the UI WO EGF.

## 4.2 Analysis and Results

Study #1 was conducted with 12 participants [N=12; M= 24.8 years old; SD=5.25 years]. There were six females and six males in the study. Study #2 was conducted with 10 participants [N=10; M=24.1 years old; SD=3.07 years]. There were six females and four males in the study. All participants either never had a prior injury that impaired mobility or had fully recovered from their injury. Participants were not repeated between studies.

Table 4.1: The mean maximum flexion/extension active joint angles for user study #1

| | Group A | | | | Group B | | | |
|---|---|---|---|---|---|---|---|---|
| | *WO EGF Mean (SD)* | *W EGF Mean (SD)* | *Levene's Test (p)* | *T-Test of Error (p)* | *W EGF Mean (SD)* | *WO EGF Mean (SD)* | *Levene's Test (p)* | *T-Test of Error (p)* |
| **SIT KNEE EX Goal Pos: -10°** | 3.00 (5.26) | -0.02 (5.07) | N (0.89) | Y (<0.01) | -0.87 (6.25) | 0.64 (6.43) | Y (<0.01) | N (0.29) |
| **STAND HIP EX Goal Pos: -25°** | -71.70 (21.21) | -58.06 (9.14) | Y (<0.01) | Y (<0.01) | -54.41 (13.37) | -66.41 (14.55) | N (0.60) | Y (<0.01) |

One participant from Group A and two participants from Group B in study #1 were removed from the quantitative results due to measurement errors.

The quantitative data is grouped into four conditions: Group A performing the exercises first WO EGF then W EGF and Group B performing the exercises first W EGF then WO EGF. Table 4.1 and 4.2 summarizes the mean and standard deviation (SD) for each of the maximum (MAX) flexion/extension angle features of the corresponding moving joint for each exercise performed by the participants for study #1 and #2, respectively. All angles are referenced from the position where the leg is straight, in the standing position. Participants were expected to achieve a MAX of -10° for SIT KNEE EX and STAND KNEE FLEX, -25° for STAND HIP EX and 25° for STAND HIP FLEX. Within each group and between conditions, the Levene's test was performed on the variance of each feature at a significance of $p < 0.05$ and independent t-tests, assuming unequal variance, were conducted on the error between the desired and achieved MAX angles at a significance of $p < 0.05$. The results from the questionnaire are summarized in Figure 4.3 and 4.4 for study #1 and #2, respectively.

### 4.2.1 User Study #1

The Levene's test revealed that the null hypothesis (SDs are equal between conditions) is rejected for STAND HIP EX for Group A and SIT KNEE EX for Group B. For each feature in which the variance is significantly different, the SD is greater in the WO EGF condition in comparison to the W EGF condition, showing that consistency in exercise performance improved when participants were exercising under the W EGF condition.

The independent t-tests revealed that the null hypothesis (target range of motion errors are equal between conditions) is rejected for every feature in Group A and and for STAND HIP EX for Group B. For all the features which are significantly different, the error value is greater in the WO EGF condition in comparison to the W EGF condition, showing that participants were performing the exercises more correctly under the W EGF condition.

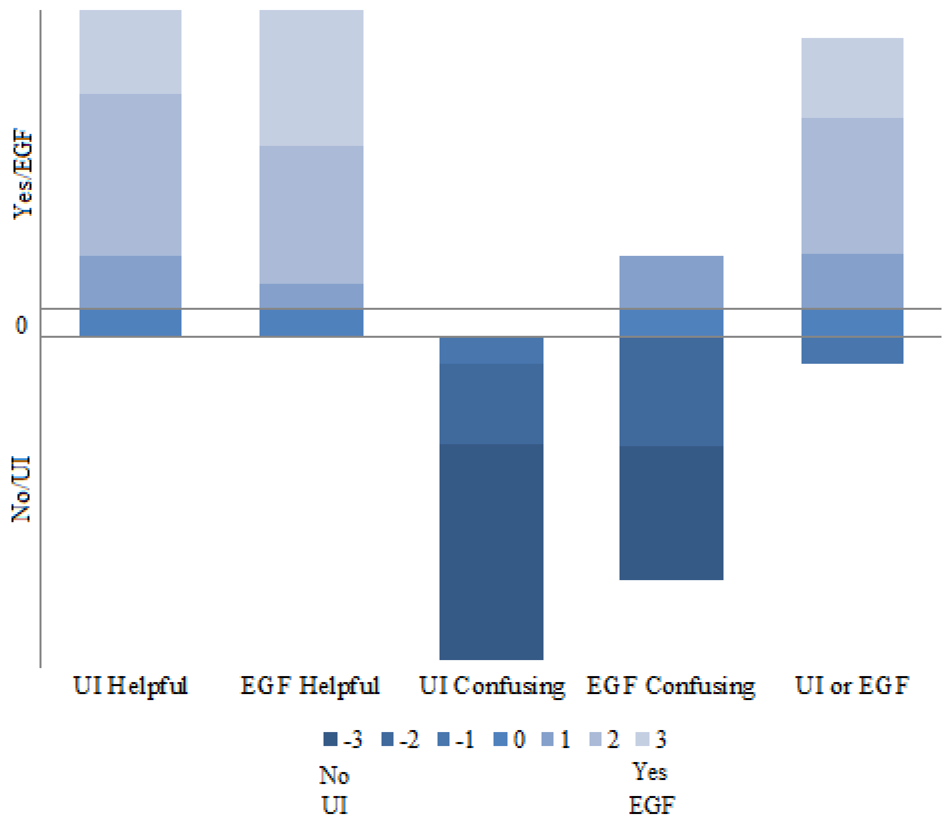


Figure 4.3: Questionnaire results from user study #1. Participants answered questions with regards to the perceived helpfulness and confusion of the user interface without the exercise guidance feature (UI) and the user interface with the exercise guidance feature (EGF). Participants were also asked if they preferred UI or EGF.

Most users found the UI and EGF helpful, and did not find the UI or EGF confusing. During the interviews, one of the questions asked was whether participants would continue using EGF after they already learned the exercise motion. Most of the participants mentioned that they preferred to use EGF even after learning the exercise. PX3 and PX7 identified that EGF encourages proper range of motion. PX3 expressed that “Keeping the guidance feature on is better for me to know that I reached the right angle every rep,” and PX7 said “...It helps to have a reference point so I know when to stop.” PX8 and PX12 identified that there was a motivation component to EGF. PX8 said “Tracking something you see is more encouraging,” and PX12 had expressed that “I like having the companion there to do the exercise with me, even if it’s just an imaginary leg.”

Table 4.2: The mean maximum flexion/extension active joint angles for user study #2

| | **Group A** | | | | **Group B** | | | |
|---|---|---|---|---|---|---|---|---|
| | *WO EGF Mean (SD)* | *W EGF Mean (SD)* | *Levene's Test (p)* | *T-Test of Error (p)* | *W EGF Mean (SD)* | *WO EGF Mean (SD)* | *Levene's Test (p)* | *T-Test of Error (p)* |
| **SIT KNEE EX Goal Pos: -10°** | -1.30 (10.59) | -7.51 (3.07) | Y (<0.01) | N (0.28) | -0.09 (5.42) | 2.70 (4.36) | Y (<0.01) | Y (<0.01) |
| **STAND KNEE FLEX Goal Pos: -90°** | -104.35 (12.83) | -103.62 (6.33) | Y (<0.01) | N (0.74) | -95.30 (5.70) | -97.28 (5.97) | N (0.16) | N (0.09) |
| **STAND HIP FLEX Goal Pos: 25°** | 78.00 (15.83) | 49.61 (12.77) | N (0.15) | N (0.76) | 48.75 (12.39) | 60.37 (11.84) | Y (<0.01) | Y (<0.01) |

### 4.2.2 User Study #2

The Levene's test revealed that the null hypothesis is rejected for every feature with the exception of STAND HIP FLEX for Group A and STAND KNEE FLEX for Group B. Similar to the results of study #1, for each feature in which the variance is significantly different, the SD is greater in the WO EGF condition in comparison to the W EGF condition, showing that consistency in exercise performance improved when participants were exercising under the W EGF condition.

The independent t-tests revealed that the null hypothesis is rejected for SIT KNEE EX and STAND HIP FLEX for Group B. For each feature in which the variance is significantly different, the SD is greater in the WO EGF condition in comparison to the W EGF condition. Exercising under the two conditions did not change the exercise performance of Group A, but Group B showed that consistency in exercise performance improved when participants were exercising under the W EGF condition for two of the exercises.

Users generally preferred the proposed system to the log sheet. During the interviews, two participants directly compared the log sheet and the UI, and expressed their preference for the UI over the log sheet. PX1 said "I can just watch the system to learn but you have to explain the sheet to me," and PX8 stated that "When using the log sheet, I might get lazy and do the exercise inconsistently, but using the system, I focus on doing it properly." Many of the participants also saw the benefits of using the EGF and comparing their motion to the guide leg. PX2 said "I don't like reaching the mark and waiting but the guide leg reminds you how far to go," and PX5 explained "In small steps, you can see how to move your leg up and then how to move your leg down." Some had mentioned that they would continue using the UI and EGF when exercising in the long term. PX9 had said "I would use the both the guide leg and software in the long term to encourage proper timing and movement," and PX10 said "(I would) use both the system and guide leg in the long term because you don't want to develop bad habits, the system reminds you what to do correctly."

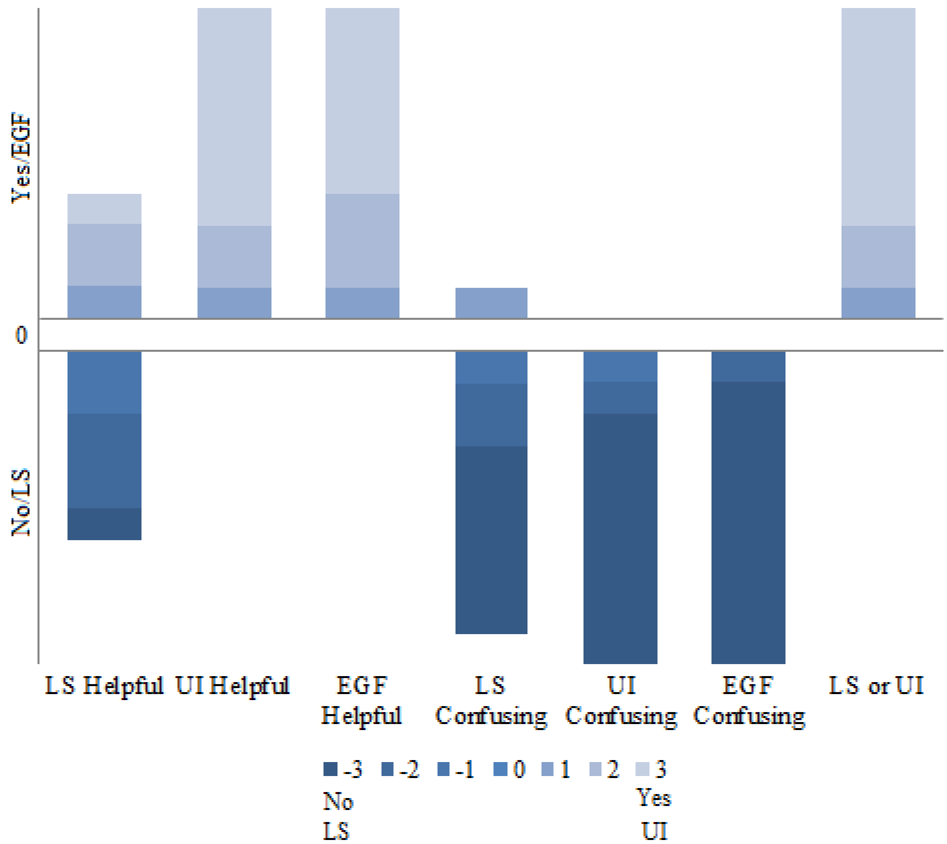


Figure 4.4: Questionnaire results from user study #2. Participants answered questions with regards to the perceived helpfulness and confusion of the log sheet (LS), overall user interface with the exercise guidance feature (UI) and the exercise guidance feature (EGF). Participants were also asked if they preferred LS or UI.

## 4.3 Discussion

The quantitative results show evidence to support H1 and H2 and the qualitative results show that H3 held true.

The results of the Levene's tests, shown in Table 4.1 and 4.2, support H1. 3/5 features of Group A and 3/5 features of Group B were statistically significant where the SD was lower in the W EGF condition. The results show that participants were more consistent in their exercise performance when using the visualization and guidance to perform the exercises.

The results of independent t-tests, shown in Table 4.1 and 4.2, support H2. 2/5 features of Group A and 3/5 features of Group B were statistically significant where the error value is greater in the WO EGF condition in comparison to the W EGF condition. The results show that participants were performing the exercises more correctly when using the visualization and guidance to perform the exercises. In particular, participants were over-extending significantly more in STAND HIP EX and over-flexing significantly more in STAND HIP FLEX without the help of guidance. This can be confirmed from the researcher's observations as some participants interpreted the exercise as having to extend or flex as far as possible, and achieved this by kicking their leg or bending their torso to compensate.

Figure 4.3 and 4.4 show support for H3. All participants' answers in study #2 and all but two participants' answers in study #1 are in the 1 to 3 range in favour of using EGF over the alternative. H3 is further supported in the answers with regards to the perceived helpfulness and reduced confusion of the various systems. All participants but one in study #1 found the UI and EGF helpful in learning the exercise. Similarly, all participants in study #2 found the UI and EGF helpful in learning the exercise. Participants in both studies did not find the UI confusing but two participants found EGF confusing to use in study #1. When participants were instructed to wait for the EGF motion to complete before executing the motion in study #2, the confusion in using the EGF was eliminated. The positive comments during the interview sessions with regards to the direct benefits of the system over the log sheet and the advantages of having a guide leg also further contribute to the support of H3.

## 4.4 Summary

The results of the user studies conducted with healthy participants showed that participants were able to successfully interpret the guidance and feedback components of the system and were influenced to perform the exercises more consistently and correctly while using EGF of the ARS UI. The system was also positively received by participants and in particular, participants found the EGF helpful in exercise performance and the system was not confusing to use. Based on the positive results of the two user studies, the system was suitable to be presented to PTs and patients in the clinical setting to evaluate the system and elicit system requirements. To do so, a focus group was first conducted with PTs, discussed in Chapter 5, and a user study was conducted with patients, described in Chapter 6.

# Chapter 5

# Focus Group with Physiotherapists

This chapter discusses the results of the focus group conducted with PTs. This focus group was conducted following the user studies conducted with healthy participants. Because the use of automated measurement rehabilitation systems is not common in current clinical protocols, an initial prototype was designed to better facilitate the discussion of the focus group and to allow PTs to better visualize this concept. The user study with healthy participants was conducted before the PT focus group to ensure that using the system had a positive effect on exercise performance before this system was presented to PTs. This chapter presents the protocol of the study conducted, and then documents the key insights generated from the discussion of the focus group. Lastly, this chapter summarizes the changes made to ARS as a result of the discussions generated by the focus group[1].

To further develop ARS tailored to the needs of a rehabilitation clinic, we conducted a focus group with PTs from a local rehabilitation center (St. Joseph's Health Centre Guelph) with the goal of eliciting system requirements from their point of view. As we will see, many of the system requirements that emerged from the focus group differ from previously established requirements for home rehabilitation systems.

## 5.1 Methods

**Participants.** Thirteen PTs participated in the focus group. However, due to time constraints, we were only able to acquire background information on six of them. These

[1] An earlier version of this chapter has been accepted for publication in *Human-Computer Interaction* [14]. The work described in this chapter was led by Danniel Verona-Martin.

six PTs were mostly female (5 females, 1 male), aged 36.5 years old (SD=11), with an average experience of 15 years (SD=6.4) in total hip and knee replacement rehabilitation. All PTs gave written consent to participate.

**Protocol.** We conducted a 90 minute focus group which consisted of three moderators and the 13 PTs as participants. The study received ethics clearance from the ethics boards of the rehabilitation clinic and the University of Waterloo. Due to the size of the focus group, we anticipated that not all PTs would get a chance to contribute to every discussion point. To address this, we audio recorded the focus group and gave each PT a questionnaire with the questions and topics (provided in Appendix B) that were discussed and they were encouraged to write down any points they could not voice.

To make the focus group discussion more concrete, we decided to walk them through an early version of the system to facilitate the discussion of how such a system could be used and potentially improve their current practice. Grounding the focus group discussion with a prototype interface was a necessity given that the concept of sensor tracking for computer assisted rehabilitation was new to the PTs. The earlier version of the prototype, designed using the EID approach [16] described in Chapter 3, was used for the walk through of the focus group.

During the focus group, the primary moderator presented the idea of computer assisted rehabilitation and demonstrated the prototype in the first 20 minutes. Afterwards, the prototype was revisited in detail. We focused the discussion on their overall assessment of the system and whether it would improve clinic rehabilitation for both the PTs and their patients. Then we elicited their feedback on each screen of the user interface, probing for comments on each design element. With each discussion, the PTs identified requirements addressed and not addressed by the prototype and substantiated them with insights from their rehabilitation practice.

**Analysis.** We analyzed the audio and written questionnaire packages at the group level because we were interested in the shared understanding between PTs. This is suitable level of analysis when focus group participants are highly homogeneous [29], as in our study. We analysed the audio and written questionnaire packages using the "scissor and sort technique" [29] where we coded and grouped discussions to extract common views. PTs were able to reach a consensus in all the discussions relevant to our research questions. From these consensus views, we extracted the design requirements presented below.

## 5.2 Results & Discussion

We present the system requirements identified by PTs to assess and manage patient progress, as well as to aid patients in improving their quality of movement while exercising. We focus the discussion on contrasting these clinic specific requirements obtained from the PTs to the home-specific requirements previously obtained in other studies using patient feedback.

### 5.2.1 Information Visualization Requirements for Assessing Progress of Patient Recovery

**ROM - Flexion and Extension. Range of Motion (ROM)** was a key metric identified by PTs. However, contrary to our initial belief, PTs did not find ROM useful as a standalone measure (i.e., 38.9 degrees). Instead, it was more important to them to know the maximal flexion and extension that contributed to that ROM (i.e., 38.9 degrees of ROM resulting from -13.3 degrees of maximal extension and -52.2 degrees of maximum flexion, as shown in the first blue bar of Figure 3.9). This information is required to enable PTs to prescribe the appropriate treatment. For example, if a patient is struggling to meet the flexion target much more than the extension target, their PT can modify their exercise regimen. To address this requirement, we chose a floating bar graph design where the top of the bar represents the extension and the bottom of the bar represents flexion. This design provides an easy and compact way of visualizing flexion and extension, as well as ROM. The ROM information can be displayed over various time intervals, displaying the ROM achieved during each repetition during a single session, or used to summarize the average ROM achieved in each session over the course of a week or a month, as illustrated in Figures 3.10 and 3.9, respectively. When average ROM is reported, the ROM bars are supplemented with error bars depicting standard deviation. Error bars are usually vertically aligned, however, we departed from this design because in some cases, the error bars would overlap, making their interpretation difficult. By misaligning them vertically as we have done, we would avoid this common problem. In place of where the error bars usually reside, we added data labels to make accurate readings of flexion and extension easier.

**ROM Targets.** The PTs added that they usually have ROM targets for the flexion and extension component of each exercise. For instance, in the sitting extension/flexion exercise, the target for a given patient may be 0 degrees for extension and 120 degrees for flexion. They requested a way to incorporate these targets into our graphs. We satisfied this requirement in our design with a green horizontal band behind the blue ROM bars, as illustrated in Fig 7. The green band can also be interpreted as the "in-recovery ROM" such that a blue bar fully inside it would indicate that the patient still has not fully recovered, whereas a blue bar laying on (or outside) the edges of the green band would indicate full recovery.

**Tempo.** Tempo is another metric PTs wanted the system to quantitatively measure and report. Other systems have attempted to provide this through measurement of repetition duration. For PTs, however, duration is a crude measure of proper tempo, as patients may exhibit significant differences in velocity between the extension and flexion portions of each repetition, for example, moving very slowly against gravity and very rapidly with gravity. This is an indication that patients may be having trouble completing the exercise, or that the motion performance is poorly controlled. ARS improves on previous systems by measuring and reporting the peak repetition velocity-a much better measure of tempo, in addition to repetition duration. ARS also measures and reports peak repetition acceleration, as shown in Figure 3.9. Although peak repetition acceleration was a metric little known to the PTs in our focus group, recent research suggests that higher peak repetition acceleration is associated with recovery. For instance, Houmanfar, Karg, and Kulić [9] found that as patients recover from a total knee or hip replacement surgery, their peak repetition acceleration increased. The PTs were receptive to using repetition acceleration in assessing recovery if its validity is confirmed as a clinically valid metric.

To *qualitatively* assess movement tempo and form, the PTs thought that comparing video playbacks of single repetitions across time would be the best way. ARS can not only playback any repetition recorded (as shown in Figure 3.10), but also allows PTs to rotate the camera view of the visualization in any direction to analyze tempo and form from different angles-a feature the PTs commented was very useful.

**Exercise difficulty.** As patients progress through their 6-week rehabilitation program, it is typical for PTs to increase the difficulty of the exercises prescribed. One common way to do this is through strapping ankle weights on their patients. The introduction of ankle weights (or an increase in the weight load) usually decreases a patient's ROM (and sometimes increases pain) temporarily due to the added difficulty. Therefore, the PTs said the system should be able to report changes in the difficulty of an exercise (i.e., weights). Absent this ability, it is more likely that PTs may erroneously interpret ARS's visualizations and attribute the change in ROM as a problem.

**Timeframe.** PTs reported that in their current practice, they mostly use weekly data to assess patient progress. In ARS, the metrics described above can not only be visualized weekly, but also for shorter timeframes such as daily, for a set of repetitions, or for a single repetition as shown in Fig 8. Given that shorter timeframe data (i.e., daily) are as easy to collect and visualize as longer timeframe data (i.e., week), the introduction of ARS in a clinical setting may encourage PTs to assess patient recovery progress more often (i.e. daily), enabling them to diagnose and address problems sooner.

Although most of the clinic-specific requirements identified by the PTs above were not surprising, one was: PTs indicated that patients should not have access to their own progress data. In the following section we discuss the PTs' point of view on *what* feedback the system should provide to patients and *how* that feedback should be delivered.

### 5.2.2 Visualization Requirements to Improve Patients' Quality of Movement

**Progress feedback.** There was unanimous agreement among the PTs that the system should not provide progress feedback to the patients. They argued that regardless of how capable the system is of measuring and reporting progress, it should be the PTs who assess the movement data in combination with other measures and the patients' goals. They believed that the sensor data alone is not enough to provide a holistic assessment of progress to the patient. Likewise, it should be the PTs who communicate progress in a way that the patient will understand and receive positively. Furthermore, the progress feedback provided by the PTs may differ from the progress feedback patients may think they want to see, as will be further discussed in Chapter 6. For example, Signh et. al. [28] report that progress feedback for chronic pain management should not only show physical gains but also the gains in confidence and satisfaction in movement, and must handle slow progression and setbacks, which was only revealed through discussion with PTs. Such careful and personalized assessment and delivery of the progress report to the patient is in contrast to the approach taken by home-based systems. For example, RVS [2] provides a "performance summary" graph showing the change in the number of repetitions performed over the six-week period. This type of feedback may be desired in home-based systems where patient interaction with the PT is very limited, but in clinical rehabilitation where patients are able to interact with their PTs on a weekly basis, PTs prefer to retain better control of the progress feedback delivered to patients.

**Quality of motion feedback.** The PTs also rejected the idea that the system should communicate to the patients whether their exercise motion is "poor, fair, or good", as some home-based rehabilitation systems have done. For instance, RVS [2] assesses every repetition using a color coding scheme (i.e., red for "poor range"). The PTs explained that a reduced ROM is acceptable as long as it is an improvement over the previous week's ROM and that the exercise is being performed with proper form and tempo. In such a case, labelling a reduced ROM as "poor" and using a red color to indicate feedback to the patient while exercising is misleading and discouraging.

The PTs recommended that the only quality of motion feedback the system should give to the patients is with regards to exercise form and tempo. Our system's unique visualization was specifically designed to provide accurate and easy to follow feedback on form and tempo. As shown in Figure 3.4, ARS's visualization overlays the ideal exercise motion over the user's current motion which makes it very simple for the patient to detect differences between his or her motion and tempo and the ideal motion and tempo. PTs worried that their older patients would not be able to understand the EGF's stick figure design so they suggested adding a silhouette of a human body to make it clearer. (We examined this with patients in Chapter 6).

Other systems, however, have recommend not using overlaid visualization, fearing that it would lead to injury by patients overexerting themselves in an effort to keep up with the exemplar motion [3]. Instead, they have opted for a split visualization design, where the patient must concentrate on either their motion or the exemplar motion, but not both simultaneously, making direct comparison difficult. As described in Section 3.2, ARS allows PTs to record exemplar motions with reduced range of motion and velocity to a level that is attainable by the patient. This removes the risk of patients overexerting themselves, while preserving the benefit of easy and accurate comparison that an overlaid visualization provides. A similar tailoring approach is used in Singh et al. [28] where the system is self-calibrated, allowing chronic pain patients to set their range of motion prior to every use. Our approach differs in that the exemplar motion is calibrated by the PT, and not the patient. While self-calibration is an important factor for chronic pain patients to learn long-term pain management techniques, our approach enables the PT to calibrate the exemplar motion such that it is still challenging to the patient. More importantly, the main advantage of a PT calibrated exemplar motion is that PTs know and are able to perform the exercise with near perfect form and tempo.

PTs commented that another way ARS could support proper tempo is by using a 5-second hold feature. PTs commonly instruct patients to hold their pose for 5 seconds at the top of a repetition. This makes the exercise more challenging and also discourages the patients from swinging their limb and using momentum to their advantage. As discussed in Chapter 6, our research team observed that patients rarely held at the top of the repetition for the full 5 seconds. To address this, when ARS detects that the patient has reached the top of the repetition, it can optionally show (if this is recommended by the PT) a 5-second countdown before the guide motion starts to complete the repetition (see Figure 3.5). To make the detection of the feature very salient to patients, the guidance leg changes from green to orange to match the numbers in the 5-seconds countdown sequence. (See Chapter

6 for patients' evaluation of this feature).

Although (to the best of our knowledge) no other rehabilitation system has used a 5-second hold feature, some systems have provided a timer instead [1, 2]. Such a timer counting the duration of the set or session could be used in place of the 5-second countdown feature. However, when we asked PTs about such a timer feature, they were quick to reject it. They explained that a timer is only useful when a patient should be striving to beat their time on an exercise, but the majority of the exercises they prescribe require patients to strive for proper form and tempo. Thus, a timer feature would only encourage patients to rush through an exercise and compromise form and tempo - a mistake our research team often observed the Physiotherapist Assistant correct. Currently, PTs only use a timer for assessments such as the "timed-up and go" test, where they are interested in how long it takes for a patient to rise from a chair, walk three metres, turn around, walk back to the chair, and sit down. (Although we removed the timer in the latest version of the system, we kept it in the version used in Study 2 as to also elicit the patients' feedback on its usefulness.)

**Feedback modality.** Visual feedback through the GUI of the system was the only modality recommended by PTs. We did not implement audio feedback because PTs believed it would be too noisy. Unlike a home environment where there is only one user exercising at any given time, a rehabilitation clinic resembles a typical gym where many users are exercising at the same time, and multiple PTs and PTAs are supervising and providing instruction and feedback. Thus, it would be noisy and potentially confusing if many rehabilitation systems were simultaneously providing voice instructions to the patients. The PTs suggested that in the clinic, voice instruction should be treated as an accessibility feature to be used only for the visually impaired patients. Unfortunately, this requirement forgoes the benefits of sound feedback that is often found in the rehabilitation literature [25, 26, 28].

## 5.3 Summary

In summary, the PTs commented that the system would be very useful for assessing patient progress once the requirements they identified were addressed. After conducting the focus group with the PTs, several changes were made to the PT interface prototype [16] as a result of the PT feedback. The ROM data displayed in the Patient History screen now includes both the flexion and extension values (as seen in Figure 3.9, whereas before only the absolute ROM value was presented. The data in the Patient History screen is also now grouped by session, days and weeks. The ability to store weight values was also included in the Planner screen. The five second hold feature of the patient interface was also added following the feedback of the focus group.

PTs also expressed a lack of confidence in their patients' ability to use our system.They could not picture themselves leaving their patients alone with the system, especially for the oldest patients and those with cognitive issues. Moreover, they suspected that a large number of patients would not be able to attach the sensors by themselves due to physical and cognitive limitations. Likewise, they suggested disabling the Quit button in the Exercise screen because they feared their patients might close the system by accident. To investigate these concerns and obtain the patients' perspective on the system, we conducted a user study with their patients, discussed in Chapter 6.

# Chapter 6

# Validation with Patients

This chapter details the user study conducted with patients in the clinical setting. The protocol of the study is first described, followed by the presentation of the data collected from the study. The motion data collected by the IMUs is first presented and discussed, followed by the qualitative data collected through the questionnaire and interviews conducted with the patients at the end of each study session. Finally, the findings of this study and their relationship with the findings from the focus group with PTs in Chapter 5 are discussed[1].

## 6.1 Protocol

Following the focus group with PTs, we conducted a user study with patients in the clinical setting to evaluate what effects using ARS has on the patient's quality of motion during exercise performance. We also wanted to evaluate the usability of the study from the perspective of patients to address the concerns stated by the PTs during the focus group described in Chapter 5. The patient study was conducted with patients undergoing out-patient rehabilitation following knee or hip replacement surgery. Patients are typically between 60 - 80 years old and it is quite common for patients to undergo knee or hip replacement for both the right and left leg, receiving the second replacement after rehabilitating and recovering from the first. Following the replacement surgery, patients attend a six week rehabilitation program at the clinic, attending a one hour physiotherapy session

[1] An earlier version of this chapter has been accepted for publication in *Human-Computer Interaction* [14].

twice a week. Training twice weekly involves a one-on-one session with their PT and also a group session where a PTA supervises a group of up to six patients. During the group sessions with the PTA, the patients' exercise regimens include warming up on the NuStep machine, then a rotation between three stations: walking between bungee cords at the parallel bars, exercising on a four step staircase and stationary exercises using the parallel bars for balance.

The user study was conducted during the participants' group exercise session with the PTA at the clinic. The study was conducted with 26 participants [N=26; M=66.7 years old; SD=8.64 years]. There were 16 females and 10 males in the study. There were four right hip, two left hip, eight right knee and 11 left knee replacement patients and one bilateral knee replacement patient (the left knee was studied in this case). A table which details the demographics of each participant in the study is provided in Appendix A. Five stationary exercises (using the parallel bars for support) from the patients' rehabilitation protocol were selected for assessment and evaluation: sitting knee extension (SIT KNEE EX), standing hip flexion (STAND HIP FLEX), standing knee flexion (STAND KNEE FLEX), standing hip extension (STAND HIP EX) and standing hip abduction (STAND HIP ABD). Figure 6.1 illustrates the five exercises selected for the study. Participants were asked to perform all the exercises as prescribed by their PT. While performing the five exercises, participants were asked to use the ARS UI, along with the EGF within the system for guidance. Patients wore two IMU sensors during the study, one above the knee and one above the ankle on the leg of the affected side. The torso sensor shown in Figure 3.2 was not used in this study. Patients were asked to observe the ARS UI only when performing the exercises with the leg on the affected side.

The rehabilitation exercise regimen differed between patients. Patients of lower functional mobility were prescribed 10-15 repetitions (REPs) of each exercise, while patients of higher functional mobility were prescribed 20-30 REPs. The higher functioning participants were asked to do one set of 10 REPs with the ARS UI and another set of 10 REP without using the ARS UI, as the control condition. The order in which the participants performed the exercises under the two conditions was counter-balanced; half the participants preformed the exercises first with the ARS UI and then under the control condition while the other half performed the conditions in the reverse order for each exercise. The lower functioning participants were asked to complete half of the exercises with the ARS UI and the other half without using the ARS UI, as the control condition. The exercises selected to be performed with and without the ARS user interface were alternated between participants. In both conditions, the IMU sensors collected motion data as the participants were exercising. As described in Section 3.2, ARS includes the ability to customize the threshold when the system considers the exercise to be completed. A lower threshold was

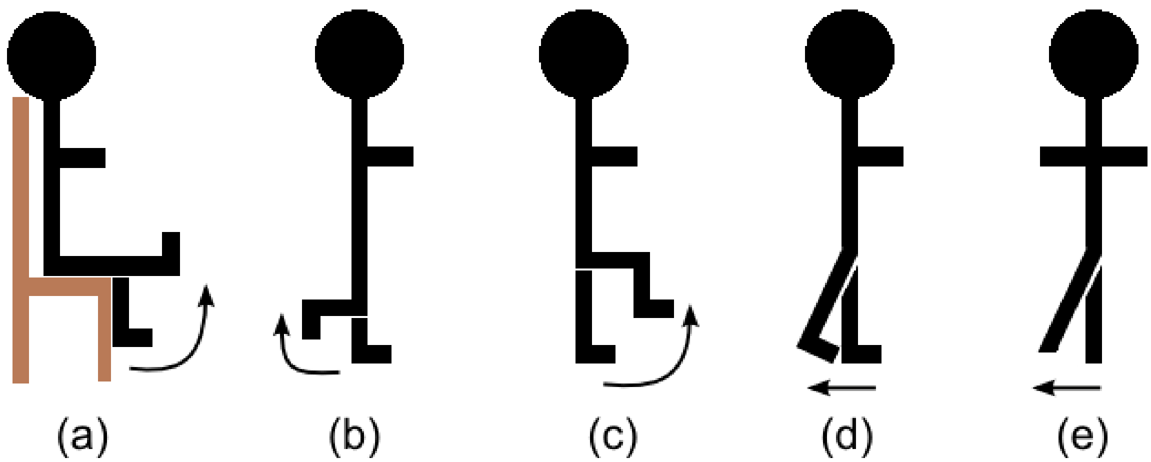


Figure 6.1: The five exercises selected for assessment for the user study, where direction of movement is indicated by the arrows: (a) sitting knee extension, (b) standing knee flexion, (c) standing hip flexion, (d) standing hip extension, (e) standing hip abduction.

set for participants who could not achieve the full range of motion displayed by EGF. The value of the lower threshold was set uniquely for each participant. The first two REPs were used to determine the level at which the lower threshold should be set and the threshold was set to a level which was comfortably achieved by the participant. Some participants were instructed by their PT to hold the exercise for five seconds while others were not. The five second hold feature was enabled for participants who were instructed to hold the exercise.

At the end of the exercise session, participants were asked to complete a questionnaire and participate in a semi-structured interview session. Participants were first asked to complete a questionnaire assessing the perceived helpfulness and usability of the UI of ARS. In the interview session, participants were asked to elaborate on their experiences using ARS while exercising.

## 6.2 Results

The motion data while exercising with the ARS UI and the qualitative data from the first six participants are not included in the results as changes were made to ARS to better accommodate the exercise protocol and the participant's abilities. As the study was conducted with the first six participants, the five second timer was added, the adjustable lower threshold of the EGF was added, and the repetition detection algorithm was tuned to improve accuracy. Results collected form the study are summarized both quantitatively and qualitatively. Quantitative results are drawn from the motion data collected from the IMUs during the exercise sessions and qualitative results are drawn from the questionnaire and interview session answers.

### 6.2.1 Quality of Movement

The quantitative results are based on the error between the guided position and the angular position achieved, the peak angular position, the peak angular velocity and the duration of each REP performed by the participants. The peak velocity reveals the pace of the exercise motion while the duration reveals how long the participant takes to perform a repetition of the exercise. First the data from the active joint of each exercise is analysed. Next, the hip joint movement during the performance of knee exercises is analyzed to determine if patients were compensating with the hip during the performance of knee exercises. These features were selected for analysis because the PTs had indicated that they were important factors for recovery during the focus group. The angular position error is calculated as the difference between the maximum angular position achieved and the bound between the threshold set to activate EGF and the angular position demonstrated by the EGF motion, shown in Equation 6.1, where $\theta$ is the peak angular position, $t_{motion}$ is the angle displayed by EGF and $t_{lower}$ is the lower threshold set for EGF. The error magnitude indicates whether the patient is over-achieving or under-achieving the required range of motion. The maximum angular position, calculated by Equation 6.2, indicates the maximum flexion or extension achieved by the participant for each REP. The peak angular velocity, calculated by Equation 6.3, and the duration of REPs, calculated by Equation 6.4, indicate whether the patient is performing the exercise in a controlled manner.

$$e_\theta = \begin{cases} |\theta - t_{motion}|, & \theta > t_{motion} \\ |\theta - t_{lower}|, & \theta < t_{lower} \\ 0, & otherwise \end{cases}, \text{for each REP} \tag{6.1}$$

$$\theta_{max} = \ max|\theta|, \text{for each REP} \tag{6.2}$$

$$\omega_{peak} = \ max|\omega|, \text{for each REP} \tag{6.3}$$

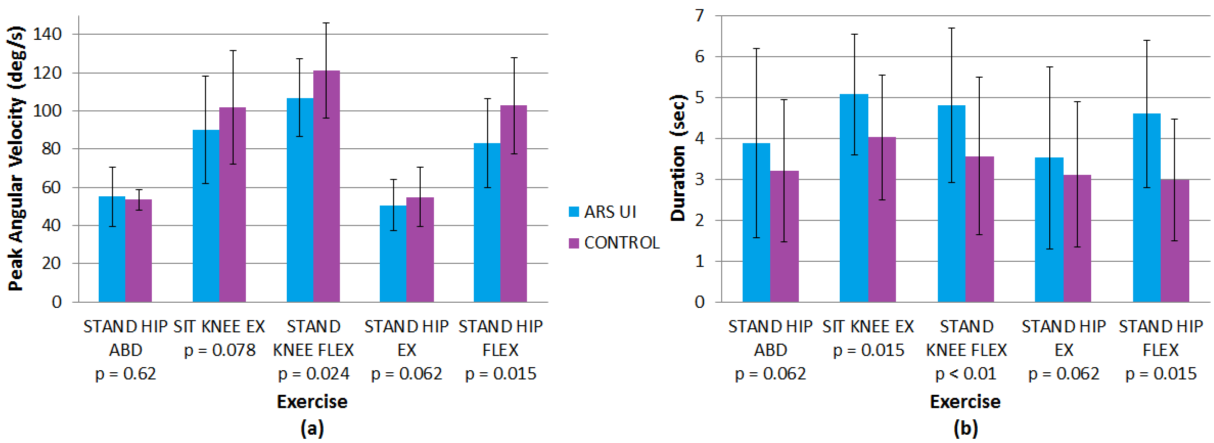


Figure 6.2: The peak velocity (a) and duration (b) data from participants who performed the exercises under both the ARS UI and control conditions, separated by exercise. The p-values of the Wilcoxon signed rank test between the two conditions are reported for each exercise. Error bars show standard deviation.

$$\Delta t = \; t_{end} - t_{start}, \text{for each REP} \tag{6.4}$$

Wilcoxon rank sum tests were conducted on the error in angular position (Equation 6.1), peak angular velocity (Equation 6.3) and duration of REPs (Equation 6.4) across the pool of all participants, between the datasets where participants performed the exercises while viewing the ARS UI (denoted ARS UI), and the control condition, without viewing the ARS UI (denoted CONTROL). The median value is taken for each set of REPs performed by each participant for each exercise and thus, there was one data point for each participant under one condition. The results of the tests revealed that the data between conditions is not significantly different when comparing across the pool of all participants. We hypothesize that differences between participants due to the variability in their health and motion capabilities dominate over differences due to the introduction of ARS, thus concealing any influence of the guidance system.

### Quality of Movement Across High Functioning Participants

The difference between conditions is more significant when the data was assessed pairwise with participants who performed the exercises under both the ARS UI and control conditions. The data showed that participants were performing four of the five exercises with a lower peak velocity in the ARS UI condition compared to the control condition. Participants were also performing all of the exercises for a longer duration in the ARS UI condition compared to the control condition. Performing exercises at a lower velocity and longer duration indicates that the exercises are being performed in a more controlled manner and that the hold position is maintained for a longer period of time. These are both qualities of exercise performance which PTs encourage, these results demonstrate that the EGF is effective at guiding patients to perform their movements at a more controlled pace.

Pairwise analysis was conducted on the data collected from participants assigned 20+ REPS who were able to preform the exercises under both conditions. Wilcoxon signed rank tests were conducted on the error in angular position (Equation 6.1), maximum angular velocity (Equation 6.3) and duration of REP (Equation 6.4). The median value is taken for each set of REPs performed by each participant for each exercise and thus, there was one data point for each participant for each condition. As not every participant was assigned all five exercises in their regimen, there were a varying number of data points for each exercise. Five participants performed STAND HIP ABD, seven participants performed SIT KNEE EX, 11 participants performed STAND KNEE FLEX, five participants performed STAND HIP EX and seven participants performed STAND HIP FLEX.

The tests revealed no significant difference between error in position datasets. Figure 6.2(a) shows the peak velocity data and the p-values of the Wilcoxon signed rank tests for each exercise. The tests showed that the difference between the velocity datasets were statically significant or showed a trend towards significance for four of the five exercises, at $p < 0.05$. The datasets for STAND KNEE FLEX and STAND HIP FLEX were significantly different and the datasets of SIT KNEE EX and STAND HIP EX showed a trend towards significance. The peak velocity was lower in the ARS UI condition compared to the control condition for all four exercises.

Figure 6.2(b) shows the duration data and the p-values of the Wilcoxon signed rank tests for each exercise.The test showed that the difference between the duration datasets were statically significant or showed a trend towards significance for all five exercises. The datasets for STAND KNEE FLEX, SIT KNEE EX and STAND HIP FLEX were significantly different and the datasets of STAND HIP ABD and STAND HIP FLEX showed a trend towards significance. The duration was higher in the ARS UI condition compared to the control condition for all five exercises.

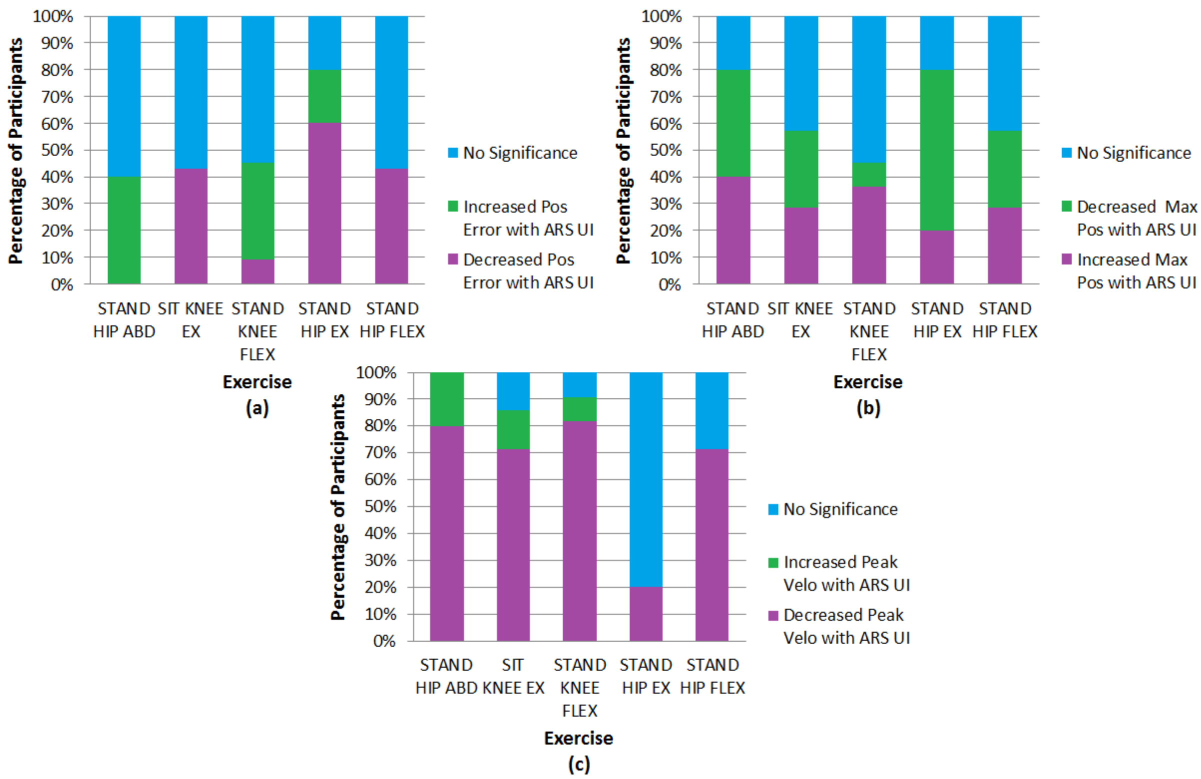


Figure 6.3: The plots of the percentage of the participants whose position error (a), maximum position (b) and peak velocity (c) values were significantly different or showed a trend towards significance at a p-value of $p < 0.05$ of the Wilcoxon rank sum tests, separated by exercise type.

### Quality of Movement of Individual High Functioning Participants

Further analysis was conducted on each participant's data individually for those who performed the exercises under both the ARS UI and control conditions. Wilcoxon rank sum tests were performed on each participant's error in angular position (Equation 6.1), maximum angular position (Equation 6.2), and peak angular velocity (Equation 6.3) datasets for each repetition of each exercise. The results are summarized in Figure 6.3, where the percentage of participants whose difference in position error, maximum position and peak velocity datasets were statically significant or showed a trend towards significance at a p-value of $p < 0.05$ is indicated.

The analysis performed on individual participant data revealed that the use of ARS

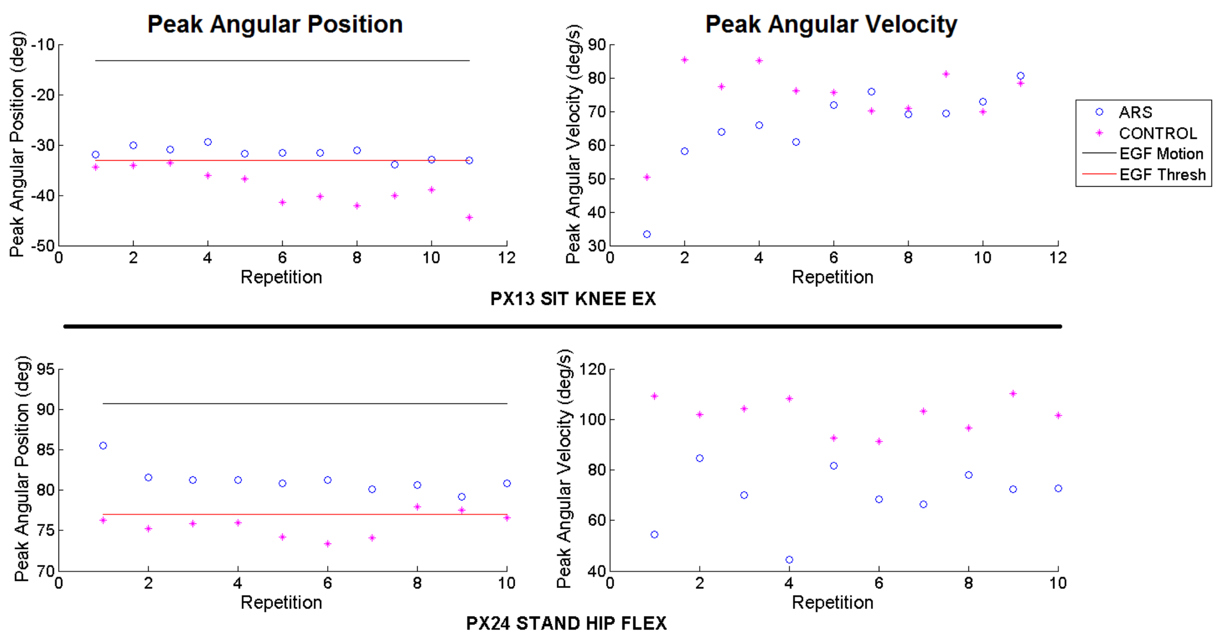


Figure 6.4: The plots of two datasets illustrating the motion profile of users who could not achieve the full range of motion displayed by the EGF, but increased their range of motion while using the ARS UI in comparison to the control condition. The first row illustrates the motion performance of Patient 13 performing the SIT KNEE EX exercise, while the second row illustrates Patient 24 performing the STAND HIP FLEX exercise. Both the maximum angular position (left) and peak velocity (right) are plotted for each repetition performed by each participant. The black line indicates the maximum angular position demonstrated by the EGF, the red line indicates the lower threshold set for the EGF, the blue circle indicates the data of each repetition from the ARS UI condition and the purple asterisk indicates the data of each repetition in the control condition. Both patients increased their range of motion while lowering or maintaining their peak velocity.

UI had a different impact on exercise performance for different participants, as well as different exercise types. This explains the insignificance in the error in position data when the analysis was preformed pairwise across all participants who performed the exercises under both conditions. Detailed analysis of the movement data revealed that there were three different types of users.

The first type were participants who couldn't achieve the full range of motion displayed by the EGF and required a lower threshold to be set. Figure 6.4 shows the plots of two user datasets which display this type of use. These users were able to increase their range of motion while exercising with the ARS UI in comparison to the control condition. The results indicate that these patients derived a considerable benefit from the EGF, as they were able to increase their ROM (a key goal of rehabilitation), without increasing movement peak velocity.

The second type of user followed the "more is better" motto. Figure 6.5 shows the plots of three datasets which illustrates this type of use. These participants were capable of achieving the full range of motion displayed by the EGF, and elected to surpass the guide motion on every iteration. These participants increased their range of motion, to a range beyond what was displayed by the guidance visualization, while maintaining a lower peak velocity when they were exercising with the ARS UI in comparison to the control condition. This indicates that while increasing their range of motion, users were still preforming the exercises in a controlled manner.

The third type of users decreased their range of motion while using the ARS UI, compared to the control condition. Figure 6.6 shows the plots of three datasets illustrating this type of use. In the case of PX21 performing STAND HIP ABD, the patient was able to exceed the range of motion demonstrated by EGF under both conditions, but was closer to the demonstrated range when performing the exercise with the ARS UI while also performing the exercise at a reduced peak velocity. In the case of PX24 performing STAND KNEE FLEX and PX17 performing STAND HIP FLEX, the patients exceeded the range of motion demonstrated by EGF when they performed the exercise in the control condition but reduced their range of motion when they were performing the exercise with the ARS UI. We hypothesize that the use of momentum helped these patients surpass the demonstrated range of motion in the control condition since their peak velocity was also higher in the control condition. The influence of the ARS UI caused these patients to reduce their range of motion because they were performing the exercises in a more controlled manner, and thus performing the exercises more correctly and effectively.

#### Compensation Analysis of High Functioning Participants

We use the two knee exercises, SIT KNEE EX and STAND KNEE FLEX, to analyze compensatory movement. For both knee exercises, the movement of the hip should be minimal, and thus large range of motion and/or high velocities in the hip joint are undesirable. The data collected from the compensatory joint of the two knee exercises revealed that the ARS UI helped reduce compensatory movement for some of the participants. The movement of the hip joint is used for the analysis of compensatory movement.

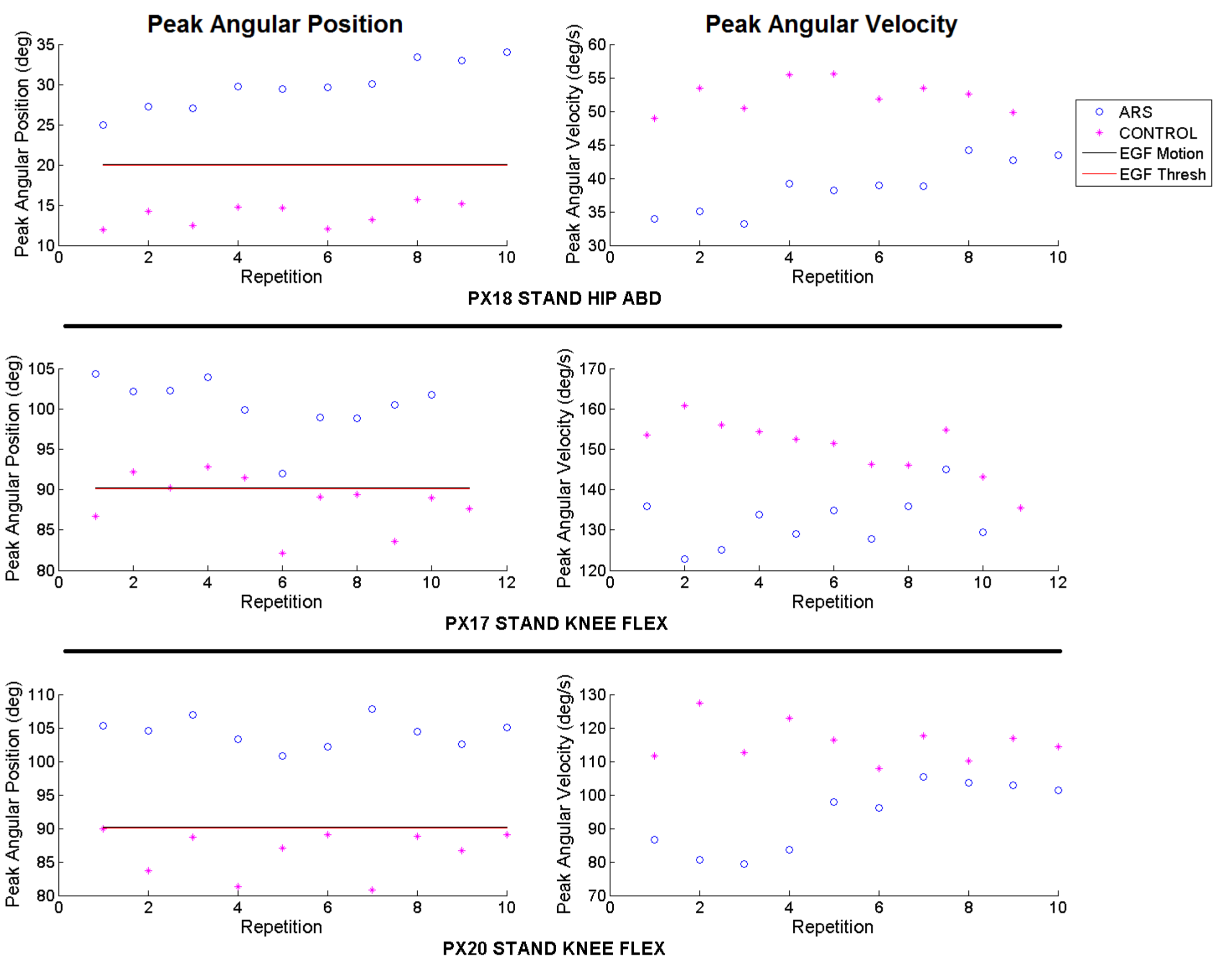


Figure 6.5: The plots of three datasets illustrating the motion profile of users who were capable of achieving the full range of motion displayed by the EGF and increased their range of motion while maintaining a lower peak velocity when using the ARS UI in comparison to the control condition. Both the maximum angular position (left) and peak velocity (right) are plotted for each repetition performed by the participant. The black line indicates the maximum angular position demonstrated by the EGF, the red line indicates the lower threshold set for the EGF, the blue circle indicates the data of each repetition from the ARS UI condition and the purple asterisk indicates the data of each repetition in the control condition.

Wilcoxon rank sum tests were performed on the data collected on hip movement in the sagittal plane (the hip degree of freedom that was in view while using the ARS UI) of the

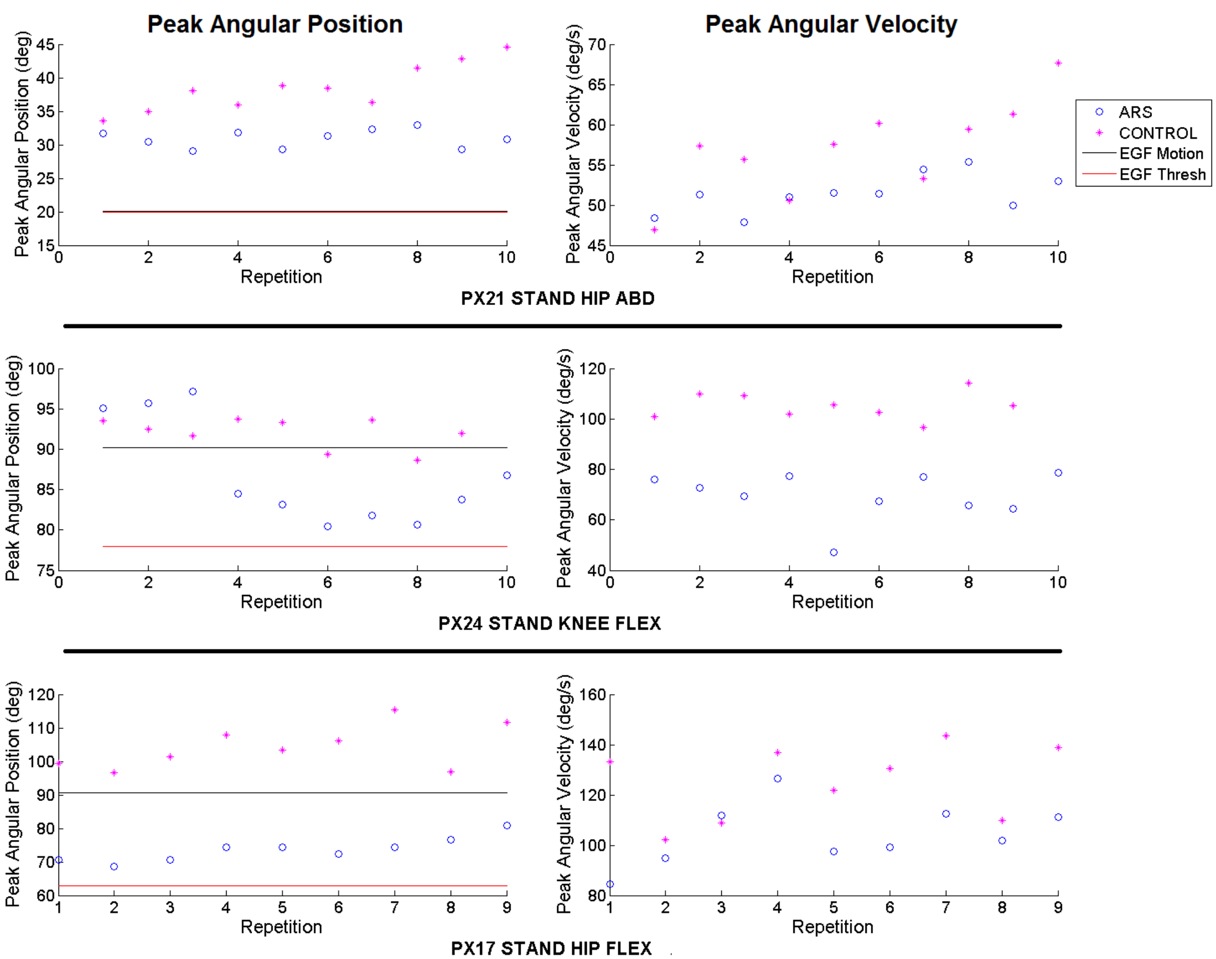


Figure 6.6: The plots of three datasets illustrating the motion profile of users who were capable of achieving the full range of motion displayed by the EGF and decreased their range of motion while maintaining a lower peak velocity when using the ARS UI in comparison to the control condition. Both the maximum angular position (left) and peak velocity (right) are plotted for each repetition performed by the participant. The black line indicates the maximum angular position demonstrated by the EGF, the red line indicates the lower threshold set for the EGF, the blue circle indicates the data of each repetition from the ARS UI condition and the purple asterisk indicates the data of each repetition in the control condition.

SIT KNEE EX and STAND HIP FLEX exercises on each repetition for each participant who performed the exercises under both conditions, looking at hip movement, and peak

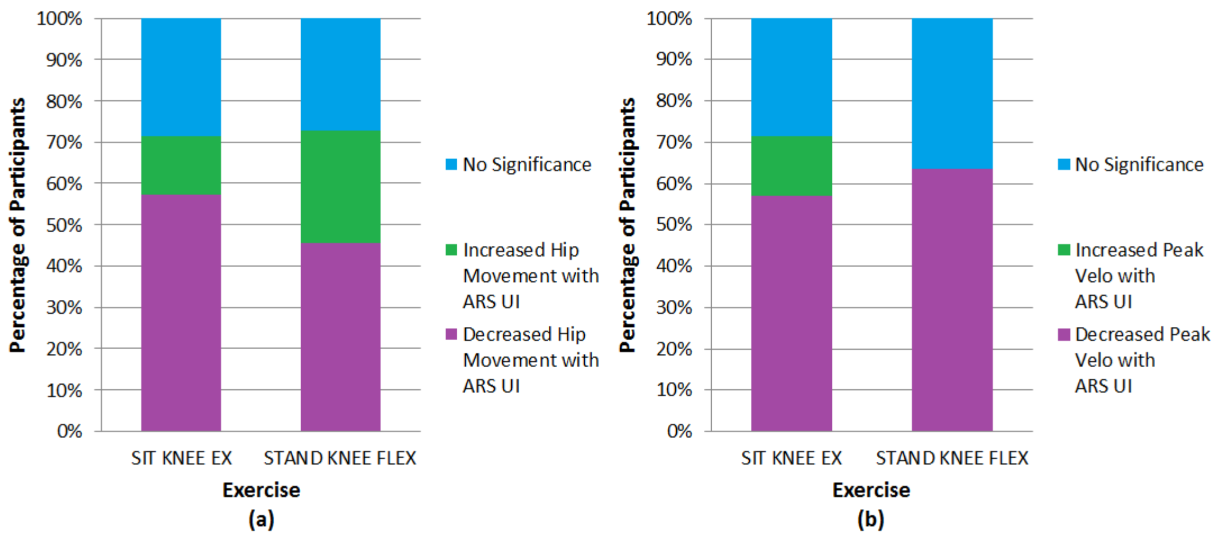


Figure 6.7: The plots of the percentage of participants whose hip movement (a) and peak velocity (b) of the compensatory joint (hip joint) were significantly different or showed a trend towards significance between the ARS UI and control conditions, at a p-value of $p < 0.05$ of the Wilcoxon rank sum tests, separated by exercise type.

angular velocity (Equation 6.3). The hip movement is calculated by taking the difference between the maximum and minimum angular positions, shown in Equation 6.5. The results are summarized in Figure 6.7, indicating the percentage of participants whose difference in position (Figure 6.7(a)) and peak velocity (Figure 6.7(b)) data were significantly different or showed a trend towards significance at a p-value of $p < 0.05$.

$$\Delta\theta_{hip} = \theta_{max} - \theta_{min}, \text{for each REP} \tag{6.5}$$

Figure 6.8 shows the hip movement (Figure 6.8(a),(b)) and peak velocity (Figure 6.8(c),(d)) data for the hip joint for all high functioning participants. Of the seven participants who performed SIT KNEE EX, four had decreased hip movement and peak velocity and one had increased hip movement and peak velocity when using the ARS UI. Of the 11 participants who performed STAND HIP FLEX, five had decreased hip movement, three had increased hip movement, seven had a decreased peak velocity and none had increased peak velocity in the hip joint while using the ARS UI.

These results show that using the ARS UI had a positive effect on reducing movement in the compensatory joint for some participants preforming knee exercises. Performing

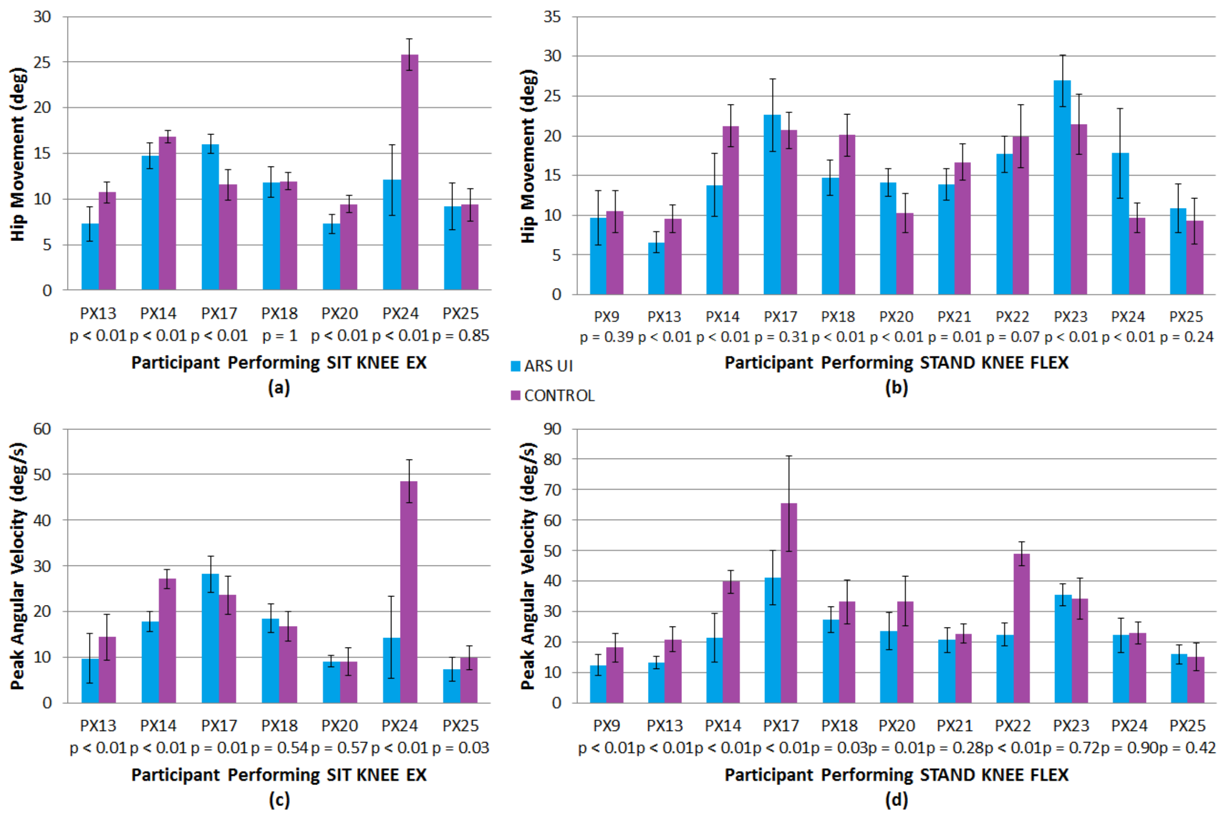


Figure 6.8: The hip movement (SIT KNEE EX - (a), STAND KNEE FLEX - (b)) and peak velocity (SIT KNEE EX - (c), STAND KNEE FLEX - (d)) in the compensatory joint (hip joint) of participants who performed the knee exercises under both the ARS UI and control conditions and showed significance or a trend towards significance. The p-values of the Wilcoxon rank sum test between the two conditions are reported for each participant. Error bars show standard deviation.

exercises with compensatory movement is a common way patients perform exercises incorrectly and PTs are constantly instructing their patients to preform the knee exercises without any hip movement. By using the ARS UI, some participants are reducing the compensation moment and thus preforming the exercises more correctly.

### 6.2.2 User Experience

**Protocol.** Following the patients' rehabilitation session using ARS, we interviewed them to obtain their feedback. We used a semi-structured interview format to allow for a more natural conversation than would be possible with a structured interview. Each interview lasted between 15 and 30 minutes. There was one interviewer and one note-taker. We also audio recorded the interviews to complement the notes for analysis and to extract participant quotes.

The questions addressed the general usefulness of the system, EGF, IMU sensors, and other design elements in the Exercise screen. To assess the general usefulness of the system, we used questions such as *"Comparing to previous exercise process without the rehab system, do you think the rehab system improves the exercise process? Why? Why not?"* We also asked questions about the sensors such as *"Do you think you would be able to attach the sensors yourself?"* Finally, we asked about the usefulness of the other currently implemented features on the Exercise screen (i.e., timer, written instructions, repetition counter) using questions such as *"Is it helpful for you to see the count of repetitions? Why? Why not?"*, and possible future features using questions such as *"Do you think adding voice instruction will help? Why? Why not?"* and *"What else would you like to have on this screen?"* With regards to the EGF, we asked *"Is it helpful for you to see the desired movement? Why? Why not?"* and *"Is it helpful for you to see your movement? Why? Why not?"* The complete set of questions can be found in Appendix B1. We also had patients evaluate the EGF using a 5-item questionnaire rated on a 7-point scale (see Figure 6.9). The questionnaire used can be found in Appendix B2.

**EGF's quality-of-motion feedback.** After reverse coding the ratings, the EGF questionnaire yielded a mean of $M$=5.90 (SD = 0.18) indicating the EGF was positively perceived by the patients. Figure 6.9 illustrates the responses to the questionnaire. We turn to the themes that emerged from the interviews to further understand the patients' evaluation of the EGF.

Almost all patients liked the EGF ability to compare their motion to the ideal motion. The most commonly cited reason was being able to self-correct. For instance, P18 said the system *" made me realize that I was going faster than that [guide] leg, so I slowed down a little bit."* Similarly, P16 said that *"It [EGF] helped me keep my knee a little more in line with the proper position, because [without the system] you think you are in that position when you are standing there, but you could be off a little bit and not realize it".* Moreover, being able to self-correct seemed to make some patients feel more confident in their movements. P13 said, *"I liked it because it gives you a feeling that you are doing the exercise properly".*

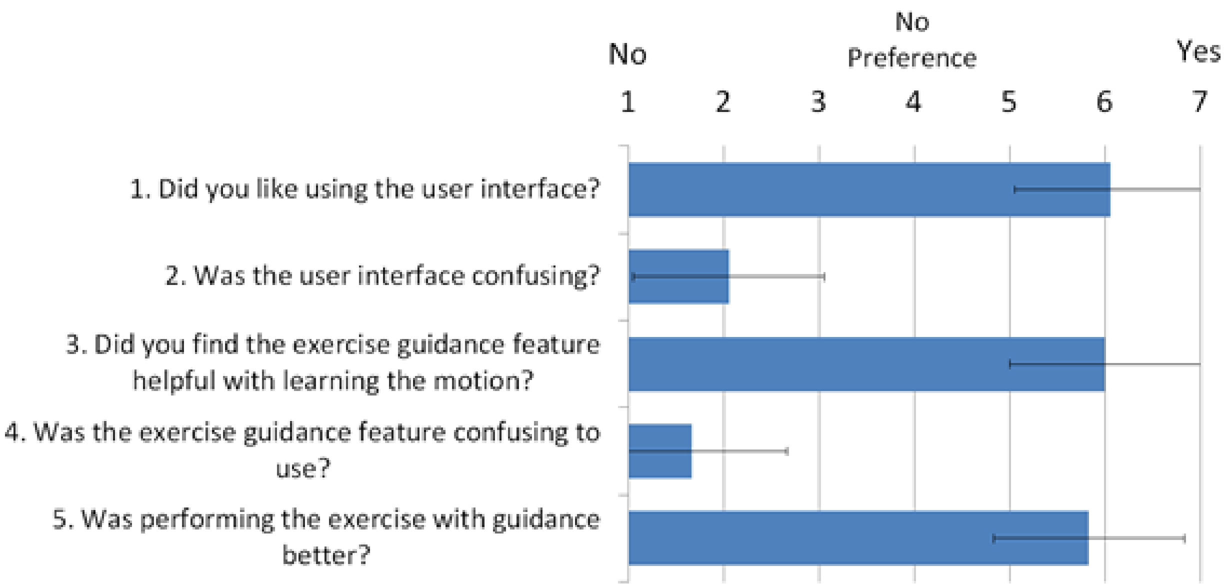


Figure 6.9: Results of the EGF questionnaire show that the EGF was positively perceived by the patients. Error bars show standard deviation.

Some patients also said watching the EGF made them exercise with more motivation. *"It was like a competition I got into, trying to get where that green [guide] leg was...it was a good workout"*, said patient P12. Another patient (P21) added that *"I like the screen because it gives you a goal to work towards. Like if I'm not quite achieving the distance that the green leg is, it shows me that there is an area I can work in"*. A similar improvement in motivation following the introduction of a rehabilitation visualization system is described by Ayoade and Baillie (2014). However, they also found that as patients progressed, motivation waned to baseline levels, possibly due a lack of increase in challenge for the targets shown in the visualizations. The ARS system includes mechanisms for modifying the exercise target to suit the patients' abilities and current level of progress, to ensure that the exercise remains challenging. Our study further revealed that targets that are too challenging may also lower motivation. Patients commented that the optimum ROM displayed by our guide motion may be an unrealistic goal for some patients, and thus discouraging. To solve this, some patients suggested that the EGF should be tailored to each individual's goal. The need for calibration of the guidance to the capability of the patients, rather than using a single optimal performance as the guide, is also discussed by Singh et al. [28]. While Singh et al. propose that the guidance is calibrated by recording the patients' own movement to enable patients to learn self-management skills, our system meets this need by allowing the PTs to record a guide motion with a reduced ROM or tempo (as discussed in the results the pilot study with PTs in Chapter 5).

According to patients, the EGF's 5 second countdown timer was very useful for adherence because they often forget to hold the target pose, or do not hold it for the entire 5 seconds, leading to a less effective workout. P7 commented: *"I loved the 5-second thing, because you actually know that you are getting the 5-seconds in."*

As discussed in Chapter 5, PTs expressed concern that some patients would find it difficult to understand the guidance visualization. Our findings from the patient responses reveal that 19 of the 20 patients liked the EGF's stick-figure and did not find the guidance feature confusing. As P13 put it *"It's nice to have somebody standing there watching you and saying 'you are doing it right', but as long as you have this [system], you can see it yourself."* Nevertheless, two patients suggested adding a silhouette of a person. Only one patient (P11) struggled to understand which way the stick-figure was facing in relation to her body.

In addition to the positive reviews of the EGF, one improvement area was identified. Some patients did not know whether they should move in synchrony with the guide motion or give the guide motion a head start before moving. We purposely did not instruct patients on which approach to take because we were interested in seeing which approach came naturally to them. Our observations revealed that about one third of the patients let the guide motion move ahead of their own motion, one third moved in synchrony with the guide motion, and the remaining one third switched between these approaches. It is not clear which of these approaches allows patients to better mimic the guide motion.

**Progress feedback.** When asked what feature they thought the system was missing, eight patients brought up the ability to receive feedback on their progress and performance. Some mentioned progress feedback could be very motivating. However, there was little agreement between patients about the progress feedback they wished to receive. Four said that they would like the system to tell them how they performed compared to their previous week of rehabilitation. For instance, P9 said that *"...if it says that you are not doing as well as last week, then you can wonder whether [it] is due to swelling or due to pain"*. Three said that feedback should be based on comparing current performance to the first few sessions of rehabilitation, or to how far they are from optimum performance (P16: *"You see that you are off, but it's just a diagram, but you don't really know [exactly] how much you are off"*). Lastly, one explained (P26) that the system should tell the patients how their performance compares to the typical performance observed from similar patients (i.e., ROM is 15% higher than what's usually observed from a 67 year old female four weeks after surgery). In contrast to the PTs' comments from the pilot study, these patients expressed a desire to receive automated progress and performance feedback.

**Sensors.** We asked patients whether they would be able to strap on both sensors without help, given that PTs feared patients would not be able to do so. However, all patients said they could easily attach the sensors, except for three patients who said they might not be able to bend over far enough to strap on the ankle sensor. Once they were attached, all patients said that wearing the sensors felt very comfortable - eight reported forgetting they were wearing them.

**Other features.** Most patients expressed the same attitude as the PTs towards the timer feature: it is not useful. P7 said *"It wouldn't matter to me whether I am doing it in three minutes or five minutes, as long as I am doing it properly."* Nevertheless, there were three patients who thought the timer was useful because it was important to them to beat their time. The PTs' concern that some patients may use a timer to rush their exercise was evident in their responses. In contrast to other rehabilitation systems [1,2], ARS no longer displays the timer feature. Moreover, corroborating the PT's stand on audio feedback, all but four patients rejected the idea of voice instruction. The most commonly cited reason was that it would be too distracting. Finally, when prompted for any remaining comments about the system, six patients said that a system like ARS may also be useful at home. This intuition from our responders is well supported by previous works in the literature demonstrating the benefit of home-based systems [1,2,23].

## 6.3 Discussion

The results of the user study with patients show that using the ARS UI while exercising had a positive effect on patients' exercise performance. In general, participants were exercising in a more controlled manner while using the ARS UI, and not relying on momentum to complete the exercise movement. Although the finding of longer REP duration while exercising with a guidance system was already reported in the work of Ayoade, Uzor, and Baillie [3], the influence of feedback in promoting exercising in a more controlled manner is further demonstrated with the findings in this study of the reduced peak velocity. This shows that not only was the exercise being performed for a longer period of time, the movement was also slower when the patient is preforming the exercise.

The results also show that depending on the patient's capabilities and interpretation of the system, different types of exercise performance can be observed. This type of observation was not reported in previous studies, where quantitative information was only reported for outcome assessments (i.e., maximum range of motion at the end of treatment), and not regarding motion performance. Patients who could not achieve the full range of motion displayed by the EGF were encouraged to increase their range of motion by the ARS UI. This is beneficial for patients as increasing range of motion is one of the main goals of rehabilitation. The patients who were able to achieve the full range of motion displayed by the EGF had two different interpretations of how to use the system. The "more is better" group believed that the more they were surpassing the guide motion, the better it was for their exercise performance, resulting in an increased range of motion when they exercised with the ARS UI. While increasing their range of motion, the second group maintained or reduced their peak velocity, indicating that the motion was still performed in a controlled manner. The third group was able to exceed the range of motion demonstrated by EGF in the control condition, but were unable to attain the same range of motion when they were exercising with the influence of the ARS UI. Because their peak velocity was also reduced when using the ARS UI, we believe this group of patients was only achieving the increased range of motion in the control condition with the help of momentum. The ARS UI influenced these patients to exercise in a more controlled manner, performing the exercises more correctly and effectively.

Using the ARS UI also measures and visualizes movement in both the hip and knee joints, which helped with reducing movement in the compensatory joint. Some participants reduced their hip movement as well as their peak velocity of the compensatory joint when they were exercising with the ARS UI, reducing both the range of motion in the compensatory joint, as well as the abruptness in the movement. With the guide motion overlaid on the user's motion, the patient is able to compare not just the movement in the desired joint, but also the movement in the joint that should be stationary. Patients were able to correct their compensatory movement as they observed their motion in ARS while comparing it to the guide motion. When patients reduce the movement in the compensatory joint, they are using more of the active joint to complete the exercise motion, preforming the exercise more correctly and effectively.

Similar to the findings reported by Singh et. al. [28] with respect to progress feedback, our studies revealed that patients and their PTs hold a fundamentally different philosophy regarding progress feedback. On the one hand, patients were interested in receiving automated progress feedback based on the sensor data. On the other, PTs believed that the sensor data alone is not enough to provide a holistic assessment and customized feedback of progress. Thus, system designers should be very careful as to the type of feedback they allow patients to receive.

We were unable to ask lower functioning participants to preform each exercise under both conditions as they were only assigned fewer than 20 REPS and we did not want to modify the exercise regimen assigned by the PT. We felt that using the ARS UI for less than 10 reps did not give participants a good grasp at understanding the use of the system. Because we could not collect the data under both conditions for each exercise, we were unable to make the pair-wise comparison for the lower functioning participants. Because of the varying exercise regimen PTs assigned to the participants, some participants were not assigned all five exercises that were used in the study and thus, some exercises had fewer data points than others.

The use of ARS can benefit both PTs and patients. As shown in the study, EGF can provide the patient with a constant reminder of what exercises they are supposed to be performing, as well as how to perform each exercise. Patients are able to make a direct comparison between their own motion and the ideal exercise motion at any point of their exercise set, and adjust accordingly if their motion does not match the EGF motion. This allows patients to correct the movement and increase range of motion in the active joint, as well as decrease compensatory movement in the inactive joints. This is especially beneficial during periods in the clinic when the patient is directly supervised by a PT.

ARS will also provide PTs with data of the patient's exercise movements which they previously did not have access to. In current clinical practice, the quantitative data gathered by PTs during rehabilitation sessions are static, for example, measuring joint angles using goniometry [22]. PTs must rely on their observations of patients to recall their exercise performance for the assessments of their patients' progress. The data collected by the IMUs of ARS will give PTs the ability to replay the patient's exercise movement on the virtual avatar after exercise sessions, and also provide PTs with data on the position, velocity, acceleration and duration of each REP of the patient's exercise sets. This new data stream can assist PTs with assessment, diagnosis and treatment planning.

## 6.4 Summary

The results of the user study conducted with patients revealed that while exercising with EGF, patients were exercising at a lower velocity and longer REP duration for a subset of the exercises, resulting in the patient performing the exercises in a more controlled manner. Three usage patterns also emerged in the study: patients who could not achieve the full range of motion shown by EGF but were motivated to increase their range of motion while using the ARS UI, patients who exceeded the guide motion by as much flexion or extension as possible, and patients who reduced their range of motion because they were no longer using momentum to perform the motion. The results also showed that the ARS UI helped some patients reduce the compensatory movement while performing knee exercises. The results from the patient interviews also revealed that the system was positively received by patients and patients were able to identify the benefits of exercising with ARS.

During the interviews with patients, a number of patients mentioned wanting more feedback from the system. A few patients mentioned wanting to know the angular values of their maximum extension, flexion and range of motion. Building on this suggestion, we wanted to evaluate whether providing more feedback in the ARS UI during exercise execution will further improve the motion quality of users. In Chapter 7, we describe a pilot study to assess the effects of various feedback methods during exercise performance.

# Chapter 7

# Evaluation of Feedback Methods

This chapter discusses a pilot study conducted with healthy participants to evaluate the effects of various feedback methods during exercise performance. In Chapter 6, patients expressed a desire to see more feedback on their motion performance when asked for additional features they would like to see in the system. As shown in [31], the design of the feedback strategy becomes more difficult when the exercise movement includes multi-joint and multi-plane movement. It was also unclear which feedback strategy was most effective for improving and correcting exercise performance. Based on the patient responses and the existing research on feedback strategies, a pilot study was conducted to evaluate the effects of various feedback methods. To investigate the influence of feedback as the exercises become more complex and address the comments of PTs from the focus group described in Chapter 5, torso tracking was also included. Participants were asked to perform exercises that were more complex than the typical rehabilitation exercises, and were given one of three feedback methods, along with the real-time motion demonstrated on the virtual avatar. This chapter details the protocol of the study, and presents the results. The key findings of the study are discussed including recommendations for potential future work.

## 7.1 Feedback Mechanisms Design

Three different forms of feedback were evaluated in the study. The first feedback method, ACTIVE VALUE, shows the real-time angle value of the active joint (hip angle or knee angle) throughout exercise execution, shown in Figure 7.1. This feedback method was influenced by the feedback from patients during the user study discussed in Chapter 6, where some patients expressed the desire to see the angle values of their flexion/extension and range of motion. The design of ACTIVE VALUE is an adoption of the "Movement Arc" component of the Wedge Visualization of [31].

The second feedback method, ACTIVE + TORSO VALUE, shows the real-time angle value of the active joint, as well as the torso joint during exercise execution, shown in Figure 7.2. This feedback method builds upon the ACTIVE VALUE feedback method and provides users with additional feedback on their torso movement. The PTs had mentioned that torso movement is another form of compensation commonly seen in patients during exercise performance. Evaluating the effects of both ACTIVE VALUE and ACTIVE + TORSO VALUE will show whether providing additional information on the torso joint will enhance exercise performance or hinder it by encouraging users to split their cognitive attention between the active and the compensatory movement.

The last feedback method, TRAFFIC LIGHT, uses the colour gradient concept adopted from [2], where the colour of the active leg progresses from red to yellow to green throughout the progression of the exercise performance. The active leg starts as red as the user is starting in the initial position. As the user preforms the exercise, the leg changes to yellow, and then green once the user has achieved the ideal range of motion. An example of TRAFFIC LIGHT is shown in Figure 7.3.

## 7.2 Protocol

Two healthy, male participants were recruited to participate in a pilot study to evaluate the effects of the three feedback methods. Participants wore three IMU sensors during the study, one above the knee, one above the ankle, and one around the torso, as shown in Figure 3.2. The torso sensor treated the torso as a rigid body and tracked the three degrees of freedom of rotation in the torso. Participants were asked to perform four different exercises and were shown a different feedback method for each exercise. The four exercises used in the study were lunging with the back foot (LUNGE BACK), lunging with the front foot (LUNGE FRONT), squat (SQUAT) and single leg deadlift (DEADLIFT). The active joint value displayed in ACTIVE VALUE and ACTIVE + TORSO VALUE showed the knee joint value for all exercises except for DEADLIFT, where the hip joint value was displayed. These exercises are more complex than the typical rehabilitation exercises used in the previous studies, and include more than one goal or movement requiring feedback, making them better suited for the investigation of more complex feedback mechanisms.

In LUNGE BACK, participants were asked to keep the sensor leg fixed, while stepping forward with the opposite leg into the lunge position, as shown in Figure 7.4 (a). While

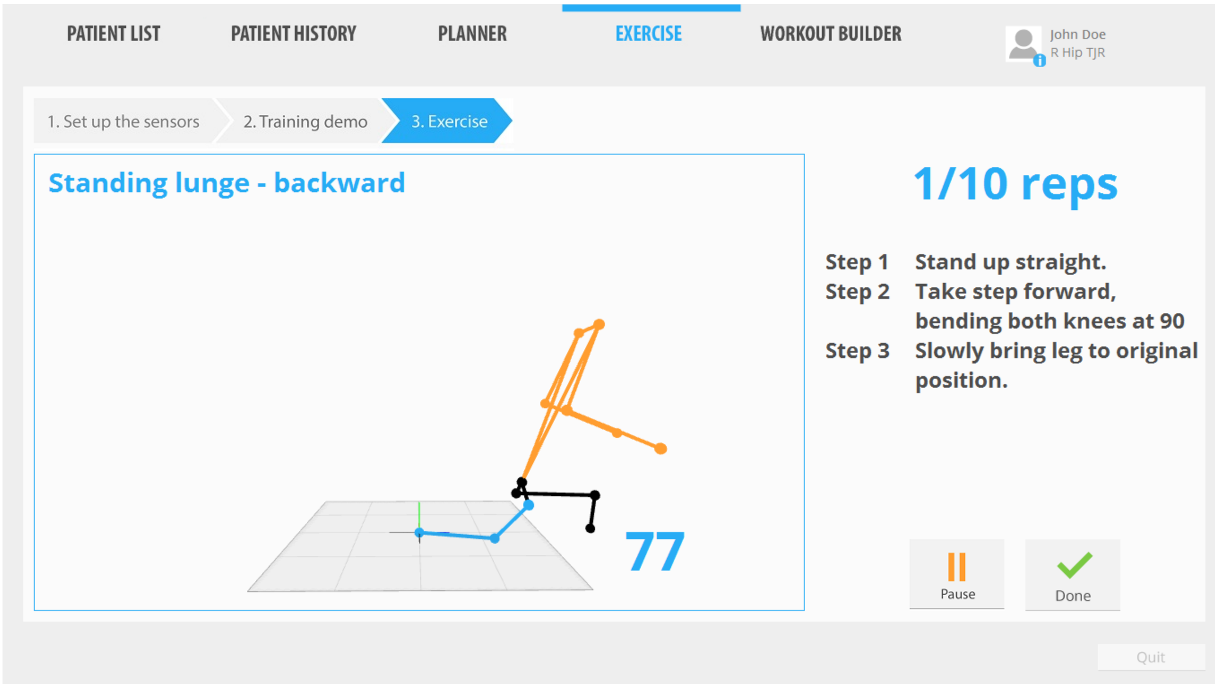


Figure 7.1: An example of the ACTIVE VALUE feedback method of the ARS UI while the user performs the LUNGE BACK exercise. The blue label (currently reads 77) to the lower right of the virtual avatar provides a real-time update of the angular value of the active joint.

performing this exercise, the exercisers typically have a difficult time seeing the flexion of their back leg without the help of a mirror and thus, do not know how much flexion is suitable to perform the exercise correctly. Using the ARS UI is hypothesized to assist users to perform this exercise as users can see their exercise motion in real-time, and are provided with additional information in the form of the feedback mechanisms.

In LUNGE FRONT, participants were asked to keep the sensor leg fixed while stepping backwards with opposite leg into the lunge position, as shown in in Figure 7.4 (a). Similar to LUNGE BACK, the exerciser typically has a hard time detecting the flexion of their front leg without seeing their motion in a mirror and using the ARS UI may also be helpful for performing this exercise.

In SQUAT, participants were asked to bend both legs until the knee is at approximately a 90°, mimicking a seated position as shown in Figure 7.4 (b). SQUAT is an exercise commonly performed incorrectly, where the exerciser tends to squat too far, or lean too

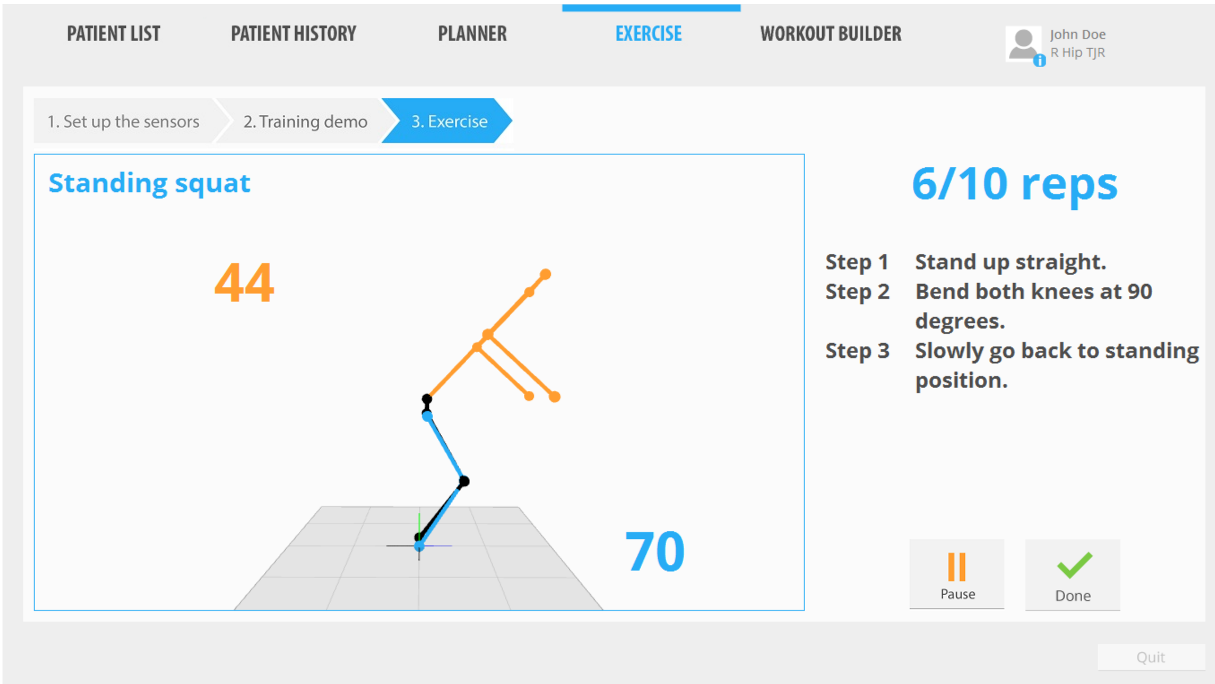


Figure 7.2: An example of the ACTIVE + TORSO VALUE feedback method of the ARS UI while the user performs the SQUAT exercise. The blue label (currently reads 70) to the lower right of the virtual avatar provides a real-time update of the angular value of the active joint while the orange label (currently reads 44) to the upper left of the virtual avatar provides a real-time update of the angular value of the torso joint.

far forward, which causes stress on the knees. Using the ARS UI would allow users to see their form as they performed the exercise.

In DEADLIFT, participants were asked to keep the sensor leg straight, and bend back at the hip while rotating the torso forward, as shown in in Figure 7.4 (c). Unlike the previous three exercises, where the goal is to maintain the torso upright throughout the entire exercise, the DEADLIFT exercise requires the exerciser to achieve a 90° flexion in the torso, as well as the leg. The ARS UI would allow users to check if both goals are achieved as they perform the exercise.

During the study, participants were asked to perform two sets of 10 REPS of each exercise. Participants were initially shown a video of how to perform the exercise. As the control condition, participants performed the first set of 10 REPS while the IMU sensors were collecting the motion data but without observing their motion in the ARS

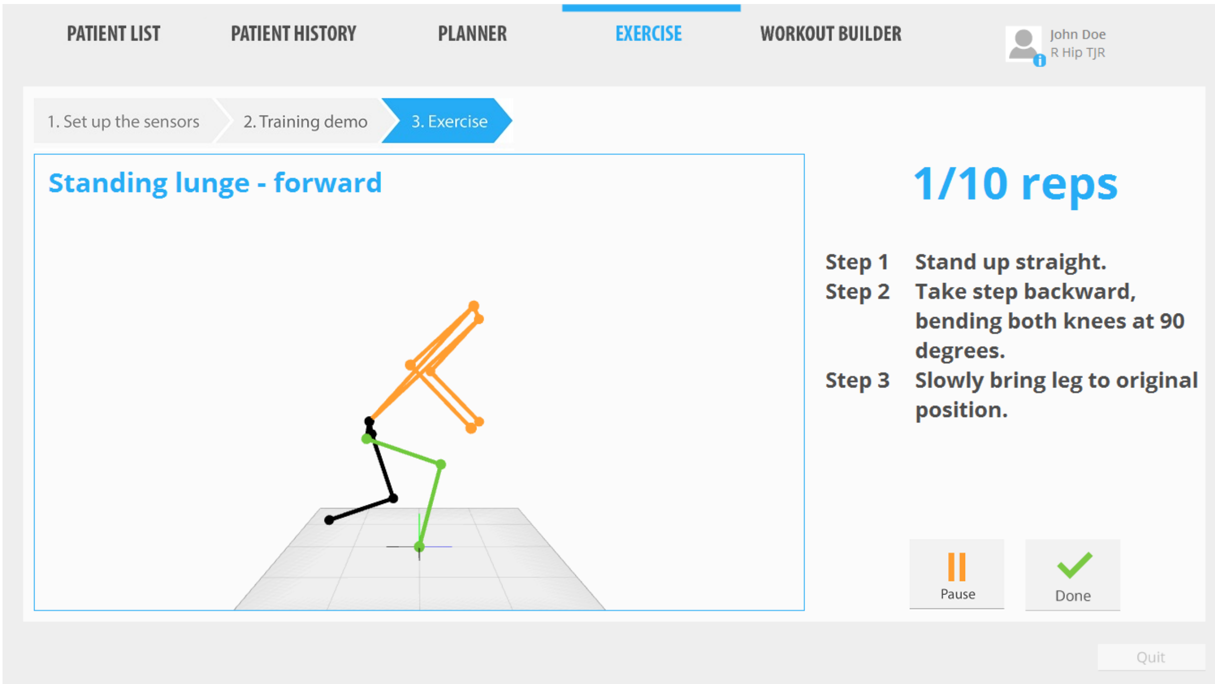


Figure 7.3: An example of the TRAFFIC LIGHT feedback method of the ARS UI while the user performs the LUNGE FRONT exercise. The active leg of the virtual avatar starts off coloured red, and then progresses to yellow and then green (current state of the virtual avatar in the figure) once the user has achieved the desired range of motion.

UI. Participants then performed a second set of 10 REPS while using the ARS UI with one of the three feedback methods. During the fourth exercise, participants performed both sets of the exercises without the use of the ARS UI (NONE). Table 7.1 shows the breakdown of which exercise was paired with which feedback method for each participant.

## 7.3 Results

The results of the study are presented grouped by the type of feedback that was seen by the participant. Figures 7.5 - 7.8 show the plots of the peak angular position of the active joint and ROM of the torso angular position for each REP of each exercise preformed by the participants, calculated by Equations 7.1 and 7.2, respectively. When performing the exercises, achieving an angular position of 90° in the active joint is desired, and a minimal

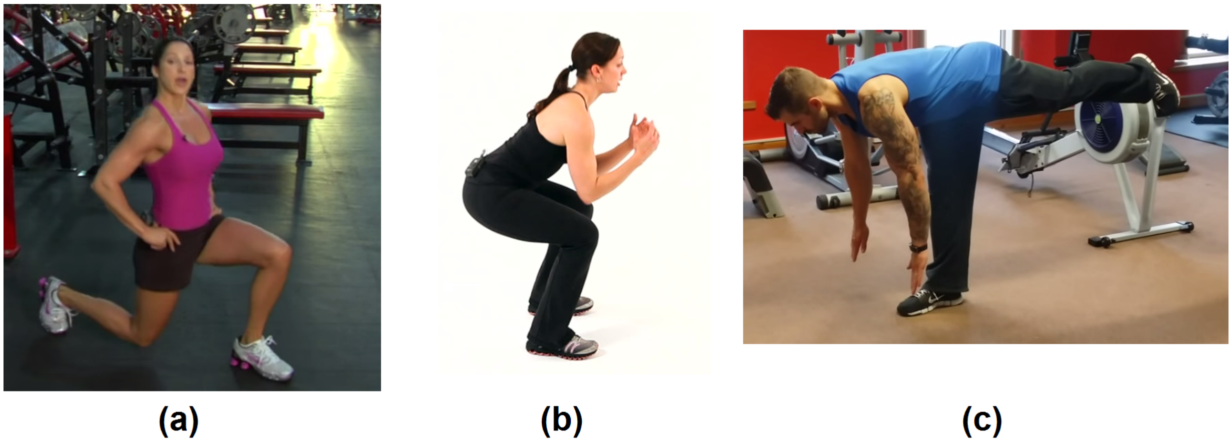

Figure 7.4: The exercises performed during the pilot study evaluating the feedback methods (a) LUNGE [36] (b) SQUAT [35] (c) DEADLIFT [34].

ROM in the torso joint is desired for all the exercises with the exception of DEADLIFT, where the desired ROM is 90°.

$$\theta_{active} = \; max|\theta|, \text{for each REP} \tag{7.1}$$

$$\Delta\theta_{torso} = \; \theta_{max} - \theta_{min}, \text{for each REP} \tag{7.2}$$

### 7.3.1 ACTIVE VALUE

Performing the exercises with the ACTIVE VALUE feedback method had a similar effect on the active joint for both participants, but a different effect on the torso joint. Figure 7.5 shows the plots of the peak angular position of the active joint and ROM of the torso angular position for the two exercises performed with the ACTIVE VALUE feedback method.

PX1, who performed LUNGE BACK with this feedback method, had a greater peak angular position in the active joint but no distinguishable difference in the torso movement. While performing the first set of LUNGE BACK exercises in the control condition, the peak angular position of the active joint was constantly below the recommended position of 90° but in the ACTIVE VALUE feedback condition, the active joint either exceeded or

Table 7.1: A table detailing which exercise received which feedback method for each participant.

| PX | Exercise | Feedback Method |
|---|---|---|
| 1 | LUNGE BACK | ACTIVE VALUE |
| | LUNGE FRONT | TRAFFIC LIGHT |
| | SQUAT | ACTIVE + TORSO VALUE |
| | DEADLIFT | NONE |
| 2 | LUNGE BACK | ACTIVE + TORSO VALUE |
| | LUNGE FRONT | NONE |
| | SQUAT | ACTIVE VALUE |
| | DEADLIFT | TRAFFIC LIGHT |

was closer to achieving 90°. In the second REP while using the feedback method, PX1 exceeded the recommended position by the greatest flexion value, but with each repetition, PX1 adjusted to meet the recommended position as the values approached 90°.

PX2, who performed SQUAT with this feedback method had a more consistent peak angular position in the active joint and a lower ROM in torso movement in the feedback condition. While performing the first set of SQUATS under the control condition, the peak angular position of the active joint exceeded the recommended position of 90° and the peak angle increased as the number of REPS progressed. In the ACTIVE VALUE feedback condition, the active joint again started by exceeding 90° but as the REPS progressed, the active joint was closer to achieving the 90° position. The ROM of the torso joint was also reduced by approximately 20° when PX2 was preforming the exercise with the feedback method.

### 7.3.2 ACTIVE + TORSO VALUE

Performing the exercises with the ACTIVE + TORSO VALUE feedback method had a different effect on each participant on the active joint but a similar effect on the torso joint. Figure 7.6 shows the plots of the peak angular position of the active joint and ROM of the torso angular position for the two exercises performed with ACTIVE + TORSO VALUE.

PX1, who performed SQUAT with this feedback method, had a more consistent peak active angular position and a lower ROM in torso movement. PX1 had a greater peak angular position of the active joint when using the feedback method, and while this exceeded the recommended position of 90° more than the control condition, the values were

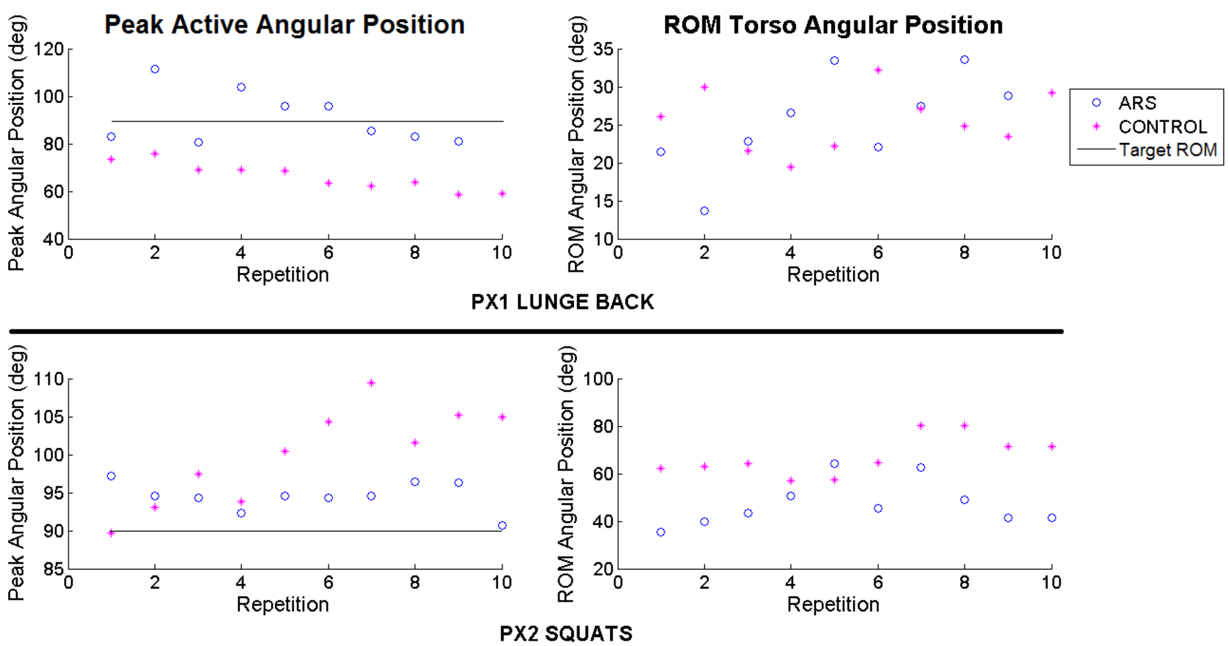


Figure 7.5: The peak angular position of the active joint and the ROM of the torso angular position of the exercises performed using the ACTIVE VALUE feedback method.

also more consistent when PX1 was using the feedback method. The ROM of the torso joint was also reduced by approximately 20° when PX1 was preforming the exercise with the feedback method.

PX2, who performed LUNGE BACK with this feedback method, had a greater peak angular position in the active joint and also had lower ROM in the torso movement. PX2 never achieved the recommended position of 90° in the active joint, but the peak angular position was greater when PX2 was using the feedback method to exercise and thus, was closer to achieving the recommended position. The ROM of the torso joint was also reduced when PX2 was preforming the exercise with the feedback method.

### 7.3.3 TRAFFIC LIGHT

Performing the exercises with the TRAFFIC LIGHT feedback method had a different effect on each participant. Figure 7.7 shows the plots of the peak angular position of the active joint and ROM of the torso angular position for the two exercises performed with TRAFFIC LIGHT.

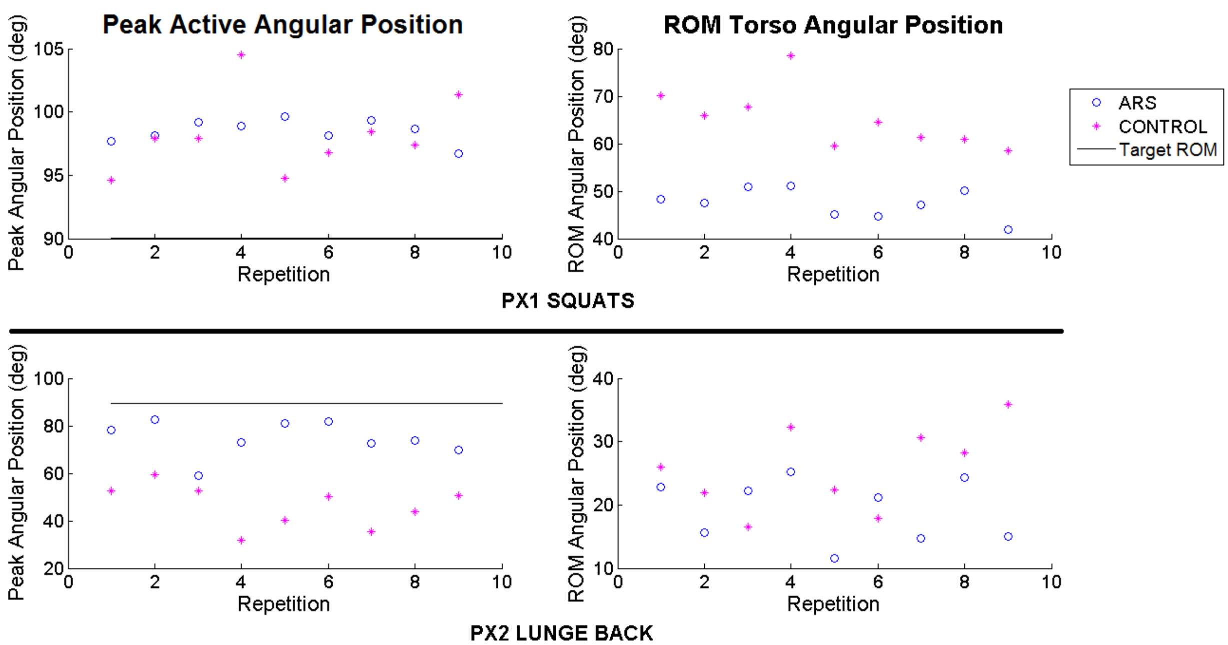


Figure 7.6: The peak angular position of the active joint and the ROM of the torso angular position of the exercises performed using the ACTIVE + TORSO VALUE feedback method.

PX1 did not show improved exercise performance while using the feedback method, in comparison to the control condition. PX1, who performed LUNGE FRONT with this feedback method, had a lower peak active angular position and higher ROM in torso movement. While preforming the exercise with the feedback method, the active joint was consistently lower than the control condition and was also below the recommended position of 90°. The ROM of the torso joint was also higher and more inconsistent when PX1 was exercising using the feedback method.

PX2, who performed DEADLIFT with this feedback method, had a greater peak active angular position and also had greater ROM in torso movement, which is desirable with this exercise. PX2 never achieved the recommended position of 90° in the active joint, but the peak angular position was greater when PX2 was using the feedback method to exercise and thus, was closer to achieving the recommended position. Similarly, PX2 never achieved a ROM of 90° in the torso joint, but the ROM was greater when PX2 was exercising with the feedback method.

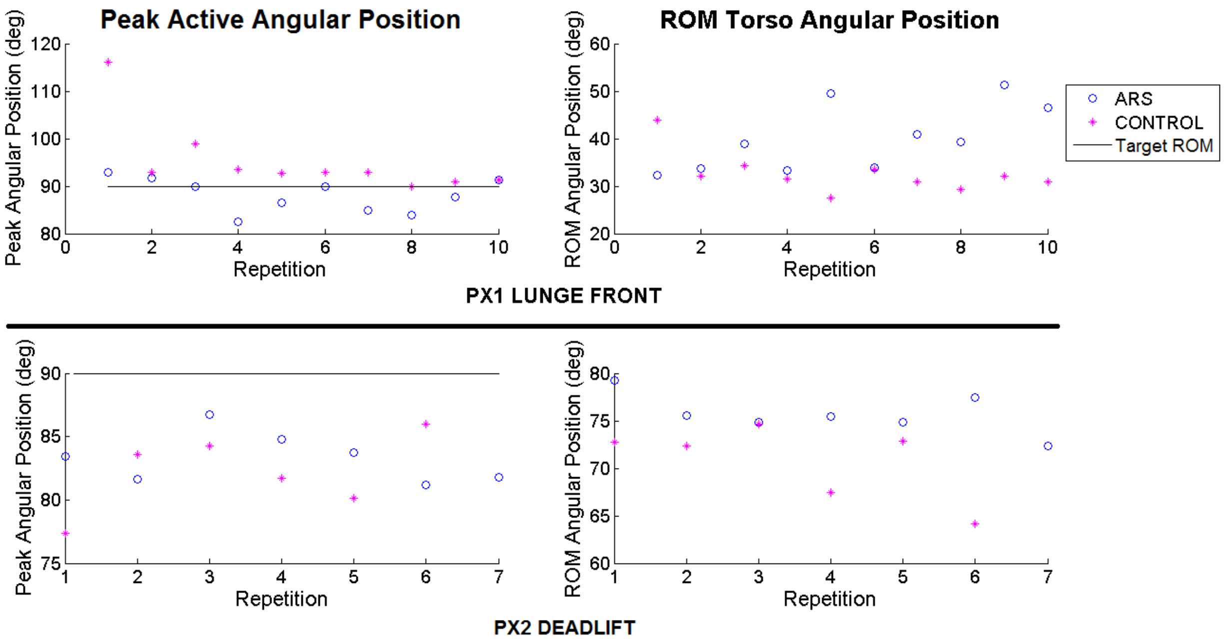


Figure 7.7: The peak angular position of the active joint and the ROM of the torso angular position of the exercises performed using the TRAFFIC LIGHT feedback method.

### 7.3.4 No Feedback Condition

Performing the exercises without feedback revealed that participants performed the exercises worse during the second set. Figure 7.8 shows the plots of the peak angular position of the active joint and ROM of the torso angular position for the two exercises performed without feedback method. Both participants had a lower peak angular position in the active joint during their second set of exercises. While performing DEADLIFT, PX1 had a lower ROM in the torso joint in the second set, which is undesirable for this exercise. While performing LUNGE FRONT, PX2 had a greater ROM in the torso joint in the second set.

## 7.4 Discussion

The exercises performed without using feedback showed that participants performed the second set of exercises worse in comparison to the first set. This is an indication that an increased number of repetitions did not cause participants to learn to perform the exercises more correctly or consistently. This result may also indicate that fatigue may have been a

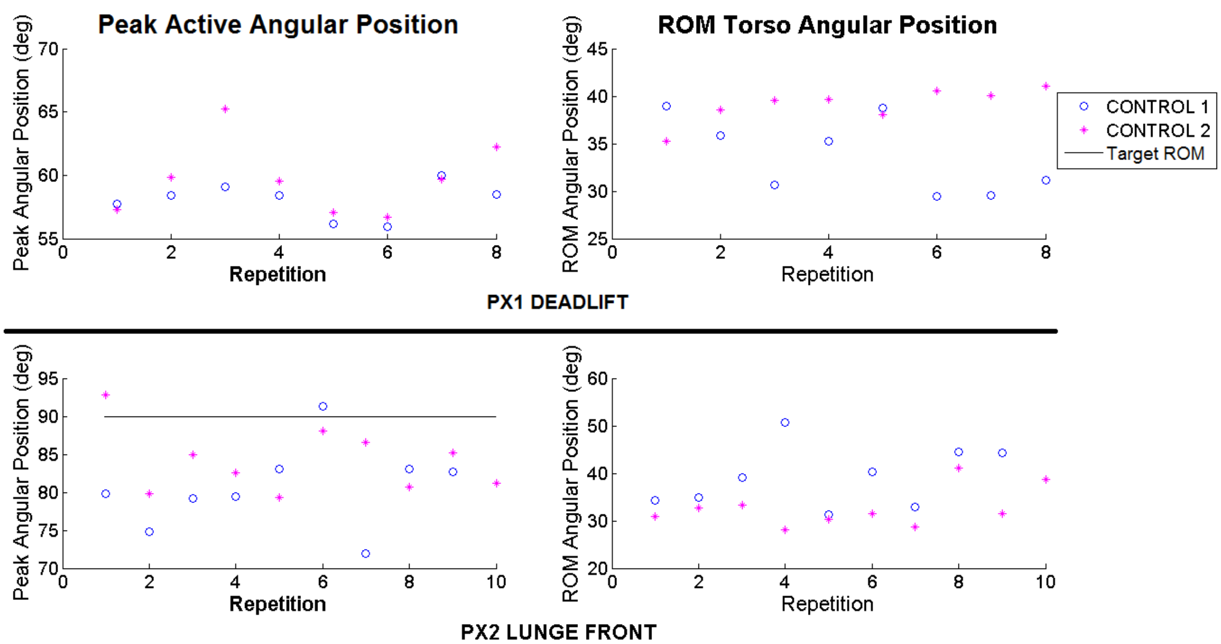


Figure 7.8: The peak angular position of the active joint and the ROM of the torso angular position of the exercises performed using NONE feedback method.

factor by the time participants started the second set, causing the decrease in the quality of movement.

Despite the possibility of fatigue factoring into the performance of the second set of exercises, participants did improve their quality of movement when they performed the exercises using the various feedback methods. The TRAFFIC LIGHT method seems to be the least effective method as PX2 performed the exercise with increased ROM, but PX1 decreased their ROM. The results show that seeing the values of the active joint and torso joint during exercise performance was a more effective feedback method for the two participants, as opposed to the traffic light analogy where different colours were used to show the different ranges. When using the active joint value as feedback, both participants were performing the exercises more correctly. With the addition of the torso joint value, both participants were able to perform the exercises more correctly while reducing the ROM in torso movement.

## 7.5 Summary

The results of this pilot study show that the feedback methods provided by ARS had a positive effect on exercise performance, both for the active joint and the torso joint. Participants demonstrated that they were able to perform the exercise more correctly, both in terms of increased range of motion and consistency in the active joint under the influence of the feedback methods. Participants were also able to reduce the range of motion in the torso joint when given explicit feedback on their torso movement.

These preliminary results show that the use of feedback mechanisms is worth further investigation. It is worth conducting a full user study to better evaluate the effects of the different feedback methods and also how the effects may differ for the different exercise types. It is also worth investigating the long term effects of how the quality of movement changes with participants after multiple exercise sessions using ARS and the different feedback methods.

# Chapter 8

# Conclusions and Recommendations

## 8.1 Summary of Contributions

This thesis presents a system designed for both PT and patient use in the rehabilitation clinical setting. Studies were conducted with healthy subjects, PTs and patients to acquire system requirements for use in the clinical setting, as well as to evaluate the effects on the quality of motion while using the system for exercise execution. The results of the studies show that exercising using the ARS UI had a positive effect on the quality of motion of users.

**Design and implementation of the user interface.** The PT interface of ARS was designed to allow PTs to customize exercises and exercise regimens for their patients, as well as to review the data collected by ARS to track the progress of their patients through motion data. The patient interface was designed to provide patients with visual guidance and feedback while preforming rehabilitation exercises. Both the patient interface and PT interface were improved based on the results and feedback attained from the various studies conducted with healthy participants, PTs and patients. Major changes to the initial prototype of the system following the findings from these studies include: the addition of the workout builder screen, changing the presentation of data in the patient history screen, adding the ability to lower the threshold of EGF in the patient interface and a five second hold timer to the patient interface.

**Evaluation of the user interface with healthy subjects.** Two studies were conducted to validate the use of visualization and guidance with healthy participants. The results showed that while using EGF, the variability in maximum flexion/extension in the joint angle was reduced compared to without using EGF, indicating more consistent exercise performance while using EGF. Participants also showed evidence of performing the exercises more correctly after using EGF, resulting in lower position error values. User feedback showed that participants found the UI and EGF helpful in performing the motions, and the UI and EGF did not introduce confusion. Using EGF was preferred by the participants over the alternatives.

**Focus group with physiotherapists.** A focus group was conducted with PTs to elicit system requirements and feedback for both the PT interface and the patient interface. During the focus group, PTs expressed that they thought the system would be useful for assessing patient progress and provided suggestions on improvements to the PT interface that would allow for the system to better fit their current workflow. The PTs also expressed that while they thought the patient interface would be helpful for patients during their exercise sessions, they were concerned that the target patient population may have trouble interpreting the virtual avatar of the system. PTs also believed that the system should not provide patients with feedback with regards to their quality of motion or progress. Using the feedback from the focus group, the workout builder screen was designed and the presentation of range of motion data was redesigned in the patient history screen. The five second hold timer was also added to the exercise screen following this focus group.

**Evaluation of the user interface with physiotherapy patients.** Following the focus group, a user study was conducted with rehabilitation patients to evaluate the effects of exercising with ARS and EGF, and also gather feedback with respect to the usability of the system. The motion data collected from the IMU sensors revealed that while exercising with EGF, patients were exercising at a lower velocity and longer REP duration for most of the exercises. This results in the patient performing the exercises in a more controlled manner, without relying on momentum or gravity to complete the motion. The position data also revealed that there were three usage patterns in the study: patients who could not achieve the full range of motion shown by EGF but were motivated to increase their range of motion while using the ARS UI, patients who exceeded the guide motion by as much flexion or extension as possible, and patients who reduced their range of motion because they were no longer using momentum to perform the motion. The hip data showed that using the ARS UI helped some patients reduce the compensatory movement in the hip joint while performing knee exercises. The results from the patient interviews also revealed that the system was positively received by patients and patients were able to identify the benefits of exercising with ARS. During this study, the ability to change the threshold of EGF was added to the exercise screen of the patient interface. Following the study, the ability to replay the demonstrated motion before exercise execution was also implemented into the system.

**Evaluation of feedback mechanisms with healthy subjects.** Building on the suggestion from patients during the patient user study requesting the ability to see more feedback on their range of motion, a pilot study was conducted with healthy participants to evaluate the effects of various feedback mechanisms. Three feedback methods were evaluated in this study while participants performed exercises that were more difficult than typical rehabilitation exercises. The results of the study reveal that with the addition of these feedback methods, participants showed a trend towards performing the exercises in a more correct and consistent manner. The ACTIVE + TORSO VALUE method appeared to be the most effective feedback method for both the leg and torso movement.

## 8.2 Limitations

The current version of ARS only tracks one leg and the torso and does not yet support the tracking of both legs. This limits the system to stationary lower body and trunk exercises. A pose estimation algorithm capable of tracking ambulatory exercises has been developed [11], the integration of this approach into the user interface would allow for the inclusion of mobile exercises, such as gait.

The current version of the system only shows one view of the virtual avatar during exercise performance. Although the virtual avatar can be rotated to be viewed from different angles, users are limited to one viewing angle as they are exercising. While this is perfectly suitable for exercises with movement along only one plane, more complex exercises where movement is along multiple planes (i.e. both the sagittal and lateral plane) would be difficult to perform with the system. An additional view may be required for more complex exercises so that the exercise can be viewed along different planes [31].

The current configuration of the system assumes that the patient's initial position is 0° at the hip and knee joint for standing exercises and 90° at the hip and knee joints for sitting exercises. Due to varying body shapes and restricted range of motion of some patients, this may not be an accurate assumption of the initial position and may introduce error to the motion data. To increase accuracy of the motion data, the system should include a calibration routine to detect the initial position of the patient before they start to exercise.

The system cannot automatically detect the amount of weights used for exercises. This information is important as it changes the difficulty in exercise performance and quality of motion of patients. The PT or PTA must manually input the weight values to log the information in the system and this may lead to potential error in the data or missing data for patients.

The current system is implemented on a laptop. If the system is instead implemented on a tablet, this would increase the portability of the system for patients. Because the software of the UI is written in JAVA, porting the system to an Android tablet should be trivial. The segmentation component of ARS may need to be optimized to reduce the computational power required to run the algorithm on a tablet.

In the patient study described in Chapter 6, each participant only used the system one time, which is not sufficient to fully evaluate the influence of the system on exercise performance, especially for participants who are several weeks into their rehabilitation program. It is possible that further improvements may be observed with longer-term use of the system. On the other hand, continued use may lead to habituation, and decreasing effectiveness of feedback [2]. Additional studies including long term evaluation are required to fully evaluate the effect of the system on exercise performance. Another limitation of the study was the low number of data points for some of the exercises. Some participants were not assigned all five exercises that were used in the study and it was important that the patient's assigned exercise regimen was not altered during the study.

## 8.3 Future Work

Future work includes implementing additional features for ARS suggested by PTs and patients in their respective studies. This includes is the suggestion made by the PTs in the focus group in Chapter 5 to accurately report the difficulty of the exercise in the patient history screen of the PT interface, by factoring in weight values used during the exercise session.

Future work also includes preforming a longitudinal study with rehabilitation patients. Instead of evaluating the effects of ARS with patients for a single exercise session, patients will be asked to use ARS during their exercise sessions throughout their rehabilitation program. A longitudinal study will capture the long term effects of using the system on the quality of the patient's movements that may not otherwise be seen after using the system for one session. For instance, it would be interesting to determining whether systems like ARS should instruct patients to exercise in synchrony with the guide motion or to give the guide motion a head start before moving. In a longitudinal study, we could determine which of these approaches leads to better outcomes. It would also be interesting to investigate whether using ARS increases the patient's rate of progress and recovery compared to the current protocol.

Conducting a user study with PTs to evaluate the usability of the PT interface during clinical use is also suggested for future work. Data collected by the IMU sensors during the patient's exercise session provides PTs with continuous data of the patient's movements throughout the duration of the exercise sessions, which was previously inaccessible by PTs. It would be beneficial to study how PTs would use the additional data of their patients' motion to improve assessment and treatment recommendations. Investigating the usability of the system from the perspective of the PTs and optimizing the PT interface to best fit their current workflow will help PTs improve rehabilitation effectiveness and assist with patient diagnosis, assessment and treatment planning.

Building on the promising results of the pilot study, a full user study to further study the effects of the various feedback mechanisms should be conducted. The larger study should confirm whether the trends in exercise performance while using the various feedback methods are seen across a larger pool of participants. If the results continue to show a positive effect on the quality of motion of healthy participants, the feedback mechanisms should next be evaluated with rehabilitation patients in the clinical setting. It would be interesting to investigate whether using these feedback mechanisms can increase the improvement and recovery rates of patients during their initial phase of rehabilitation.

# APPENDICES

# Appendix A

# Demographics From Patient Study

Table A.1: Demographics of the patients who participated in the user study detailed in Chapter 6. The participants who performed less than 20 repetitions of each exercise are considered low functioning patients, and the participants who performed 20 or more repetitions of each exercise are considered high functioning patients.

| **PX #** | **Surgery Type** | **Age** | **Gender** | **# of Reps** |
|---|---|---|---|---|
| 1 | Knee R | 66 | M | 20 |
| 2 | Knee R | 66 | F | 20 |
| 3 | Knee R | 66 | M | 20 |
| 4 | Hip R | 51 | M | 10 |
| 5 | Knee R | 60 | F | 10 |
| 6 | Knee R | 79 | F | 20 |
| 7 | Knee L | 71 | F | 15 |
| 8 | Knee L | 64 | F | 10 |
| 9 | Knee L | 59 | F | 20 |
| 10 | Hip L | 78 | M | 15 |
| 11 | Hip L | 78 | F | 10 |
| 12 | Hip R | 59 | M | 10 |
| 13 | Knee R | 81 | M | 20 |
| 14 | Knee R | 53 | F | 30 |
| 15 | Knee L | 65 | F | 10 |
| 16 | Knee L | 56 | M | 10 |
| 17 | Knee L | 79 | F | 25 |
| 18 | Hip R | 74 | F | 20 |
| 19 | Knee L | 72 | M | 10 |
| 20 | Hip R | 64 | F | 20 |
| 21 | Knee L | 61 | F | 20 |
| 22 | Knee R | 72 | F | 30 |
| 23 | Knee Bilateral (L) | 75 | M | 20 |
| 24 | Knee L | 67 | F | 20 |
| 25 | Knee L | 52 | F | 20 |
| 26 | Knee L | 67 | M | 20 |

# Appendix B

# Questions From Semi-Structured Interview of PT Pilot Study

**GENERAL**

Comparing to the previous exercise process without the automatic rehab system, do you think the automatic rehab system improves the exercise process for patients? Why or why not?

Do you think viewing the screen will be distracting while the patients are doing the rehabilitation exercises? Why? Why not?

Would you like your patients to use this system in the future during the rehabilitation exercises? Why or why not?

Would you like to use this system in the future? Why? Why not?

What is the ideal monitor screen size to display this program for you?

Do you think the patient would be able to attach the sensors themselves?

**PATIENT HISTORY SCREEN**

Component 1 Navigation bar
Component 2 Access to patient information
Component 3 Exercise selection panel
Component 4 Measures
Component 5 View toggles
Component 6 Bar graph
Component 7 Patient motion playback

Component 8  Line graph

Overall, what component(s) do you like or dislike on this screen?

Can you see the information clearly on screen? Is the text legible?

Is it helpful for you to see the navigation bar (Component 1)? Why? Why not?

Is it helpful for you to have an access to patient Information (Component 2)? Why? Why not?

Is it helpful for you to see the exercise selection panel (Component 3)? Why? Why not?

What other measures do you want to see (Component 4)?

What other types of data do you want to see (Component 4)?

Is it helpful for you to see the view toggles (Component 5)? Why? Why not?

Is it helpful for you to see the bar graph (Component 6)? Why? Why not? Is there additional/alternate data you would like to see on the bar graph?

Is it helpful for you to see the patient motion playback (Component 7)? Why? Why not?

Is it helpful for you to see the line graph (Component 8)? Why? Why not?

What else would you like to have on this screen?

**TRAINING DEMO SCREEN**

Component 1 - Current type of exercise.
Component 2 - Desired movement
Component 3 - List of instructions

Overall, what component(s) do you like or dislike on this screen?

Can you see the information clearly on screen? Is the text legible?

Is it helpful for the patient to see the type of exercise (Component 1)? Why? Why not?

Is it helpful for the patient to see the desired movement (Component 2)? Why? Why not?

Is it helpful for the patient to have the instructions (Component 3)? Why? Why not?

What else would you like to have on this screen?

**EXERCISE SCREEN**

Component 1 - Current type of exercise
Component 2 - Current and total repetitions; current elapsed time
Component 3 - Desired movement (green)
Component 4 - Your movement (blue)
Component 5 - List of Instructions

Overall, what component(s) do you like or dislike on this screen?

Can you see the information clearly on screen? Is the text legible?

Compared to the current method used by patients while exercising, do you think this program will be helpful? Why or why not?

Do you think adding voice instruction will help? Why? Why not?

Is it helpful for the patient to see the current type of exercise (Component 1)? Why? Why not?

Is it helpful for the patient to see the count of repetitions (Component 2)? Why? Why not?

Is it helpful for the patient to see the time elapsed (Component 2)? Why? Why not?

Is the current method of displaying the desired movement beneficial for patients? If not, how should the desired movement be presented to the patients?

Is the current method of displaying the desired movement beneficial for physiotherapists? If not, how should the desired movement be presented?

Is it helpful for the patient to see the actual movement (Component 4)? Why? Why not?

Is it helpful for the patient to have the instructions (Component 5)? Why? Why not?

Should the patient have the ability to click the Quit button? Why? Why not?

What else would you like to have on this screen?

**EXERCISE PLANNER SCREEN**

Component 1 Available exercises
Component 2 Planned exercises
Component 3 Edit tools

Overall, what component(s) do you like or dislike on this screen?

Can you see the information clearly on the screen? Is the text legible?

Is it helpful to see the available exercises (Component 1)? Why? Why not?

Is it helpful to see the planned exercises (Component 2)? Why? Why not?

Is it helpful to have edit tools (Component 3)? Why? Why not?

What else would you like to have on this screen?

**CLOSING REMARKS**

How do you think this system incorporates into your current workflow?

Are there any final comments or remarks to take back to the whole concept of Automatic Physiotherapy Assistant and Rehabilitation System?

# Appendix C

# Questions From Semi-Structured Interview of Patient Study

## C.1 Interview Questions

**GENERAL**

Comparing to previous exercise process without the rehab system, do you think the rehab system improves the exercise process? Why? Why not?

Do you feel using the user interface distracting while you are doing your rehabilitation exercises? Why? Why not?

Would you like to use this user interface in the future during your rehabilitation exercise? Why? Why not?

What is the ideal screen size to display this user interface for you?

**SENSORS**

Did you feel comfortable with the sensors while you were doing your exercises?

Do you think you would be able to attach the sensors yourself?

**TRAINING DEMO SCREEN**

Component 1 - Current type of exercise.
Component 2 - Desired movement
Component 3 - List of instructions

Overall, what component(s) do you like or dislike on this screen?

Can you see the information clearly on screen? Is the text legible?

Can you see the video playback clearly on screen?

Is the video playback helpful? Why? Why not?

Is it helpful for you to see the type of exercise (Component 1)? Why? Why not?

Is it helpful for you to see the list of instructions (Component 2)? Why? Why not?

Is it helpful for you to see the desired motion (Component 3)? Why? Why not?

What else would do you like to have on this screen?

**EXERCISE SCREEN**

Component 1 - Current type of exercise
Component 2 - Current and total repetitions; current elapsed time
Component 3 - Desired movement (green)
Component 4 - Your movement (blue)
Component 5 - List of Instructions

Overall, what component(s) do you like or dislike on this screen?

Can you see the information clearly on screen? Is the text legible?

Compared to exercising without this system, do you think this user interface helpful? Why? Why not?

Do you think adding voice instruction will help? Why? Why not?

Is it helpful for you to see the current type of exercise (Component 1)? Why? Why not?

Is it helpful for you to see the count of repetitions (Component 2)? Why? Why not?

Is it helpful for you to see the time elapsed (Component 2)? Why? Why not?

Is it helpful for you to see the desired movement (Component 3)? Why? Why not?

Is it helpful for you to see your movement (Component 4)? Why? Why not?

Is it helpful for you to have the instructions (Component 5)? Why? Why not?

What else would you like to have on this screen?

Are there any final comments or remarks you would like to make about the system?

## C.2 Exercise Guidance Feature Questionnaire

**Did you like using the user interface?**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No | | | No Preference | | | Yes |

**Was the user interface confusing?**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No | | | No Preference | | | Yes |

**Did you find the exercise guidance feature helpful with learning the motion?**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No | | | No Preference | | | Yes |

**Was the exercise guidance feature confusing to use?**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No | | | No Preference | | | Yes |

**Was performing the exercise with guidance better?**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No | | | No Preference | | | Yes |

# Appendix D

# Full Analysis of Motion Data Collected During Patient Study

## D.1 Mean Error in Angular Position Across All Participants

Table D.1: Table of the number of participants, the mean error in angular position across all participants, the standard deviation and the p-values of the Wilcoxon rank sum test

| Error in Angular Position | Num. of PX | Mean (°) | STD | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|
| STAND HIP ABD (ARS) | 10 | 12.57 | 8.27 | 0.16 |
| STAND HIP ABD (CONTROL) | 12 | 7.87 | 6.26 | |
| SIT KNEE EX (ARS) | 8 | 6.13 | 5.56 | 0.50 |
| SIT KNEE EX (CONTROL) | 8 | 9.27 | 7.39 | |
| STAND KNEE FLEX (ARS) | 15 | 5.5 | 6.29 | 0.46 |
| STAND KNEE FLEX (CONTROL) | 18 | 3.72 | 6.2 | |
| STAND HIP EX (ARS) | 10 | 5.82 | 6.32 | 0.31 |
| STAND HIP EX (CONTROL) | 11 | 7.92 | 4.93 | |
| STAND HIP FLEX (ARS) | 10 | 1.5 | 4.73 | 0.14 |
| STAND HIP FLEX (CONTROL) | 16 | 2.97 | 4.44 | |

## D.2 Mean in Angular Velocity Across All Participants

Table D.2: Table of the number of participants, the mean peak angular velocity across all participants, the standard deviation and the p-values of the Wilcoxon rank sum test.

| Peak Velocity | Num. of PX | Mean (°/sec) | STD | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|
| STAND HIP ABD (ARS) | 10 | 49.2 | 12.82 | 0.72 |
| STAND HIP ABD (CONTROL) | 12 | 48.15 | 7.78 | |
| SIT KNEE EX (ARS) | 8 | 87.47 | 26.98 | 0.50 |
| SIT KNEE EX (CONTROL) | 8 | 96.76 | 30.56 | |
| STAND KNEE FLEX (ARS) | 15 | 104.61 | 19.69 | 0.40 |
| STAND KNEE FLEX (CONTROL) | 18 | 109.76 | 31.17 | |
| STAND HIP EX (ARS) | 10 | 51.47 | 13.62 | 0.38 |
| STAND HIP EX (CONTROL) | 11 | 60.31 | 18.83 | |
| STAND HIP FLEX (ARS) | 10 | 81.6 | 19.45 | 0.07 |
| STAND HIP FLEX (CONTROL) | 16 | 91.45 | 22.81 | |

## D.3 Mean Repetition Duration Across All Participants

Table D.3: Table of the number of participants, the mean duration of REP across all participants, the standard deviation and the p-values of the Wilcoxon rank sum test.

| Duration | Num. of PX | Mean (sec) | STD | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|
| STAND HIP ABD (ARS) | 10 | 3.7 | 2.41 | 0.60 |
| STAND HIP ABD (CONTROL) | 12 | 3.17 | 1.68 | |
| SIT KNEE EX (ARS) | 8 | 5.1 | 1.37 | 0.038 |
| SIT KNEE EX (CONTROL) | 8 | 3.95 | 1.43 | |
| STAND KNEE FLEX (ARS) | 15 | 5.24 | 2.31 | 0.017 |
| STAND KNEE FLEX (CONTROL) | 18 | 3.58 | 1.62 | |
| STAND HIP EX (ARS) | 10 | 3.2 | 1.55 | 0.50 |
| STAND HIP EX (CONTROL) | 11 | 3.07 | 1.33 | |
| STAND HIP FLEX (ARS) | 10 | 4.65 | 1.82 | 0.016 |
| STAND HIP FLEX (CONTROL) | 16 | 3.38 | 1.48 | |

## D.4 Mean Error in Angular Position Across High Functioning Participants

Table D.4: Table of the number of participants, the mean error in angular position across high functioning participants who performed the exercises under both conditions, the standard deviation and the p-values of the Wilcoxon signed rank test.

| Error in Angular Position | Num. of PX | Mean (°) | STD | Wilcoxon Signed Rank Test p-value |
|---|---|---|---|---|
| STAND HIP ABD (ARS) | 5 | 13.62 | 10.2 | 0.44 |
| STAND HIP ABD (CONTROL) | | 9.83 | 6.53 | |
| SIT KNEE EX (ARS) | 7 | 5.83 | 5.93 | 0.22 |
| SIT KNEE EX (CONTROL) | | 7.3 | 5.24 | |
| STAND KNEE FLEX (ARS) | 11 | 5.73 | 6.55 | 0.38 |
| STAND KNEE FLEX (CONTROL) | | 3.68 | 5.4 | |
| STAND HIP EX (ARS) | 5 | 8.01 | 5.85 | 0.81 |
| STAND HIP EX (CONTROL) | | 8.01 | 5.5 | |
| STAND HIP FLEX HIP (ARS) | 7 | 2.14 | 5.66 | 0.62 |
| STAND HIP FLEX HIP (CONTROL) | | 3.71 | 5.22 | |

## D.5 Mean Angular Velocity Across High Functioning Participants

Table D.5: Table of the number of participants, the mean peak angular velocity across high functioning participants who performed the exercises under both conditions, the standard deviation and the p-values of the Wilcoxon signed rank test.

| Peak Angular Velocity | Num. of PX | Mean (°/sec) | STD | Wilcoxon Signed Rank Test p-value |
|---|---|---|---|---|
| STAND HIP ABD (ARS)<br>STAND HIP ABD (CONTORL) | 5 | 54.95<br>53.46 | 15.68<br>5.36 | 0.62 |
| SIT KNEE EX (ARS)<br>SIT KNEE EX (CONTORL) | 7 | 89.94<br>101.55 | 28.09<br>29.66 | 0.08 |
| STAND KNEE FLEX (ARS)<br>STAND KNEE FLEX (CONTORL) | 11 | 106.88<br>121.04 | 20.4<br>24.94 | 0.02 |
| STAND HIP EX (ARS)<br>STAND HIP EX (CONTORL) | 5 | 47.39<br>52.56 | 13.56<br>15.48 | 0.06 |
| STAND HIP FLEX HIP (ARS)<br>STAND HIP FLEX HIP (CONTORL) | 7 | 83.16<br>102.85 | 23.43<br>25.2 | 0.02 |

## D.6 Mean Repetition Duration Across High Functioning Participants

Table D.6: Table of the number of participants, the mean duration of REP across high functioning participants who performed the exercises under both conditions, the standard deviation and the p-values of the Wilcoxon signed rank test.

| Duration | Num. of PX | Mean (sec) | STD | Wilcoxon Signed Rank Test p-value |
|---|---|---|---|---|
| STAND HIP ABD (ARS)<br>STAND HIP ABD (CONTORL) | 5 | 3.87<br>3.21 | 2.31<br>1.74 | 0.06 |
| SIT KNEE EX (ARS)<br>SIT KNEE EX (CONTORL) | 7 | 5.07<br>4.02 | 1.48<br>1.53 | 0.02 |
| STAND KNEE FLEX (ARS)<br>STAND KNEE FLEX (CONTORL) | 11 | 4.8<br>3.56 | 1.89<br>1.93 | <0.01 |
| STAND HIP EX (ARS)<br>STAND HIP EX (CONTORL) | 5 | 3.52<br>3.11 | 2.22<br>1.78 | 0.06 |
| STAND HIP FLEX HIP (ARS)<br>STAND HIP FLEX HIP (CONTORL) | 7 | 4.6<br>2.98 | 1.8<br>1.48 | 0.02 |

## D.7 STAND HIP ABD Analysis For Each High Functioning Participant

Table D.7: Analysis of the STAND HIP ABD exercise. Table consists of the participant number, the mean error in angular position, maximum angular position and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests.

| PX Num | Type of Data | Mean W EGF (°, °/sec) | Mean CONTROL (°, °/sec) | STD W EGF | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 18 | Pos Error | 9.75 | 6.24 | 2.96 | 1.41 | 0.01 |
| | Max Pos | 29.85 | 13.76 | 2.96 | 1.41 | <0.01 |
| | Max Velo | 38.78 | 52.38 | 3.87 | 2.34 | <0.01 |
| 21 | Pos Error | 10.80 | 18.39 | 1.33 | 3.52 | <0.01 |
| | Max Pos | 30.90 | 38.49 | 1.33 | 3.52 | <0.01 |
| | Max Velo | 51.42 | 56.98 | 2.39 | 5.85 | 0.02 |
| 22 | Pos Error | 28.70 | 8.84 | 5.18 | 1.96 | <0.01 |
| | Max Pos | 48.80 | 28.94 | 5.18 | 1.96 | <0.01 |
| | Max Velo | 64.70 | 52.02 | 5.67 | 3.44 | <0.01 |
| 23 | Pos Error | 2.25 | 1.88 | 1.00 | 0.83 | 0.29 |
| | Max Pos | 18.37 | 21.92 | 2.87 | 1.00 | 0.01 |
| | Max Velo | 46.60 | 51.75 | 2.51 | 3.05 | <0.01 |
| 26 | Pos Error | 14.25 | 14.54 | 5.30 | 3.51 | 0.93 |
| | Max Pos | 34.35 | 34.64 | 5.30 | 3.51 | 0.93 |
| | Max Velo | 41.81 | 47.08 | 2.39 | 3.15 | <0.01 |

## D.8 SIT KNEE EX Analysis For Each High Functioning Participant

Table D.8: Analysis of the SIT KNEE EX exercise. Table consists of the participant number, the mean error in angular position, maximum angular position and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests.

| PX Num | Type of Data | Mean W EGF (°, °/sec) | Mean CONTROL (°, °/sec) | STD W EGF | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 13 | Pos Error | 0.10 | 5.37 | 0.28 | 3.61 | <0.01 |
| | Max Pos | -31.68 | -38.37 | 1.32 | 3.61 | <0.01 |
| | Max Velo | 65.57 | 74.59 | 12.54 | 9.71 | 0.03 |
| 14 | Pos Error | 2.97 | 4.05 | 2.07 | 1.10 | 0.16 |
| | Max Pos | -10.35 | -9.25 | 2.11 | 1.10 | 0.16 |
| | Max Velo | 84.98 | 103.35 | 4.81 | 3.52 | <0.01 |
| 17 | Pos Error | 2.04 | 3.50 | 1.11 | 1.05 | <0.01 |
| | Max Pos | -11.36 | -9.80 | 1.34 | 1.05 | <0.01 |
| | Max Velo | 90.82 | 103.39 | 5.89 | 10.45 | <0.01 |
| 18 | Pos Error | 13.12 | 12.71 | 1.13 | 0.95 | 0.49 |
| | Max Pos | -0.18 | -0.59 | 1.13 | 0.95 | 0.49 |
| | Max Velo | 122.35 | 133.33 | 10.38 | 5.38 | 0.02 |
| 20 | Pos Error | 8.13 | 12.42 | 3.16 | 1.25 | <0.01 |
| | Max Pos | -5.17 | -0.88 | 3.16 | 1.25 | <0.01 |
| | Max Velo | 92.65 | 84.08 | 3.76 | 5.16 | <0.01 |
| 24 | Pos Error | 0.00 | 0.00 | 0.00 | 0.00 | - |
| | Max Pos | -18.67 | -20.13 | 0.94 | 0.78 | <0.01 |
| | Max Velo | 50.92 | 90.14 | 5.63 | 8.60 | <0.01 |
| 25 | Pos Error | 12.94 | 12.06 | 3.54 | 2.88 | 0.38 |
| | Max Pos | -0.36 | -1.24 | 3.54 | 2.88 | 0.38 |
| | Max Velo | 52.33 | 51.94 | 7.18 | 3.77 | 0.73 |

## D.9 STAND KNEE FLEX Analysis For Each High Functioning Participant

Table D.9: Analysis of the STAND KNEE FLEX exercise. The table consists of the participant number, the mean error in angular position, maximum angular position and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests.

| PX Num | Type of Data | Mean ARS UI (°, °/sec) | Mean CONTROL (°, °/sec) | STD ARS UI | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 9 | Pos Error | 0.00 | 0.00 | 0.00 | 0.00 | - |
| | Max Pos | 78.39 | 79.25 | 1.32 | 1.82 | 0.13 |
| | Max Velo | 77.50 | 88.28 | 7.09 | 3.97 | <0.01 |
| 13 | Pos Error | 5.22 | 3.65 | 1.45 | 2.51 | 0.17 |
| | Max Pos | 95.42 | 93.71 | 1.45 | 2.76 | 0.17 |
| | Max Velo | 69.88 | 82.06 | 4.69 | 6.21 | <0.01 |
| 14 | Pos Error | 0.24 | 0.00 | 0.47 | 0.00 | 0.04 |
| | Max Pos | 88.47 | 89.11 | 2.19 | 0.79 | 0.64 |
| | Max Velo | 88.78 | 113.63 | 13.52 | 6.87 | <0.01 |
| 17 | Pos Error | 10.24 | 0.93 | 3.53 | 1.15 | <0.01 |
| | Max Pos | 100.44 | 88.56 | 3.53 | 3.38 | <0.01 |
| | Max Velo | 131.94 | 150.40 | 6.42 | 7.04 | <0.01 |
| 18 | Pos Error | 5.11 | 10.02 | 4.23 | 3.62 | 0.02 |
| | Max Pos | 95.00 | 100.22 | 4.70 | 3.62 | 0.02 |
| | Max Velo | 117.35 | 136.29 | 17.77 | 21.86 | 0.06 |
| 20 | Pos Error | 14.10 | 0.93 | 2.13 | 1.65 | <0.01 |
| | Max Pos | 104.30 | 86.51 | 2.13 | 3.40 | <0.01 |
| | Max Velo | 93.74 | 115.79 | 10.18 | 5.88 | <0.01 |
| 21 | Pos Error | 0.00 | 0.00 | 0.00 | 0.00 | - |
| | Max Pos | 85.65 | 85.25 | 1.42 | 1.05 | 0.72 |
| | Max Velo | 74.12 | 74.08 | 3.94 | 4.82 | 0.66 |
| 22 | Pos Error | 16.22 | 14.33 | 1.72 | 3.55 | 0.02 |
| | Max Pos | 106.42 | 104.53 | 1.72 | 3.55 | 0.02 |
| | Max Velo | 104.66 | 144.59 | 14.74 | 7.41 | <0.01 |
| 23 | Pos Error | 12.43 | 11.97 | 1.56 | 2.98 | 0.78 |
| | Max Pos | 102.63 | 102.17 | 1.56 | 2.98 | 0.78 |
| | Max Velo | 88.37 | 103.98 | 8.81 | 16.17 | 0.01 |
| 24 | Pos Error | 1.74 | 2.10 | 2.85 | 1.40 | 0.37 |
| | Max Pos | 86.90 | 92.03 | 6.57 | 1.89 | 0.16 |
| | Max Velo | 69.62 | 105.10 | 9.41 | 5.37 | <0.01 |
| 25 | Pos Error | 0.00 | 0.35 | 0.00 | 1.10 | 0.19 |
| | Max Pos | 74.05 | 66.18 | 2.28 | 3.79 | <0.01 |
| | Max Velo | 78.55 | 68.82 | 14.81 | 5.64 | 0.07 |

## D.10 STAND HIP EX Analysis For Each High Functioning Participant

Table D.10: Analysis of the STAND HIP EX exercise. Table consists of the participant number, the mean error in angular position, maximum angular position and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests.

| PX Num | Type of Data | Mean ARS UI (°, °/sec) | Mean CONTROL (°, °/sec) | STD ARS UI | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 9 | Pos Error | 0.39 | 2.33 | 0.67 | 1.34 | 0.14 |
| | Max Pos | 19.90 | 22.83 | 1.80 | 1.34 | <0.01 |
| | Max Velo | 26.81 | 27.72 | 1.82 | 2.33 | 0.42 |
| 21 | Pos Error | 13.31 | 12.07 | 2.69 | 1.14 | 0.38 |
| | Max Pos | 33.81 | 32.57 | 2.69 | 1.14 | 0.38 |
| | Max Velo | 49.74 | 55.61 | 7.90 | 5.70 | 0.12 |
| 22 | Pos Error | 8.16 | 15.30 | 3.47 | 2.08 | <0.01 |
| | Max Pos | 28.66 | 35.80 | 3.47 | 2.08 | <0.01 |
| | Max Velo | 42.58 | 52.10 | 4.82 | 12.59 | 0.27 |
| 23 | Pos Error | 5.77 | 8.08 | 2.11 | 1.90 | 0.05 |
| | Max Pos | 26.27 | 28.58 | 2.11 | 1.90 | 0.05 |
| | Max Velo | 53.17 | 65.88 | 4.43 | 3.42 | <0.01 |
| 26 | Pos Error | 24.27 | 3.42 | 14.44 | 1.18 | <0.01 |
| | Max Pos | 44.77 | 23.92 | 14.44 | 1.18 | <0.01 |
| | Max Velo | 63.59 | 68.04 | 10.26 | 6.56 | 0.47 |

## D.11 STAND HIP FLEX Analysis For Each High Functioning Participant

Table D.11: Analysis of the STAND HIP FLEX exercise. Table consists of the participant number, the mean error in angular position, maximum angular position and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests

| PX Num | Type of Data | Mean ARS UI (°, °/sec) | Mean CONTROL (°, °/sec) | STD ARS UI | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 17 | Pos Error | 0.00 | 13.59 | 0.00 | 6.56 | <0.01 |
| | Max Pos | 73.65 | 104.29 | 3.73 | 6.56 | <0.01 |
| | Max Velo | 104.41 | 125.08 | 12.36 | 14.97 | 0.01 |
| 20 | Pos Error | 0.00 | 0.00 | 0.00 | 0.00 | - |
| | Max Pos | 62.99 | 61.04 | 3.37 | 1.61 | 0.21 |
| | Max Velo | 57.98 | 102.47 | 8.17 | 5.08 | <0.01 |
| 21 | Pos Error | 0.00 | 0.00 | 0.00 | 0.00 | - |
| | Max Pos | 74.37 | 70.11 | 3.13 | 2.03 | <0.01 |
| | Max Velo | 68.74 | 79.42 | 11.03 | 7.73 | 0.05 |
| 22 | Pos Error | 0.72 | 3.52 | 1.51 | 3.56 | 0.01 |
| | Max Pos | 88.29 | 89.99 | 3.67 | 7.70 | 0.71 |
| | Max Velo | 90.67 | 89.81 | 20.84 | 20.88 | 0.81 |
| 23 | Pos Error | 14.02 | 9.04 | 6.64 | 4.88 | 0.18 |
| | Max Pos | 104.72 | 99.74 | 6.64 | 4.88 | 0.18 |
| | Max Velo | 127.16 | 139.05 | 20.61 | 15.07 | 0.26 |
| 24 | Pos Error | 0.00 | 1.44 | 0.00 | 1.27 | <0.01 |
| | Max Pos | 81.25 | 75.71 | 1.64 | 1.47 | <0.01 |
| | Max Velo | 69.31 | 101.92 | 12.19 | 6.64 | <0.01 |
| 26 | Pos Error | 0.00 | 0.00 | 0.00 | 0.00 | - |
| | Max Pos | 71.91 | 73.86 | 2.09 | 1.85 | 0.08 |
| | Max Velo | 57.21 | 71.41 | 3.76 | 5.45 | <0.01 |

## D.12 Hip Compensation Analysis For SIT KNEE EX For Each High Functioning Participant

Table D.12: Analysis of the hip compensation of the SIT KNEE EX exercise. Table consists of the participant number, the mean hip movement,and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests.

| PX Num | Type of Data | Mean ARS UI (°, °/sec) | Mean CONTROL (°, °/sec) | STD ARS UI | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 13 | Hip Mov | 7.3 | 10.72 | 1.89 | 1.13 | <0.01 |
| | Max Velo | 9.79 | 14.43 | 5.51 | 5.02 | <0.01 |
| 14 | Hip Mov | 14.74 | 16.84 | 1.46 | 0.71 | <0.01 |
| | Max Velo | 17.77 | 27.17 | 2.19 | 2.08 | <0.01 |
| 17 | Hip Mov | 16.04 | 11.56 | 1.03 | 1.68 | <0.01 |
| | Max Velo | 28.19 | 23.65 | 3.9 | 4.16 | <0.01 |
| 18 | Hip Mov | 11.84 | 11.96 | 1.7 | 0.95 | 1 |
| | Max Velo | 18.54 | 16.79 | 3.21 | 3.2 | 0.54 |
| 20 | Hip Mov | 7.27 | 9.45 | 1.03 | 0.96 | <0.01 |
| | Max Velo | 9.16 | 8.99 | 1.27 | 3.05 | 0.57 |
| 24 | Hip Mov | 12.1 | 25.86 | 3.87 | 1.74 | <0.01 |
| | Max Velo | 14.3 | 48.56 | 8.98 | 4.73 | <0.01 |
| 25 | Hip Mov | 9.18 | 9.36 | 2.57 | 1.82 | 0.85 |
| | Max Velo | 7.42 | 9.91 | 2.62 | 2.54 | 0.03 |

## D.13 Hip Compensation Analysis For STAND KNEE FLEX For Each High Functioning Participant

Table D.13: Analysis of the hip compensation of the STAND KNEE FLEX exercise. Table consists of the participant number, the mean hip movement,and maximum angular velocity for each participant who performed the exercise under both conditions, the standard deviation and the p-values of the Wilcoxon rank sum tests.

| PX Num | Type of Data | Mean ARS UI ( (°, °/sec)) | Mean CONTROL ( (°, °/sec)) | STD ARS UI | STD CONTROL | Wilcoxon Rank Sum Test p-value |
|---|---|---|---|---|---|---|
| 9 | Hip Mov | 9.71 | 10.5 | 3.43 | 2.63 | 0.39 |
| | Max Velo | 12.5 | 18.2 | 3.46 | 4.65 | <0.01 |
| 13 | Hip Mov | 6.61 | 9.56 | 1.31 | 1.76 | <0.01 |
| | Max Velo | 13.22 | 20.97 | 2.07 | 4.04 | <0.01 |
| 14 | Hip Mov | 13.79 | 21.25 | 3.98 | 2.66 | <0.01 |
| | Max Velo | 21.45 | 39.81 | 8.1 | 3.68 | <0.01 |
| 17 | Hip Mov | 22.6 | 20.71 | 4.56 | 2.29 | 0.31 |
| | Max Velo | 41.17 | 65.54 | 9.04 | 15.71 | <0.01 |
| 18 | Hip Mov | 14.68 | 20.08 | 2.2 | 2.67 | <0.01 |
| | Max Velo | 27.48 | 33.21 | 4.16 | 7.07 | 0.03 |
| 20 | Hip Mov | 14.08 | 10.25 | 1.72 | 2.49 | <0.01 |
| | Max Velo | 23.67 | 33.5 | 6.19 | 8.13 | 0.01 |
| 21 | Hip Mov | 13.91 | 16.68 | 1.98 | 2.29 | 0.01 |
| | Max Velo | 20.78 | 22.74 | 4.11 | 3.11 | 0.28 |
| 22 | Hip Mov | 17.66 | 19.9 | 2.32 | 3.96 | 0.07 |
| | Max Velo | 22.47 | 49.02 | 3.73 | 4.01 | <0.01 |
| 23 | Hip Mov | 26.95 | 21.42 | 3.23 | 3.78 | <0.01 |
| | Max Velo | 35.58 | 34.31 | 3.51 | 6.69 | 0.72 |
| 24 | Hip Mov | 17.78 | 9.67 | 5.67 | 1.82 | <0.01 |
| | Max Velo | 22.29 | 23.02 | 5.6 | 3.65 | 0.90 |
| 25 | Hip Mov | 10.86 | 9.3 | 3.06 | 2.88 | 0.24 |
| | Max Velo | 16.08 | 15.12 | 3.14 | 4.48 | 0.42 |

# References

[1] Swamy Ananthanarayan, Miranda Sheh, Alice Chien, Halley Profita, and Katie A Siek. Designing wearable interfaces for knee rehabilitation. In *Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare*, pages 101–108. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2014.

[2] Mobolaji Ayoade and Lynne Baillie. A novel knee rehabilitation system for the home. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*, pages 2521–2530. ACM, 2014.

[3] Mobolaji Ayoade, Stephen Uzor, and Lynne Baillie. The development and evaluation of an interactive system for age related musculoskeletal rehabilitation in the home. In *Human-Computer Interaction–INTERACT 2013*, pages 1–18. Springer, 2013.

[4] Adrian Burns, Barry R Greene, Michael J McGrath, Terrance J O'Shea, Benjamin Kuris, Steven M Ayer, Florin Stroiescu, and Victor Cionca. Shimmer–a wireless sensor platform for noninvasive biomedical research. *Sensors Journal, IEEE*, 10(9):1527–1534, 2010.

[5] Catherine M Burns and John Hajdukiewicz. *Ecological interface design*. CRC Press, 2013.

[6] Cristina Costa, David Tacconi, Roberto Tomasi, Flavio Calva, and Valerio Terreri. Riablo: a game system for supporting orthopedic rehabilitation. In *Proceedings of the Biannual Conference of the Italian Chapter of SIGCHI*, page 11. ACM, 2013.

[7] Martin Friedrich, Thomas Cermak, and Petra Maderbacher. The effect of brochure use versus therapist teaching on patients performing therapeutic exercise and on changes in impairment status. *Physical Therapy*, 76(10):1082–1088, 1996.

[8] Rachel Gockley and Maja J MatariĆ. Encouraging physical therapy compliance with a hands-off mobile robot. In *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*, pages 150–155. ACM, 2006.

[9] R. Houmanfar, M. Karg, and D. Kulić. Movement analysis of rehabilitation exercises: Distance metrics for measuring patient progress. *Systems Journal, IEEE*, PP(99):1–12, 2014.

[10] Jun-Da Huang. Kinerehab: A kinect-based system for physical rehabilitation: A pilot study for young adults with motor disabilities. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility*, pages 319–320. ACM, 2011.

[11] Vladimir Joukov, Michelle Karg, and Dana Kulić. Online tracking of the lower body joint angles using imus for gait rehabilitation. In *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*, pages 2310–2313. IEEE, 2014.

[12] Janna C Kimel. Thera-network: A wearable computing network to motivate exercise in patients undergoing physical therapy. In *Distributed Computing Systems Workshops, 2005. 25th IEEE International Conference on*, pages 491–495. IEEE, 2005.

[13] Agnes W.K. Lam, Ahmed HajYasien, and Dana Kulić. Improving rehabilitation exercise performance through visual guidance. In *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*, pages 1735–1738. IEEE, 2014.

[14] Agnes W.K. Lam, Danniel Varona-Marin, Yeti Li, Mitchell Fergenbaum, and Dana Kulić. Automated rehabilitation system: movement measurement and feedback for patients and physiotherapists in the rehabilitation clinic. In *Human–Computer Interaction*. Taylor & Francis, (accepted).

[15] Belinda Lange, Evan A Suma, Brad Newman, Thai Phan, Chien-Yen Chang, Albert Rizzo, and Mark Bolas. Leveraging unencumbered full body control of animated virtual characters for game-based rehabilitation. In *Virtual and Mixed Reality-Systems and Applications*, pages 243–252. Springer, 2011.

[16] Yeti Li, Catherine M Burns, and Dana Kulić. Ecological interface design for knee and hip automatic physiotherapy assistant and rehabilitation system. In *Proceedings of the International Symposium of Human Factors and Ergonomics in Healthcare*, volume 3, pages 1–7. SAGE Publications, 2014.

[17] Jonathan Feng-Shun Lin and Dana Kulić. Human pose recovery for rehabilitation using ambulatory sensors. In *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*, pages 4799–4802. IEEE, 2013.

[18] Jonathan Feng-Shun Lin and Dana Kulić. Online segmentation of human motion for automated rehabilitation exercise analysis. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 22(1):168–180, 2014.

[19] Jonathan FS Lin and Dana Kulić. Human pose recovery using wireless inertial measurement units. *Physiological measurement*, 33(12):2099, 2012.

[20] Robert W Lindeman, Yasuyuki Yanagida, Kenichi Hosaka, and Shinji Abe. The tactapack: A wireless sensor/actuator package for physical therapy applications. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2006 14th Symposium on*, pages 337–341. IEEE, 2006.

[21] Justine Naylor, Alison Harmer, Marlene Fransen, Jack Crosbie, and Lesley Innes. Status of physiotherapy rehabilitation after total knee replacement in australia. *Physiotherapy research international*, 11(1):35–47, 2006.

[22] Cynthia C Norkin and D Joyce White. *Measurement of joint motion: a guide to goniometry*. FA Davis, 2009.

[23] Merce Piqueras, Ester Marco, Maria Coll, Ferran Escalada, Alex Ballester, Carme Cinca, Roser Belmonte, and Josep M Muniesa. Effectiveness of an interactive virtual telerehabilitation system in patients after total knee arthroplasty: A randomized controlled trial. *Journal of Rehabilitation Medicine*, 45(4):392–396, 2013.

[24] Ewa M Roos. Effectiveness and practice variation of rehabilitation after joint replacement. *Current opinion in rheumatology*, 15(2):160–162, 2003.

[25] Giulio Rosati, Fabio Oscari, Simone Spagnol, Federico Avanzini, and Stefano Masiero. Effect of task-related continuous auditory feedback during learning of tracking motion exercises. *J. Neuroeng. Rehabil*, 9:79, 2012.

[26] Gerd Schmitz, Daniela Kroeger, and Alfred O Effenberg. A mobile sonification system for stroke rehabilitation. 2014.

[27] Joon-Ho Shin, Hokyoung Ryu, and Seong Ho Jang. A task-specific interactive game-based virtual reality rehabilitation system for patients with stroke: a usability test

and two clinical experiments. *Journal of neuroengineering and rehabilitation*, 11(1):32, 2014.

[28] Aneesha Singh, Annina Klapper, Jinni Jia, Antonio Fidalgo, Ana Tajadura-Jiménez, Natalie Kanakam, Nadia Bianchi-Berthouze, and Amanda Williams. Motivating people with chronic pain to do physical activity: opportunities for technology design. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*, pages 2803–2812. ACM, 2014.

[29] David W Stewart and Prem N Shamdasani. *Focus groups: Theory and practice*, volume 20. Sage Publications, 2014.

[30] L Enrique Sucar, Felipe Orihuela-Espina, Roger Luis Velazquez, David J Reinkensmeyer, Ron Leder, and Jorge Hernandez-Franco. Gesture therapy: An upper limb virtual reality-based motor rehabilitation platform. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 22(3):634–643, 2014.

[31] Richard Tang, Anthony Tang, Xing-Dong Yang, Scott Bateman, and Joaquim Jorge. Physio@ home: Exploring visual guidance and feedback techniques for physiotherapy exercises. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 4123–4132. ACM, 2015.

[32] Stephen Uzor and Lynne Baillie. Exploring & designing tools to enhance falls rehabilitation in the home. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1233–1242. ACM, 2013.

[33] Shih-Ching Yeh, Shun-Min Chang, Shu-Ya Chen, Wu-Yuin Hwang, Tzu-Chuan Huang, and Te-Lu Tsai. A lower limb fracture postoperative-guided interactive rehabilitation training system and its effectiveness analysis. In *e-Health Networking, Applications and Services (Healthcom), 2012 IEEE 14th International Conference on*, pages 149–154. IEEE, 2012.

[34] YouTube. Zeus top 10 bodyweight only leg exercises for all levels, https://youtu.be/M5WQF7Sa4fY?t=47s.

[35] YouTube. How to do a squat — boot camp workout, https://youtu.be/UXJrBgI2RxA?t=2m11s.

[36] YouTube. How to do lunges, https://youtu.be/Z2n58m2i4jg?t=31s.

[37] Huiyu Zhou and Huosheng Hu. Human motion tracking for rehabilitationa survey. *Biomedical Signal Processing and Control*, 3(1):1–18, 2008.