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Automated Rehabilitation System: Movement Measurement and Feedback for Patients and Physiotherapists in the Rehabilitation Clinic

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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 article proposes the Automated Rehabilitation System (ARS), a system designed specifically for rehabilitation clinics 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 that continuously measure the patient's pose. The measured 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

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patient movement, assess recovery progress, and manage and schedule exercise regimens for patients. The system requirements and design requirements were derived through a focus group with 13 physiotherapists. For patients, ARS provides visual feedback and a novel exercise guidance feature to aid them while exercising. The patient interface was evaluated in a user study with 26 outpatients. The results show that performing the exercises with the visual guidance tool improves the quality of exercise performance.

CONTENTS

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

(Friedrich, Cermak, & Maderbacher, 1996). 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 among 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, performing 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. 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 that exercise session. 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 home use; few have been designed for a clinical setting. 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.

In this article, our focus is on rehabilitation 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. Patients who have additional medical conditions or complications postsurgery require additional monitoring at a medical facility and are typically admitted to in-patient care. Patients who do not require additional monitoring following their surgical procedure have the options of either out-patient or at-home rehabilitation. Patients who are able to transport to a rehabilitation clinic are admitted to out-patient rehabilitation, whereas patients who lack any form of transportation or are unable to leave their homes receive at-home rehabilitation.

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 toward 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, repetitions for each exercise, and the number 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 Physiotherapist Assistant (PTA) is supervising multiple patients simultaneously. Common mistakes made by patients during exercise performance include using the hip joint for compensation during knee exercises and performing the exercises at too high of a velocity, using momentum and/or gravity to perform the motion.

To improve exercise performance and tracking for both patients and physiotherapists, this paper proposes the use of an Automated Rehabilitation System (ARS). ARS is a system specialized for clinical use, consisting of separate user interfaces (UIs) 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 patients 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 and knee joint angles, enabling assessment of range of motion, tempo, and compensation. The motion data are stored and can be subsequently reviewed by the PT through a visual UI. An elicitation of system requirements was conducted through a focus group with PTs. This article describes the various components of ARS, the focus group conducted with PTs to elicit system requirements, the user study conducted with patients in the clinical setting to evaluate the effects of using of ARS, and the results and discussion from the two studies with regards to motion quality during exercise execution and usability of the system.

2. RELATED WORK

Guidance Systems for Home Use

Rehabilitation systems designed for home use are very popular in the literature. Because 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. The Rehabilitation Visualisation System (RVS) is intended for the home environment and utilizes two IMUs to track the exercise motion as users perform knee exercises (Ayoade & Baillie, 2014). Users are provided with real-time feedback on their exercise motion, and the correct exercise motion is demonstrated on a virtual avatar on a separate screen of the UI. The feedback is provided in the form of a graphical fan with changing color 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 postoperative 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 did not mention whether the system includes the capability of modifying the exercise programs, which is necessary in clinical use. Ayoade, Uzor, and Baillie (2013) 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 overextending or flexing while trying to keep up with the range of movement and pace. The trade-off, however, is that patients can focus their attention only 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 perform knee exercises (Piqueras et al., 2013). The interactive application of this system consists of a 3D avatar that 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 places little emphasis on the PT's interaction with the system. IVT consists of 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 that uses bend sensors to detect the bend angle of the knee (Ananthanarayan, Sheh, Chien, Profita, & Siek, 2014). A wire bar graph on the device gives visual notification of the bend progression as the patient performs the knee extension exercise. The device provides the user only with feedback on how much knee flexion the user achieved and does not provide guidance on how to perform various exercise motions. PT Vis also does not include any interface for the PTs.

All the aforementioned systems 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 aforementioned systems also do not provide patients with any guidance and feedback with respect to the tempo of the exercise motion.

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 (2013) 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 consisting of a knee brace and an online system (Kimel, 2005). The brace tracks the knee angle, and Electroluminescent strips light up as users increase 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 provided with information only in the form of the level of Electroluminescent 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 begun to look at detecting compensation during exercise performance. Gesture Therapy is a virtual reality-based system for rehabilitation of the upper limbs (Sucar et al., 2014). Sucar et al. introduced 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.

Guidance Systems for Clinical Use

Although 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 (Huang, 2011). 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 patients with their movements or correct incorrect movement, but the body of the PT could also block the line of sight of a camera-based system. Hung mentioned 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 (Lindeman, Yanagida, Hosaka, & Abe, 2006). 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 he or she has 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. (2012) described 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 validated only 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 these data would be displayed.

Exer-Gaming and Motivational Systems for Clinical Use

Finally, several systems have been designed to address compliance and motivation in the clinic. RIABLO is intended to be used in both clinical and home settings and utilizes five inertia sensors and a board of pressure sensors to capture the movement of the patient (Costa, Tacconi, Tomasi, Calva, & Terreri, 2013). Patients collect rewards for performing 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. (2011) 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 (2006) developed a social robot that 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. 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 poststroke rehabilitation of the upper extremities (Shin, Ryu, & Jang, 2014). The RehabMaster uses a PrimeSense 3D awareness sensor and tracks the patients' upper extremities as they engage in rehabilitation games in the seated position. Although 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.

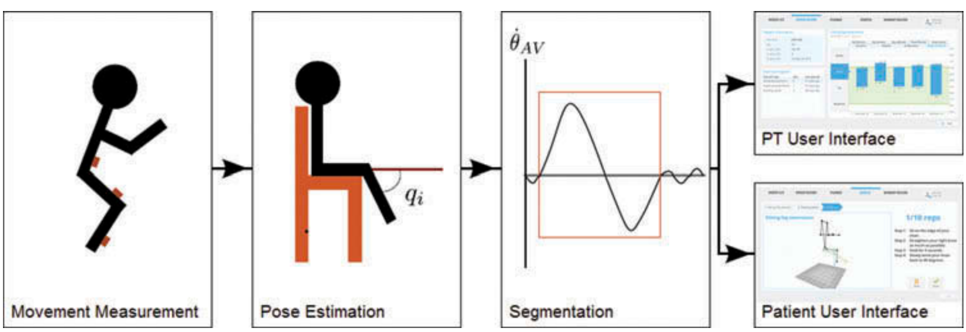
Although the systems designed for clinical use have developed approaches for both patient and therapist feedback, none of the systems provide patients with real-time guidance and feedback on their exercise performance. In addition, most of the research just described has not analyzed the motion data 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 PTs to assess their patients. The goal of our research 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 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 analyzes the motion data collected to assess how the use of such a system affects the exercise performance of patients.

3. AUTOMATED REHABILITATION SYSTEM

The ARS is a measurement and data visualization system targeted for clinical use in physiotherapy for both PTs and physiotherapy patients. Figure 1 provides a workflow of the four major components of ARS. Patients wear IMU sensors that track their movement as they perform rehabilitation exercises. The current configuration of the system uses SHIMMER (Burns et al., 2010) sensors. The system takes accelerometer and gyroscope data from the IMUs and converts it to joint angles using a pose estimation algorithm (Lin & Kulić, 2012) and segments the time series data of the exercises online using a segmentation algorithm (Lin & Kulić, 2014). Both the motion of the hip (three joint angles) and the motion of the knee (two joint angles) are simultaneously estimated, allowing the system to be used for any knee or hip exercise. Modelling and displaying the hip joint not only allows 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 data collected and processed by the system are displayed to the patients via a graphical UI. Screenshots of the patient interface is shown in Figures 2 to 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 6 to 9 consist of 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 repetitions 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 is written in JAVA, allowing for the option of running on an

FIGURE 1. Process workflow of the Automated Rehabilitation System.



Note. **The Movement Measurement component consists of inertial measurement units (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 physiotherapist (PT) Interface is used by PTs to review schedule workouts and review patient motion data.**

FIGURE 2. Screenshot of the patient user interface of the Automated Rehabilitation System showing patients how to place the sensors prior to beginning their exercise session.

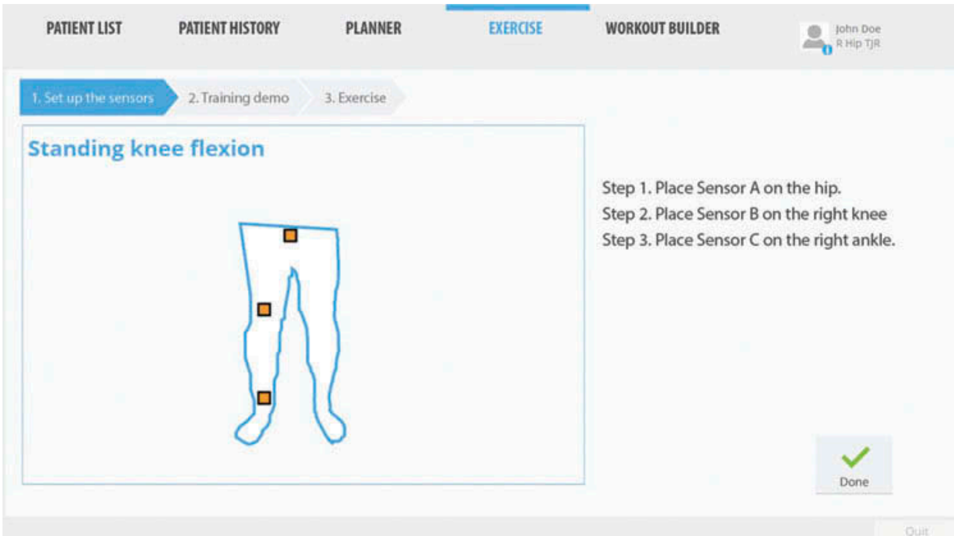
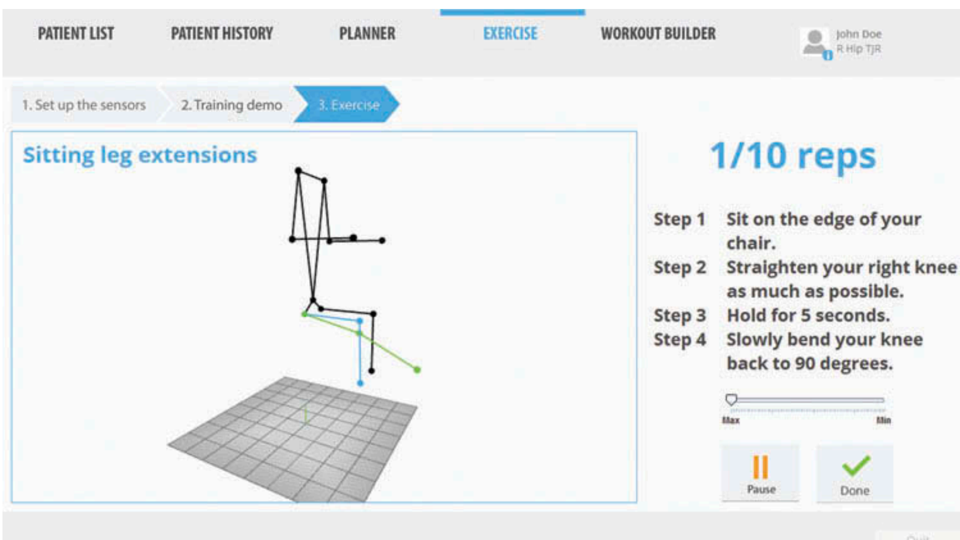


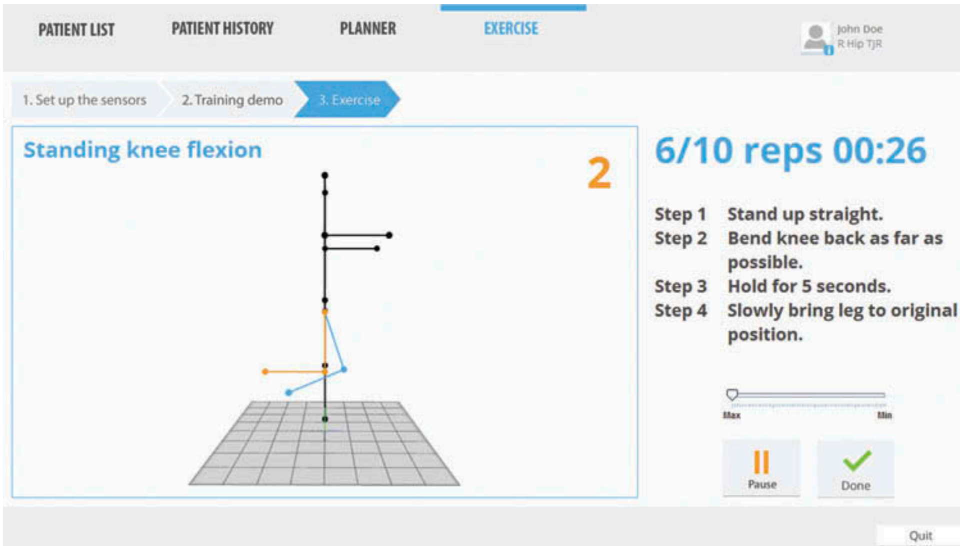
FIGURE 3. Screenshot of the patient user interface of the Automated Rehabilitation System during exercise execution.



Note. **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.**

Android tablet in the future, increasing portability. When compared to motion capture, the pose estimation system achieves an average root mean square error of 4.27 cm for unconstrained motion, with an average joint error of 6.5. The average root mean

FIGURE 4. Screenshot of the patient user interface of the Automated Rehabilitation System displaying an example of compensatory movement in the hip while performing the standing knee flexion exercise.



Note. **Patients using the system can detect their compensatory movement by observing how their upper leg is misaligned with the guide leg.**

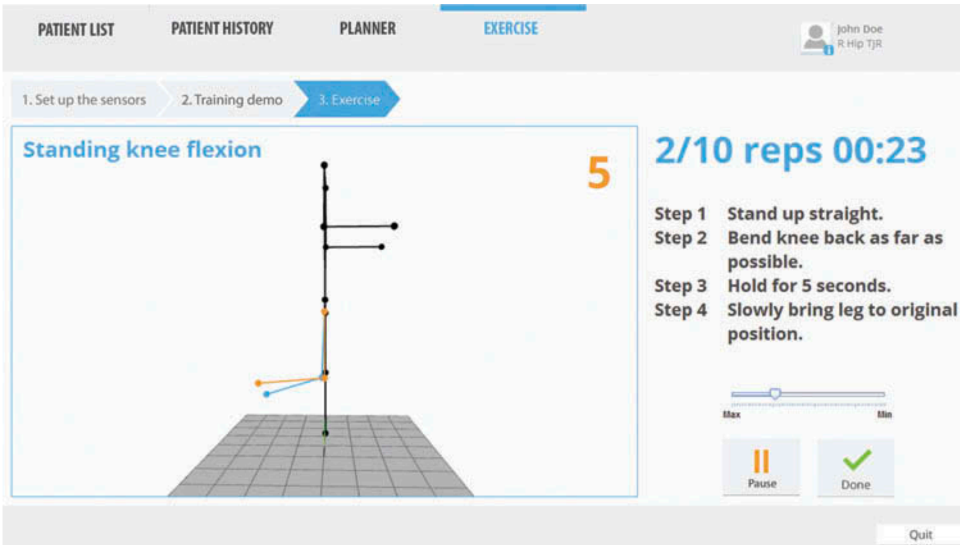
square error is 3.31 cm for planar motion, with an average joint error of 4.3 (Lin & Kulić, 2013).

3.1. Patient Interface

The patient interface first shows the patient where to place the IMU sensors. This screen, shown in Figure 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. The patient has the option to replay the demonstration if so desired. Once the demonstration is completed, the patient is taken to the exercise execution screen, shown in Figure 3. The exercise execution screen includes a virtual avatar that displays the user's exercise movements in real time as the user is exercising. The system tracks both hip and knee movement, allowing for patients 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 4. The patient UI also provides other information with regards to the exercise set: name of the exercise, list of instructions, repetitions completed, and time elapsed.

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

FIGURE 5. Screenshot of the patient user interface of the Automated Rehabilitation System when the 5-s hold feature is activated during exercise execution.



Note. **The guide leg changes color from green to orange and a 5-s countdown appears in the upper right-hand corner.**

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 repeats and renders the first half of the motion again, and this is repeated for each repetition 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, where the threshold is set to the final flexion or extension position as demonstrated by EGF. As the slider is moved toward the minimum end, shown in Figure 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 repetition of their exercise set, allowing users to visually identify errors in their exercise motion and correct their motion to better match the ideal motion.

FIGURE 6. Screenshot of the physiotherapist (PT) user 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.

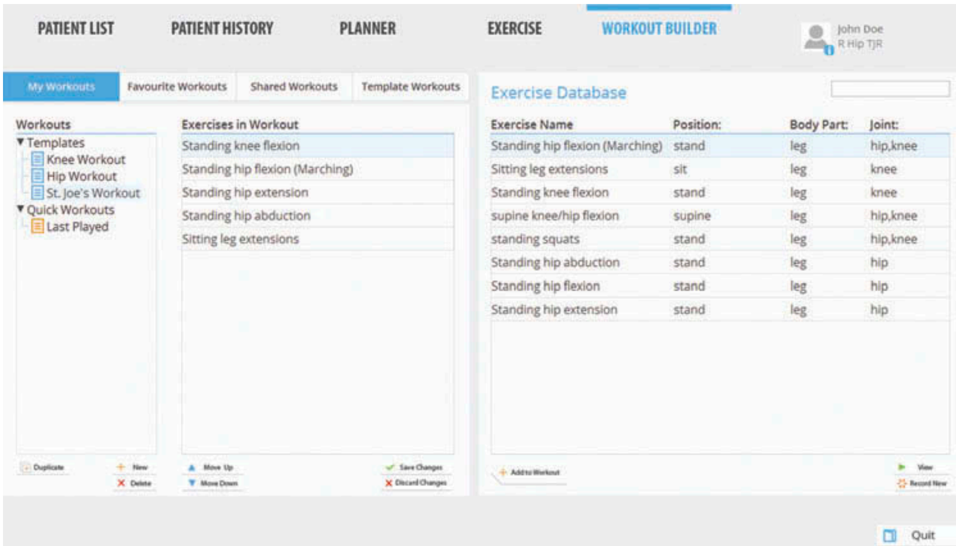
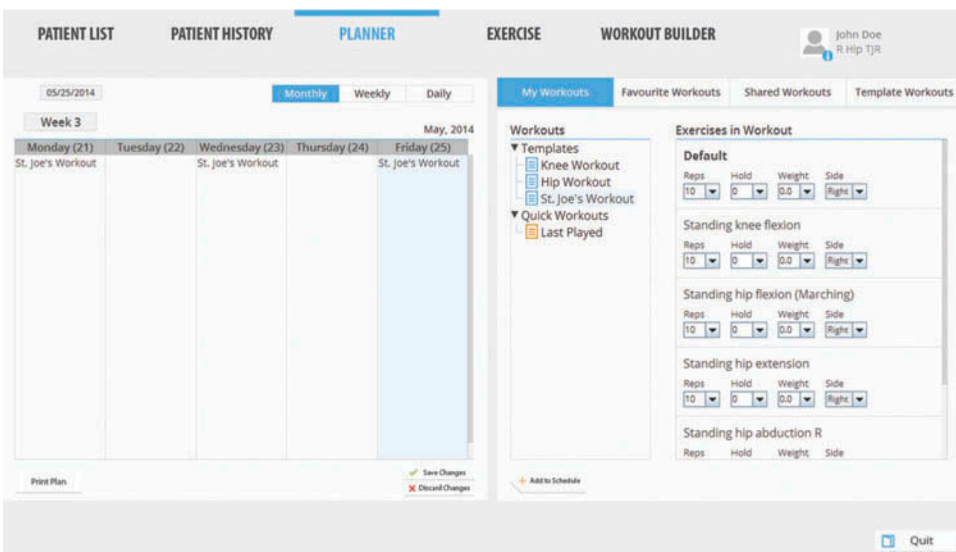


FIGURE 7. Screenshot of the physiotherapist (PT) user interface of the Automated Rehabilitation System showing the Planner screen where PTs schedule exercise regimens for their patients and set the parameters for the exercises.



The system also includes an optional 5-s hold feature. When the 5-s hold feature is enabled, the avatar guide leg will change colors and hold for 5 s 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 5-s countdown

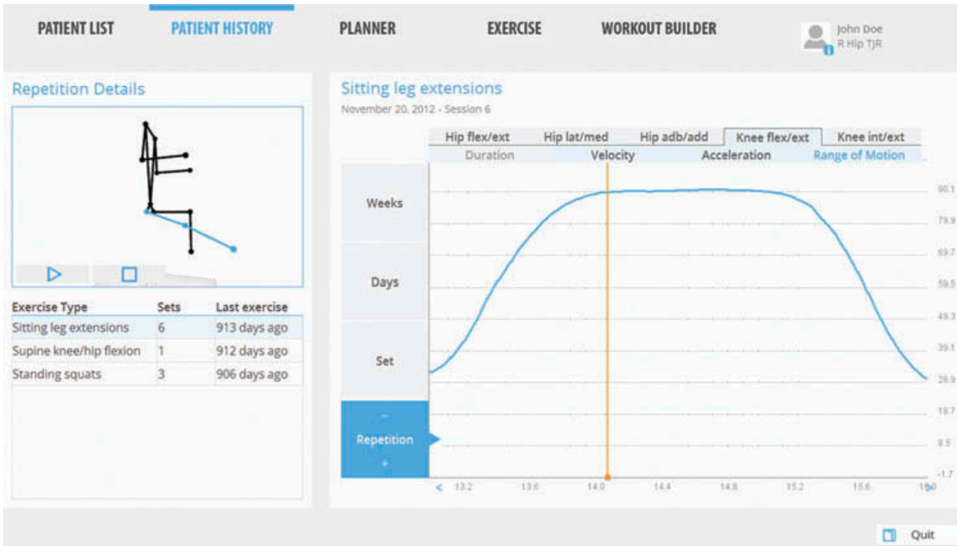
FIGURE 8. Screenshot of the physiotherapist (PT) user interface of the Automated Rehabilitation System showing the Patient History screen where PTs track the progress of their patients by reviewing the data collected by the system.

Note. **The data displayed in this screenshot show the range of motion of a patient performing sitting knee extensions over 5 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.**

also appears on the screen during the hold portion of the exercise. The 5-s 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 5-s countdown will activate before the user has achieved the full range of motion for users with restricted movement. The 5-s 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 5 shows a screenshot of ARS when the 5-s countdown is activated during exercise performance.

Although it was mentioned by Ayoade, Uzor, and Baillie (2013) that overlaying an exemplar motion could cause patients in early stages of recovery to overextend 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 and the velocity of the motion demonstrated by the PT, and thus ARS renders the exemplar motion exactly how the PT 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 attention between two

FIGURE 9. Screenshot of the physiotherapist user interface of the Automated Rehabilitation System showing the Patient History screen displaying the information for one repetition of an exercise.



Note. **This screen shows the motion profile of the repetition (right) as well as a replay of the motion on the virtual avatar (left).**

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.

3.2. 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 6, allows the PT to set up exercise regimens for their patients. PTs can build a workout from scratch or select a preexisting 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 planner screen, shown in Figure 7, 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 repetitions, 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 8, 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 the rehabilitation program. The patient history screen plots the duration, range of motion, peak velocity, and peak acceleration of each repetition for each exercise. PTs can view the data grouped by session, days, or weeks. 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 PT can also look at each repetition individually, shown in Figure 9. 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.

4. STUDY 1: FOCUS GROUP WITH PHYSIOTHERAPISTS

To develop a system 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.

4.1. Methods

Participants

Thirteen PTs participated in the focus group. However, due to time constraints, we were able to acquire background information on only six of them. These six PTs were mostly female (five female, one male), 36.5 years of age ($SD = 11$), 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-min focus group that 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 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. To design a prototype interface for this complex sociotechnical system we used an Ecological Interface Design (Burns & Hajdukiewicz, 2013). The Ecological Interface Design approach helped us understand 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 requirements for ARS's prototype interface. The development of this prototype interface is described in Li, Burns and Kulić (2014).

During the focus group, the primary moderator presented the idea of computer-assisted rehabilitation and demonstrated the prototype in the first 20 min. Afterward, 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 (Stewart, Shamdasani, & Rook, 2007), as in our study. We analyzed the audio and written questionnaire packages using the "scissor and sort technique" (Stewart et al., 2007), 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 next.

4.2. Results and 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.

Information Visualization Requirements for Assessing Progress of Patient Recovery

Range of Motion—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 stand-alone 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° of maximal extension and −52.2° of maximum flexion, as shown in the first blue bar of Figure 8). 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 9 and 8, 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° for extension and 120° 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 Figure 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 lying 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 8. Although peak repetition acceleration was a little-known metric 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 (2014) 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 best. ARS can not only play back any repetition recorded (as shown in Figure 9) 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 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. We are currently implementing this ability into ARS.

Timeframe

PTs reported that in their current practice, they mostly use weekly data to assess patient progress. In ARS, the metrics previously described can be visualized not only weekly but also also for shorter time frames such as daily, for a set of repetitions, or for a single repetition as shown in Figure 8. Given that shorter time frame data (i.e., daily) are as easy to collect and visualize as longer time frame 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 presented earlier 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.

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 is further discussed in Study 2. For example, Singh et al. (2014) reported that progress feedback for chronic pain management should show not only 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 (Ayoade & Baillie, 2014) provides a "performance summary" graph showing the change in the number of repetitions performed over the 6-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 (Ayoade & Baillie, 2014) 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, 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 Study 2.)

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 (Ayoade, Uzor & Baillie, 2013). 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 3.1, 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. (2014), 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. Although 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-s hold feature. PTs commonly instruct patients to hold their pose for 5 s at the top of a repetition. This makes the exercise more challenging and discourages the patients from swinging their limb and using momentum to their advantage. During Study 2, our research team observed that patients rarely held at the top of the repetition for the full 5 s. 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-s countdown before the guide motion starts to complete the repetition (see Figure 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-s countdown sequence. (See Study 2 for patients' evaluation of this feature.)

Although (to the best of our knowledge) no other rehabilitation system has used a 5-s hold feature, some systems have provided a timer instead (Ananthanarayan et al., 2014; Ayoade & Baillie, 2014). Such a timer counting the duration of the set or session could be used in place of the 5-s countdown feature. However, when we asked PTs about such a timer feature, they were quick to reject it. They explained that a timer is useful only when patients 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 3 m, 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 graphical UI 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 (Rosati, Oscari, Spagnol, Avanzini, & Masiero, 2012; Schmitz, Kroeger, & Effenberg, 2014; Singh et al., 2014).

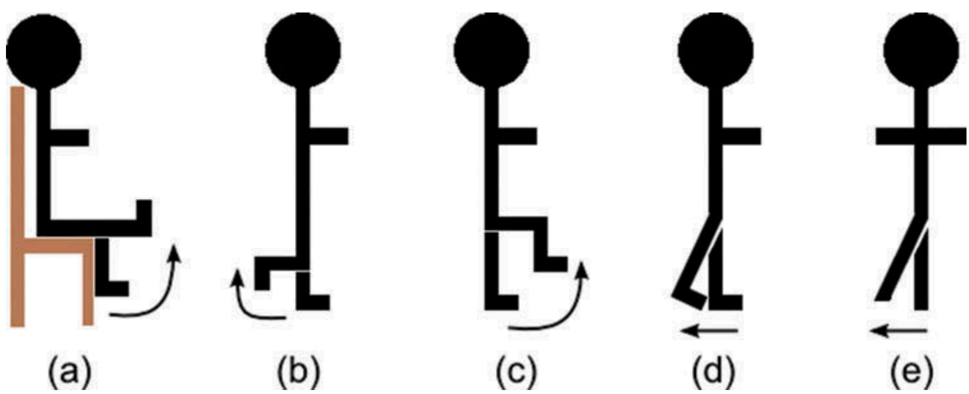
In summary, the PTs commented that the system would be very useful for assessing patient progress once the requirements they identified were addressed. After conducting the focus group with the PTs, several changes were made to the PT interface prototype (Li et al., 2014) as a result of the PT feedback. The ROM data displayed in the Patient History screen now include both the flexion and extension values (as seen in Figure 8), whereas before only the absolute ROM value was presented. The Patient History screen now also includes a playback window where PTs can playback each repetition of their patient's exercise sequence (illustrated in Figure 9). The ability to store weight values was also included in the Planner screen. The 5-s 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 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 study with their patients.

5. STUDY 2: USER STUDY WITH PATIENTS

Following the focus group with PTs, we first conducted an initial pilot study with healthy participants to verify system functionality and the study protocol (Lam, HajYasien, & Kulić, 2014). We then 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 Study 1. The study was conducted with patients undergoing out-patient rehabilitation following knee or hip replacement surgery. Patients are typically between 60 and 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 6-week rehabilitation program at the clinic, attending a 1-hr physiotherapy session twice a week. Training twice weekly involves a one-on-one session with their PT and 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 female and 10 male participants 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). Table A1 in Appendix A details the demographics of each participant in the study. 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 10 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 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.

FIGURE 10. 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.



The rehabilitation exercise regimen differed between patients. Patients of lower functional mobility were prescribed 10–15 repetitions of each exercise, whereas patients of higher functional mobility were prescribed 20–30 repetitions. The higher functioning participants were asked to do one set of 10 repetitions with the ARS UI and another set of 10 repetition without using the ARS UI, as the control condition. The order in which the participants performed the exercises under the two conditions was counterbalanced; half the participants performed the exercises first with the ARS UI and then under the control condition, whereas 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 3.1, ARS includes the ability to customize the threshold when the system considers the exercise to be completed. A lower threshold was 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 repetitions 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 5 s, whereas others were not. The 5-s 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 semistructured interview session. Participants were first asked to complete a questionnaire assessing the perceived helpfulness and confusion while using the UI of ARS. In the interview session, participants were asked to elaborate on their experiences using ARS while exercising.

6. 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. After the study was conducted with the first six participants, the 5-s timer was added, the adjustable lower threshold of the EGF was added, and the repetition detection algorithm was tuned to improve accuracy. Results collected from 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. The results that led to key findings are presented next; the full analysis of all motion data collected from the study can be found in the supplementary material.

6.1. Quality of Movement

The quantitative results are assessed 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 repetition performed by the participants. The peak velocity reveals the pace of the exercise motion, whereas 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 are 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 1 where θ 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 overachieving or underachieving the required range of motion. The maximum angular position, calculated by Equation 2, indicates the maximum flexion or extension achieved by the participant for each repetition. The peak angular velocity, calculated by Equation 3, and the duration of repetitions, calculated by Equation 4, indicate whether the patient is performing the exercise in a controlled manner.

$$e_\theta = \begin{cases} |\theta - t_{motion}|, & \theta > t_{motion} \\ |\theta - t_{lower}|, & \theta < t_{lower} \\ 0, & otherwise \end{cases} \text{, for each repetition} \tag{1}$$

$$\theta_{max} = max\,|\theta|\text{, for each repetition} \tag{2}$$

$$\omega_{peak} = max\,|\omega|\text{, for each repetition} \tag{3}$$

$$\Delta t = t_{end} - t_{start}\text{, for each repetition} \tag{4}$$

Wilcoxon rank sum tests were conducted on the error of angular position (Equation 1), peak angular velocity (Equation 3), and duration of repetitions (Equation 4) across the pool of all participants, between the data sets 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 repetitions 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 are 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 differences due to the introduction of ARS, thus concealing any influence of the guidance system.

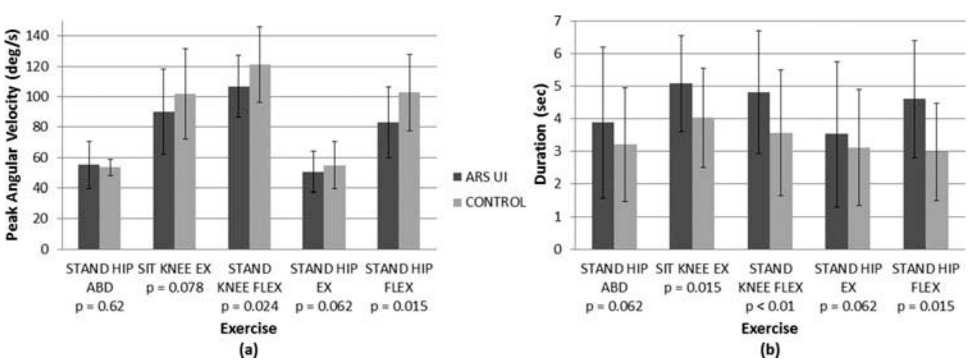
Quality of Movement Across High-Functioning Participants

The difference between conditions is more significant when the data were 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. These are both qualities of exercise performance that PTs encourage, and 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+ repetitions who were able to perform the exercises under both conditions. Wilcoxon signed rank tests were conducted on the error in angular position (Equation 1), maximum angular velocity (Equation 3), and duration of repetition (Equation 4). The median value is taken for each set of repetitions 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 data sets. Figure 11(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 data sets were statistically significant or showed a trend toward significance for four of the

FIGURE 11. The peak velocity (a) and duration (b) data from participants who performed the exercises under both the ARS user interface and control conditions, separated by exercise.



***Note.* The *p* values of the Wilcoxon signed rank test between the two conditions are reported for each exercise. Error bars show standard deviation.**

five exercises, at $p < .05$. The data sets for STAND KNEE FLEX and STAND HIP FLEX were significantly different, and the data sets of SIT KNEE EX and STAND HIP EX showed a trend toward significance. The peak velocity was lower in the ARS UI condition compared to the control condition for all four exercises.

Figure 11(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 data sets were statistically significant or showed a trend toward significance for all five exercises. The data sets for STAND KNEE FLEX, SIT KNEE EX, and STAND HIP FLEX were significantly different, and the data sets of STAND HIP ABD and STAND HIP FLEX showed a trend toward significance. The duration was higher in the ARS UI condition compared to the control condition for all five exercises.

Quality of Movement of Individual High-Functioning Participants

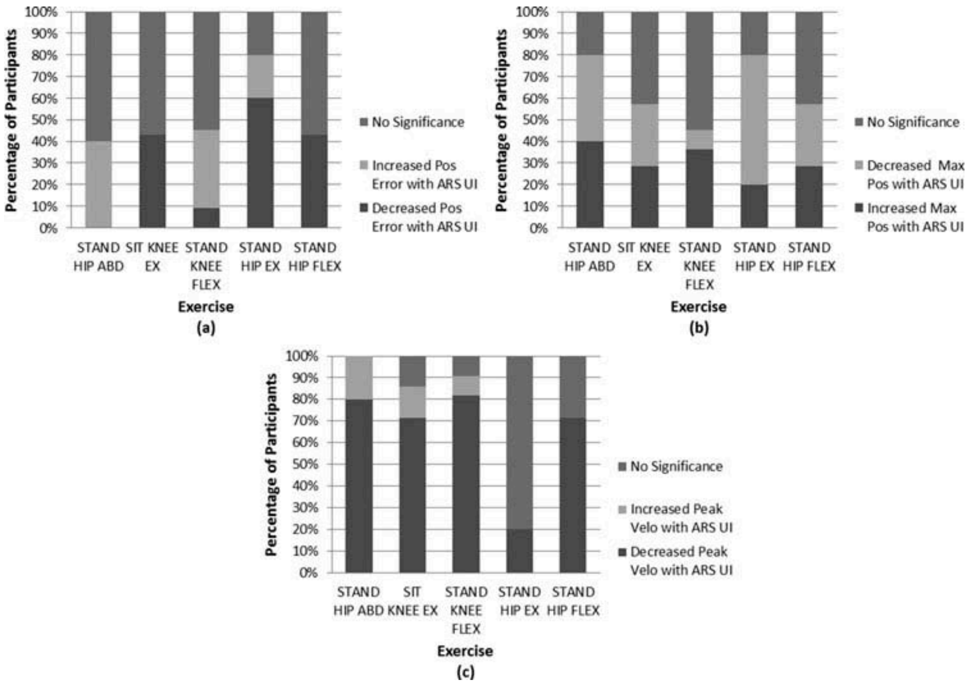
Further analysis was conducted on each participant's data individually for those who performed the exercises under both the ARS UI and control conditions. Wilcoxon rank sum tests were performed on each participant's error in angular position (Equation 1), maximum angular position (Equation 2), and peak angular velocity (Equation 3) data sets for each repetition of each exercise. The results are summarized in Figure 12, where the percentage of participants whose difference in position error, maximum position, and peak velocity data sets were statistically significant or showed a trend toward significance at a p value of $p < .05$ is indicated.

The analysis performed on individual participant data revealed that the use of ARS UI had a different impact on exercise performance for different participants, as well as different exercise types. This explains the lack of significance in the error in position data when the analysis was performed pairwise across all participants who performed the exercises under both conditions. Detailed analysis of the movement data revealed three types of users.

The first type was participants who couldn't achieve the full range of motion displayed by the EGF and required a lower threshold to be set. Figure 13 shows the plots of two data sets that 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 14 shows the plots of three data sets that 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 performing the exercises in a controlled manner.

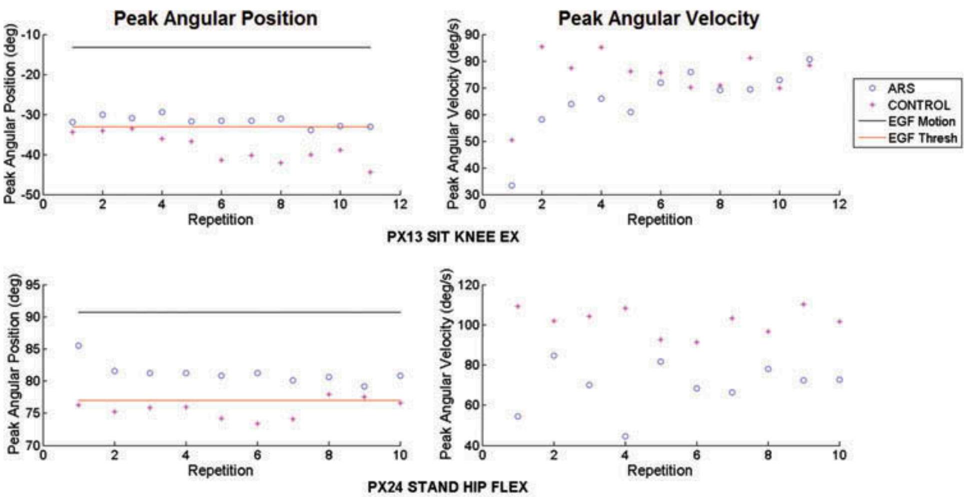
FIGURE 12. The plots of the percentage of the participants whose position error (a), maximum position (b) and peak velocity (c) values were significantly different or showed a trend towards significance at a *p* value of $p < .05$ of the Wilcoxon rank sum tests, separated by exercise type.



Note. **ARS = Automated Rehabilitation System; UI = user interface.**

The third type of users decreased their range of motion while using the ARS UI, compared to the control condition. Figure 15 shows the plots of three data sets 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 because 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.

FIGURE 13. The plots of two data sets illustrating the motion profile of users who could not achieve the full range of motion displayed by the exercise guidance feature (EGF) but increased their range of motion while using the Automated Rehabilitation System (ARS) user interface (UI) in comparison to the control condition.



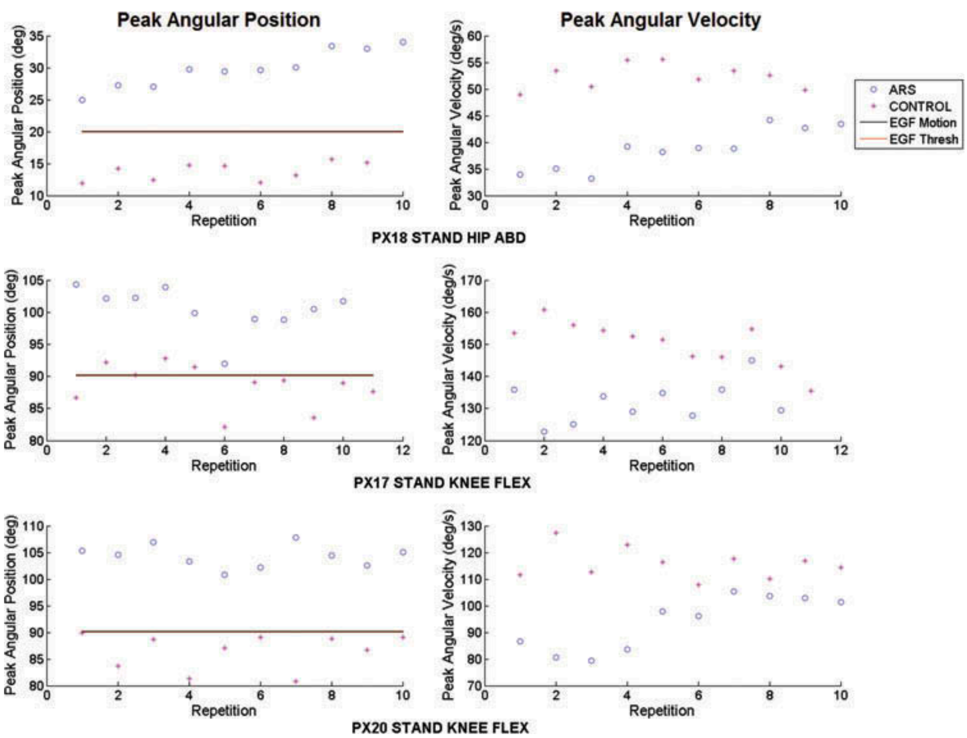
Note. **The first row illustrates the motion performance of Patient 13 performing the SIT KNEE EX exercise, and the second row illustrates Patient 24 performing the STAND HIP FLEX exercise. Both the maximum angular position (left) and peak velocity (right) are plotted for each repetition performed by 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.**

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.

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 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 angular velocity (Equation 3). The hip movement is calculated by taking the difference between the maximum and minimum angular positions, shown in Equation 5. The results are summarized in Figure 16, indicating the percentage of participants whose difference in position (Figure 16(a)) and peak velocity (Figure 16(b))

FIGURE 14. The plots of three data sets illustrating the motion profile of users who were capable of achieving the full range of motion displayed by the exercise guidance feature (EGF) and increased their range of motion while maintaining a lower peak velocity when using the Automated Rehabilitation System (ARS) user interface (UI) in comparison to the control condition.



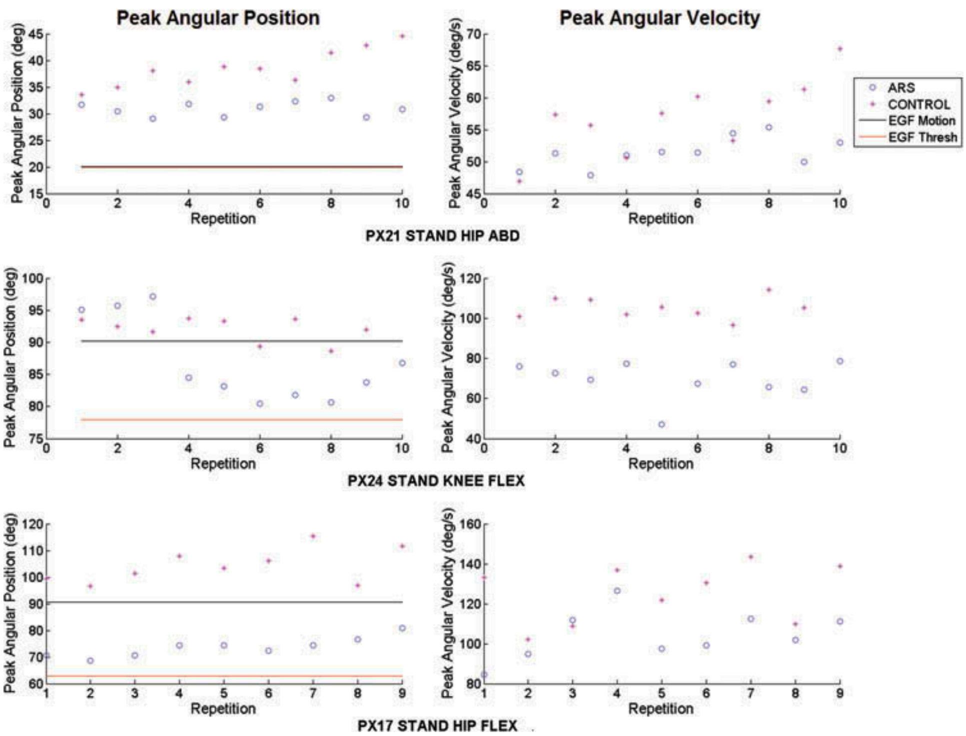
***Note.* Both the maximum angular position (left) and peak velocity (right) are plotted for each repetition performed by the participant. The black line indicates the maximum angular position demonstrated by the EGF, the red line indicates the lower threshold set for the EGF, the blue circle indicates the data of each repetition from the ARS UI condition, and the purple asterisk indicates the data of each repetition in the control condition.**

data were significantly different or showed a trend toward significance at a p value of $p < .05$.

$$\Delta\theta_{hip} = \theta_{max} - \theta_{min}, \text{ for each repetition} \tag{5}$$

Figure 17 shows the hip movement (Figure 17(a),(b)) and peak velocity (Figure 17(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.

FIGURE 15. The plots of three data sets illustrating the motion profile of users who were capable of achieving the full range of motion displayed by the exercise guidance feature (EGF) and decreased their range of motion while maintaining a lower peak velocity when using the ARS user interface (UI) in comparison to the control condition. *Note.* 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.



These results show that using the ARS UI had a positive effect on reducing movement in the compensatory joint for some participants performing knee exercises. Performing exercises with compensatory movement is a common way that patients perform exercises incorrectly, and PTs are constantly instructing their patients to perform the knee exercises without any hip movement. By using the ARS UI, some participants are reducing the compensation moment and thus performing the exercises more correctly.

6.2. User Experience

Protocol

Following the patients' rehabilitation session using ARS, we interviewed them to obtain their feedback. We used a semistructured interview format to allow for a

FIGURE 16. **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 Automated Rehabilitation System (ARS) user interface (UI) and control conditions, at a p value of $p < .05$ of the Wilcoxon rank sum tests, separated by exercise type.**

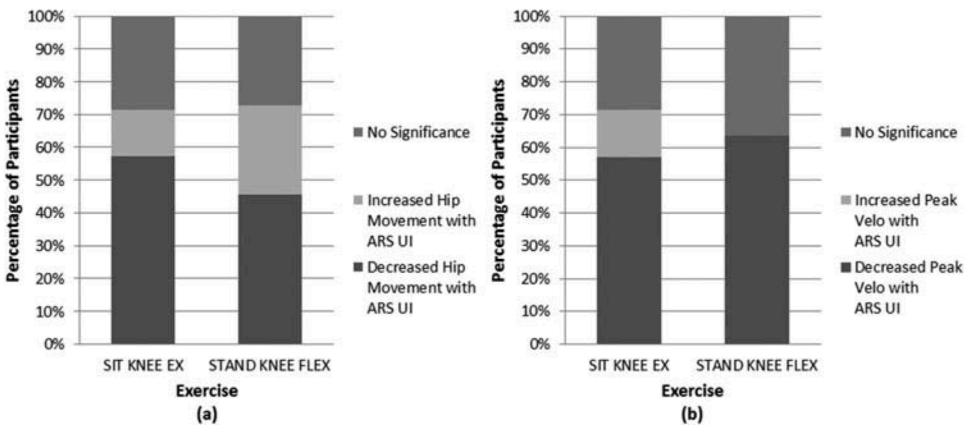
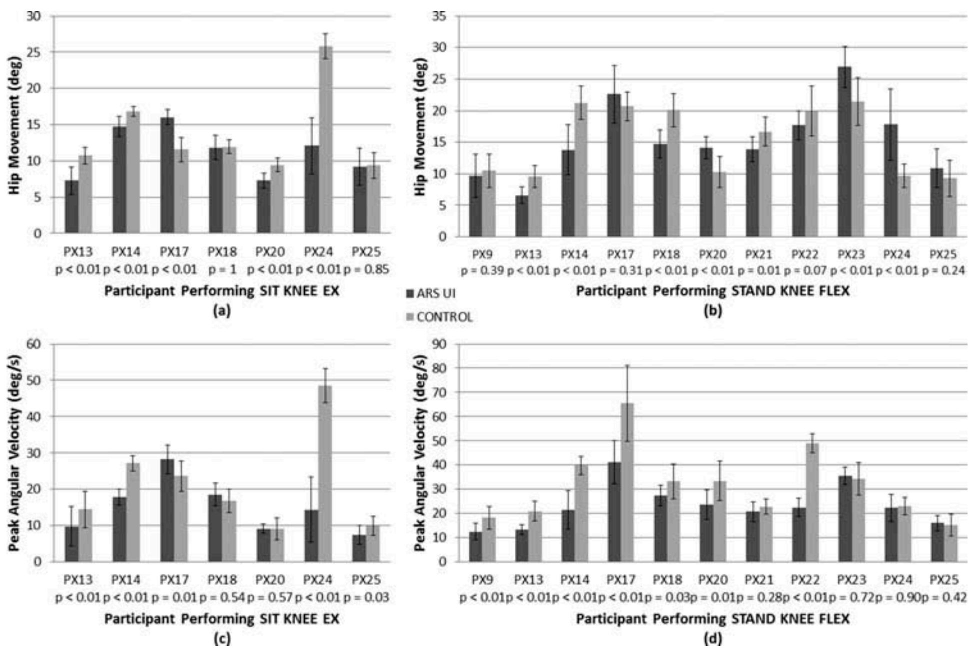
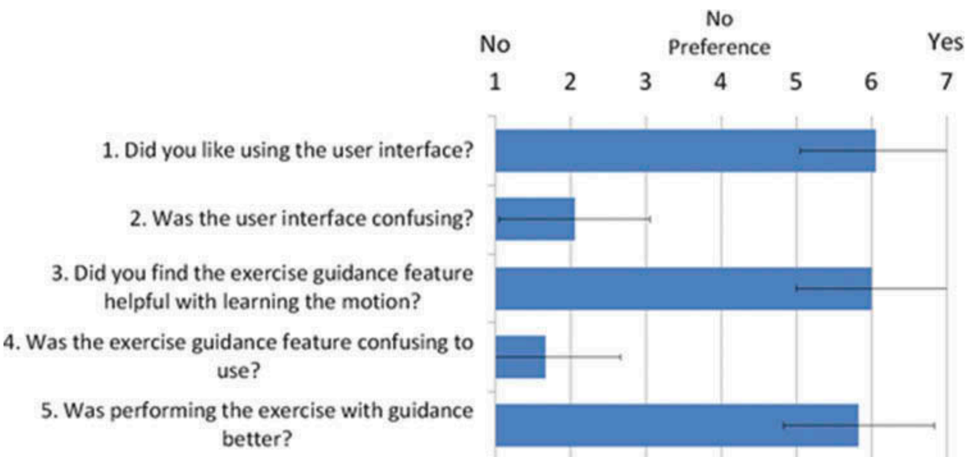


FIGURE 17. **The hip movement (SIT KNEE EX—(a), STAND KNEE FLEX—(b)) and peak velocity (SIT KNEE EX—(c), STAND KNEE FLEX—(d)) in the compensatory joint (hip joint) from participants who performed the knee exercises under both the ARS user interface and control conditions and showed significance or a trend towards significance.**



Note. **The p values of the Wilcoxon rank sum test between the two conditions are reported for each participant. Error bars show standard deviation.**

FIGURE 18. Results of the exercise guidance feature (EGF) questionnaire show that the EGF was positively perceived by the patients.



Note. **Error bars show standard deviation.**

more natural conversation than would be possible with a structured interview. Each interview lasted between 15 and 30 min. 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 five-item questionnaire rated on a 7-point scale (see Figure 18). 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 18 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, "[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."

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, "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. (2014). Although Singh et al. (2014) proposed 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 of Study 1).

According to patients, the EGF's 5-s 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 s, 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 Section 3, 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"). Last, 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 4 weeks after surgery). In contrast to the PTs' comments from Study 1, 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 toward the timer feature: It is not useful. P7 said, "It wouldn't matter to me whether I am doing it in 3 minutes or 5 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 best 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 (Ananthanarayan et al., 2014; Ayoade & Baillie, 2014), ARS no longer displays the timer feature. Moreover, corroborating the PT's stance 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 (Ananthanarayan et al., 2014; Ayoade & Baillie, 2014; Piqueras et al., 2013).

7. 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 repetition duration while exercising with a guidance system was already reported in the work of Ayoade, Uzor, and Baillie (2013), 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 but the movement was slower when the patient is performing 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 reported only 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 members 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 members 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 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 that this group of patients was achieving the increased range of motion in the control condition only 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 and 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, performing the exercise more correctly and effectively.

Similar to the findings reported by Singh et al. (2014) with respect to progress feedback, our studies revealed that patients and their PTs hold a fundamentally different philosophy regarding progress feedback. On 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 are 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 perform each exercise under both conditions, as they were assigned fewer than 20 repetitions and we did not want to modify the exercise regimen assigned by the PT. We felt that using the ARS UI for fewer than 10 repetitions 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 pairwise 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, to which they previously did not have access. In current clinical practice, the quantitative data gathered by PTs during rehabilitation sessions are static, for example, measuring joint angles using goniometry (Norkin & White, 2009). 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 provide PTs with data on the position, velocity, acceleration, and duration of each repetition of the patient's exercise sets. This new data stream can assist PTs with assessment, diagnosis, and treatment planning.

8. CONCLUSIONS AND FUTURE WORK

This article presents a system designed for both PT and patient use in the rehabilitation clinical setting. The PT interface of ARS allows the PT to customize exercises and exercise regimens for their patients, as well as review the data collected by ARS to track the progress of their patients through motion data. The patient interface provides patients with visual guidance and feedback while performing rehabilitation exercises. A focus group was conducted with PTs to elicit system requirements for both the PT interface, as well as the patient interface.

Following the focus group, a user study was conducted with rehabilitation patients to evaluate the effects of exercising with ARS and EGF and to 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 repetition duration for a subset of the exercises. This results in the patient performing the exercises in a more controlled manner. The position data also revealed that three type of users emerged from 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 also showed that using the ARS UI helped some patients reduce the compensatory movement while performing knee exercises. All of these quantitative results have positive effects on patient rehabilitation. 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.

Future work includes performing a longitudinal study with rehabilitation patients. Instead of evaluating the effects of ARS with patients for one 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, we would be interested in 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.

Future work also includes conducting a user study with PTs to evaluate the usability of the PT interface during clinical use. 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. We would like to study how PTs would use the additional data of their patients' quality of 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.

NOTES

Background. This article is based on the master's thesis of the first author.

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APPENDIX A. TABLE OF PATIENT DEMOGRAPHICS FROM STUDY 2

TABLE A1. Demographics of the Patients Who Participated in Study 2.

PX No.	Surgery Type	Age	Gender	No. of Repetitions
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

Note. The participants who performed fewer than 20 repetitions of each exercise are considered low-functioning patients, and participants who performed 20 or more repetitions of each exercise are considered high-functioning patients.

APPENDIX B. QUESTIONS FROM THE SEMISTRUCTURED INTERVIEW OF STUDY 2

B1. 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?

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?

B2. Exercise Guidance Feature Questionnaire

Did you like using the user interface?

Was the user interface confusing?

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

Was the exercise guidance feature confusing to use?

Was performing the exercise with guidance better?