Providing Real-time Exercise Feedback to Patients Undergoing Physical Therapy

by

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To my parents and brother, for their continuing guidance and support.

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List of Abbreviations

- AHRS: Altitude and Heading Reference System
- DOF: degree-of-freedom
- IMU: Inertial Measurement Unit
- IRB: Institutional Review Board
- PI: Principal Investigator
- POM: Plane of motion
- POME: Plane of motion error
- PT: Physical Therapist
- ROM: Range of motion
- UK: University of Kentucky

Abstract

Musculoskeletal conditions, often requiring rehabilitation, affect one-third of the U.S. population annually. RehabBuddy is a rehabilitation assistance system that extends the reach of a physical rehabilitation specialist beyond the clinic. This thesis presents a system that uses body-worn motion sensors and a mobile application that provides the patient with assistance to ensure that home exercises are performed with the same precision as under clinical supervision. Assisted by a specialist in the clinic, the wearable sensors and user interface developed allow the capture of individualized exercises unique to the patient's physical abilities. Beyond the clinical setting, the system can assist patients by providing real-time corrective feedback to repeat these exercises through a correct and complete arc of motion for the prescribed number of repetitions. An inertial measurement unit (IMU) is used on the body part to be exercised to capture its pose. Presented is a kinematics data processing approach to defining custom exercises with flexibility in terms of where it is worn and the nature of the exercise, as well as real-time corrective feedback parameters. This thesis goes through the engineering approach, initial student investigator trials, and presents new preliminary subject data from subject trials currently ongoing at the University of Kentucky. The system is tested on multiple exercises performed by multiple subjects. It is then demonstrated how it can improve exercise adherence by assisting patients in reaching the full prescribed range of motion and avoid overextension, assist in adherence to the ideal plane of motion, and affect hold time.

Chapter 1: Introduction

Musculoskeletal injury rehabilitation, such as the one used to treat rotator cuff tendinopathy, requires highly individualized intervention to address patient-specific physical limitations such as dressing, toileting, grooming, and occupational demands to return to normal function. The current methods of home exercise instruction do not provide adequate monitoring or flexibility to support individualized patient education programs. When a patient performs home exercises, there is no feedback to ensure that exercises are performed correctly, which has been identified as a barrier to exercise adherence [1]. Lack of confidence or low self-efficacy has been directly connected with poor exercise adherence and poor treatment outcomes [2, 3]. This issue is further supported from the social cognitive theory perspective, which identifies that in order to change behavior, an intervention has to address issues of self-efficacy to be effective [4, 5]. Extending this concept to rehabilitation by providing exercise feedback beyond the clinic to empower the patient to manage their injury requires a novel approach that introduces automation while maintaining personalization by the rehabilitation specialists for the patient.

In the clinical setting, rehabilitation specialists such as physical therapists (PTs), occupational therapists, athletic trainers or physicians prescribe and individualize exercises in order to minimize the patient's pain and address their current level of disability [6]. Throughout rehabilitation, these exercises are constantly modified based on the patient's response, symptoms, and physical capacity [7]. The patient is asked to perform the same exercises at home or outside of clinical supervision to facilitate recovery [8]. There are many methods used to illustrate home exercise performance and encourage exercise independence. The most common form is written instruction using static images with arrows. However, clinicians must constantly modify an illustration or rewrite verbal instructions to meet individual patient needs following exercise instruction. This can potentially confuse the patient and reduce their confidence in performing the exercises independently. In addition, treatment adherence with prescribed home exercises is a common concern [1] and is associated with poor patient outcomes [2, 3].

It is this at-home portion of physical therapy exercise that was targeted and addressed in the project undertaken in this masters' thesis. Presented in this paper is the realization of a system that extends the reach of the healthcare provider by providing both real-time feedback on individualized prescribed exercises and a less burdensome method to monitor exercise adherence.

The approach, named as RehabBuddy, as illustrated in Figure 1, is based on body-worn inertial measurement units (IMUs) capable of body motion capture outside of a laboratory environment. This device is attached to the body around the joint being rehabilitated, such as the arm in the case of a shoulder injury. The IMU data is processed to find the three degree-of-freedom (DOF) rotation of the exercise, as well as other parameters such as the body pose relative to inertial space (e.g., whether the patient is lying down or standing). The current standard of care in the clinic is that the patient is educated by the healthcare provider to perform the exercises correctly. Once the patient is instructed, RehabBuddy is designed to allow the healthcare provider to record prescribed home exercises tailored to a particular patient at a specific time in their recovery schedule. With the aid of a mobile application, the RehabBuddy will provide patients with reminders to perform the correct number of repetitions of each exercise, while providing a graphical demonstration of the exercises to help the patient to recall them and providing real-time feedback on how accurately they are performing the exercises. These elements are expected to have an impact on compliance and ultimately on patient outcomes.

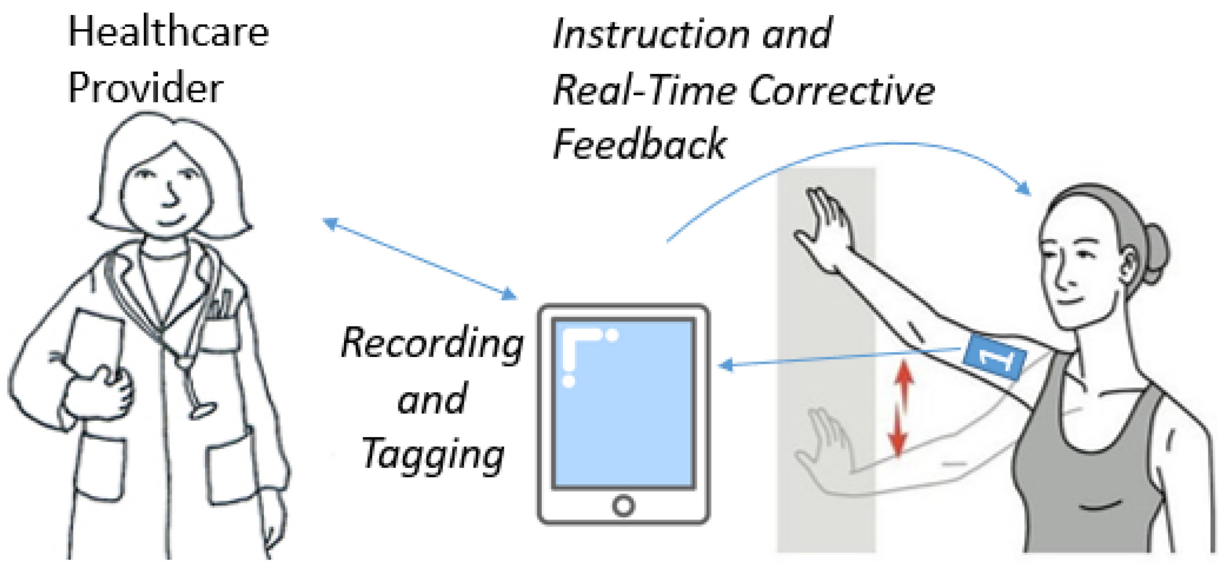

Figure 1. RehabBuddy extends the reach of the rehabilitation specialist to the home. In the clinic, the patient is prescribed exercises, which are recorded by the system. Beyond the clinic, the system assists the patient in performing the correct number

To realize RehabBuddy, the final system is a fulfillment of the following list of requirements that will reappear throughout this paper as the guiding design objectives for the project:

- *Define* the prescribed form of the exercise as closely guided by the PT.
- *Compare* the exercise as performed in real-time by the patient to this saved prescribed form as the patient attempts the exercise motion by tracking motion between start and target position.
- *Inform* the patient in near real-time of the difference between their current position and what position they should be holding for that given point in time according to the prescribed exercise.

1.1 Contributions

Currently, a patient's visit entails progress assessment and training on a set of exercises that the patient is expected to carry out until the next visit. The prescription is highly individualized and depends on the phase of healing, current symptoms, and functional level. Unfortunately, exercise adherence is often low, negatively affecting patient outcomes as will be discussed in detail in the next section.

RehabBuddy combats this by introducing a new step into the visit, where the healthcare provider instruments the patient with the wearable IMUs at the joint of interest. Then, the mobile application on a tablet is placed in a training mode to allow the healthcare provider to sequentially move the patient through the specific exercise. The tablet user interface is designed to allow the healthcare provider to indicate the beginning and target poses and specify the number of repetitions to be performed each day and hold times for each exercise. These parameters serve as reminders for the patients when they are on their own and are also used to build feedback visualizations. It will be demonstrated that this feedback improves the fidelity of exercise performance to the exercise prescribed by a PT.

Chapter 2: Clinical Literature Review

Healthcare providers incorporate home exercise programs to promote patient self-reliance and improve the patient's functional scale by reducing physical impairments of weakness or inflexibility [9, 10]. The effectiveness of home exercise in improving function, reducing pain, and returning toward normal function is well established and a critical adjunct to clinic-based rehabilitation [11, 12, 13]. However, two consistent problems arise in treating patients and evaluating treatment effectiveness: (i) objective measure of adherence and (ii) low exercise adherence [2, 14]. Measuring exercise adherence is challenging, as it is currently limited to a self-report diary, which is often an overestimation of activities and burdens the patient [15]. A system that objectively records prescribed home exercises would provide an accurate representation of the exercise dosage being performed outside the clinic. Exercise adherence is commonly poor, with a completion rate ranging from 33–66% in patients with musculoskeletal injuries [16, 17]. Greater exercise adherence improves outcomes [18]. The primary factors associated with low adherence to home exercises in patients with musculoskeletal disorders are (i) discomfort when performing the exercise, (ii) time barriers to performing exercises, (iii) lack of confidence in performing exercises alone, and (iv) dependence on health care provider input to resolve challenges with the patient's disability [1]. These factors, along with the manner in which the healthcare provider provides directions to the patient and the patient's motivation to carry out the treatment intervention, directly affect adherence [19].

Providing biofeedback is beneficial to improving the patient's physical limitations and can be done in many forms [20]. Specifically, inertial sensors have been used to improve the patient's balance and modify incorrect movements and postures in the clinical setting [21, 22, 23, 24]. While in the clinical setting, patients have input from the healthcare provider when exercising. However, a greater need exists at home for similar input to be offered. RehabBuddy can objectively monitor exercise adherence and can be used at home to provide exercise feedback without the presence of a healthcare provider.

Some related work identifies motivation as a primary challenge for physical therapy beyond the clinic and addresses motivation by "gamification" of the exercises. While it is arguable that boredom or enjoyment are not critical elements of motivation [1], several projects have investigated ways on how to turn rehabilitation exercises into a game. For example, several projects are "gamifying" rehabilitation by using a visual motion capture system (Microsoft Kinect) and developing video games controlled by motion gestures [25, 26]. Other notable instances include a system for ankle sprain rehabilitation [27], balance training of adults with neurological injuries [28], fall rehabilitation [29], and "RIABLO" games for orthopedic exercises [30].

Such rehabilitation games which can motivate patients, provide feedback, and track progress, are particularly proving useful in cases where general movement is desired or coarse accuracy is acceptable, such as with patients recovering from a stroke. However, musculoskeletal rehabilitation is prescribed with deliberate motions and postures to target specific muscles while avoiding specific arcs of motion that can further damage healing tissues [31]. RehabBuddy is designed for explicit motions to be replicated later by the patient to remind them how to perform exercises correctly and warn them if moving beyond the safe range. Incorrect exercise and the lack of proper precautions have led to rotator cuff re-tears in post-operative patients. [32]. Therefore, a more targeted and precise approach is needed.

Chapter 3: Engineering Background

Wearable sensor technology used for activity monitoring may be an option to assess data on exercise adherence. The use of inertial sensors for motion capture and analysis is well documented in the literature [33, 34] [35, 36, 37, 38, 39, 40] and includes commercial fitness activity trackers. Examples related specifically to physical therapy include several projects [41, 42, 43, 44] designed to track patient activity for the purpose of remote monitoring by the healthcare provider, yet with no real-time feedback component. The primary limitation and challenges with passive monitoring systems are that they are prone to gross false-positive detections because of the large amount of time the devices must be active and the presence of activities of daily living that must be discerned from the rehabilitation exercises. RehabBuddy addresses this by being an interactive system instead of a passive listener as the patient performs the exercises. Our system is started by the patient indicating they are ready, and the system prompts the patient to begin progressing through the exercise poses while monitoring quality and quantity of performance.

Iosa et al. published an extensive literature survey on the medical use of inertial sensors in human movement analysis [45]. They identified a wealth of literature on patient monitoring and assessment in post-processing, and concluded that "…it is conceivable that in the next few years, wearable inertial devices will allow human movement analysis to go a step further, from assessment to a combined approach including assessment and rehabilitation at the same time."[*45*] Another recent survey of wearables used for upper extremity rehabilitation includes some systems that provide feedback [46]. However, none targets musculoskeletal rehabilitation, which requires patients to exercise targeted muscles by moving and holding precise postures. Rather, the prior work discussed is primarily targeting patients recovering from a stroke, where gross movement is desired, and motivation is the main concern. There is a void in the literature on effective methods for real-time patient guidance and feedback for musculoskeletal rehabilitation is an open research area.

Some emerging rehabilitation systems are based on visual approaches for motion capture, such as using the Xbox Kinect or a similar technology [47, 48]. While there is potential with these approaches, there are limitations, which are overcome using wearable inertial sensors. (i) The use of IMUs is portable and not constrained to a specific location; patients often perform their exercises at the workplace and on the go. (ii) Items used in rehabilitation, such as elastic bands or wheelchairs, are known to interfere with a vision-based motion capture system. (iii) Also, some exercises utilize elements of the environment, such as rolling a ball on a wall to strengthen the shoulder or tying a resistive band to a door handle. It is difficult to guarantee that a vision-based motion capture system such as a Kinect will have a clear view for all types of exercises needed. RehabBuddy overcomes the limitations of visual motion capture systems with the freedom and portability of body-worn IMUs without infrastructure assistance.

Using wearables, a system named PT-Vis uses visualization approaches for a feedback system for knee injury rehabilitation [49, 50]. Through trials with six knee injury patients, they found great utility and promise in using wearable sensors to provide visual and numeric feedback on joint angle and progress to assist with knee rehab. The patients report positive experiences on the usefulness of feedback. However, PT-Vis uses a flex sensor to provide a single degree of freedom (DOF) measurement of the knee angle. Flex sensors and similar approaches such as an optical linear encoder (OLE) [51] would not work for a multi-joint structure with more degrees of freedom like the shoulder. Also, with RehabBuddy, we go beyond providing feedback only on range of motion to also provide feedback on taking the correct pose along the correct plane of motion. This requires sensing in more degrees of freedom, which IMUs provide.

Using IMUs, the Rehabilitation Visualization System (RVS) utilizes two sensors to track knee exercises [52, 53]. RVS provides patients with a demonstration of the exercise and on a separate screen provides real-time feedback on the range of motion for the knee and leg elevation. In a randomized clinical trial, they found improved outcomes for patients who used RVS, which is encouraging for our proposed general solution. Interactive Virtual Telerehabilitation (IVT) is a similar system that also uses IMUs, intended for tele-rehabilitation, and is used to track knee exercises [54]. The third project in this category is the Automated Rehabilitation System (ARS), which also focuses on knee exercises and is intended for use in the clinic where the physical therapist is training several patients at once. RVS, IVT, ARS, and a fourth unnamed similar project

[55] are all designed specifically for the knee, with pre-defined exercises but with no ability to tune them (except for ARS) or capability to define custom exercises. They demonstrate the potential and effectiveness of a wearable approach using IMUs. With RehabBuddy, the goal is a general solution to be able to mount the sensor on any joint and prescribe an arbitrary arc of motion. This provides the ability to individualize physical therapy to a patient-centric approach which is key for wide applicability and use.

Each wearable sensor node is based on a set of orthogonal inertial sensors, commonly referred to together as an Inertial Measurement Unit (IMU). Pose estimation is done using a sensor fusion algorithm, where the 3 degree-of-freedom orientation/pose of the device can be tracked in inertial space. The sensor suite and algorithm are commonly used in unmanned vehicle control systems to provide stability and are often referred to as an Attitude and Heading Reference System (AHRS). This pose estimator is used to process the raw data (rotation rates, acceleration, and magnetic field) and produce the orientation angles in a world reference frame defined by the gravity vector and magnetic north. The sensor fusion algorithm utilizes knowledge of dynamics to propagate the orientation changes based on the rate gyroscope data and fuses the propagated estimate with the direct orientation estimate based on the accelerometer and compass. This way, the AHRS can tolerate shocks and vibration and maintain a stable estimate of the device's orientation. The RehabBuddy's worn sensors measure and report their 3DOF orientation, typically referred to as "pose". Off-the-shelf units, Shimmer3 IMU made by Shimmer Sensing, were used to design this system.

Chapter 4: Mathematical Modeling and System Design

The core measurement that each IMU along with its sensor fusion algorithm produces is the orientation/pose estimate in three-dimensional space $\mathbb{R}3$ in the world reference frame. The pose can be represented in several ways, including a Direction Cosine Matrix, Euler Angles, the Eigen Axis and Angle representation, and Quaternions [56]. We note that conversion between these forms of representing pose is a direct calculation. The orientation of an object, like RehabBuddy's worn sensor units, is represented as a rotation in $\mathbb{R}3$ between the world reference frame and the object's body frame. In this discussion, we use Quaternions to represent orientation. An orientation quaternion can be defined as**:**

$$\boldsymbol{q} = q_w + \boldsymbol{i}\, q_x + \boldsymbol{j}\, q_y + \boldsymbol{k}\, q_z \qquad \text{Eq. 1}$$

$$\boldsymbol{q} = cos\left(\frac{\theta}{2}\right) + \boldsymbol{i}\, e_x\, sin\left(\frac{\theta}{2}\right) + \boldsymbol{j}\, e_y\, sin\left(\frac{\theta}{2}\right) + \boldsymbol{k}\, e_z\, sin\left(\frac{\theta}{2}\right) \qquad \text{Eq. 2}$$

$$\theta = angle(\boldsymbol{q}) = 2\cos^{-1} q_w \qquad \text{Eq. 3}$$

where **q** is an orientation quaternion defined by a rotation around the axis $\vec{\boldsymbol{e}} = [e_x, e_y, e_z]$ by an angle θ. Eq. 1 relates the mathematically favorable Quaternion form for orientation representation with the more intuitive representation of orientation, the Eigen-axis ($\vec{\boldsymbol{e}}$) and Angle (θ) representation (Eq. 2), which represents a 3DOF rotation by a single rotation about an arbitrary axis. The Eigen-axis represents the plane of motion between two reference frames, while the angle represents the range of motion (Eq. 3).

Defining the ideal exercise is defining the quaternion that encapsulates that exercise motion from the start position to the target position. Comparing this ideal quaternion to the quaternion representing their current position, the difference between the correct form and the actual form is found. To inform the patient of their error, this difference quaternion can be translated to an error in degrees. To inform the patient of where they are in the exercise, this difference quaternion can be compared with a reference quaternion (start or target position) to give the ROM (range of motion) in either degrees or percent of the final pose (where 100% indicates they are at the target position).

However, there are issues using quaternions in the world reference frame to this end. Most patients are accustomed to performing directions relative to their current pose, not with respect to a universal outside coordinate system they are oriented within. Take an exercise starting with an arm resting at the patient's side and moving up to be parallel to the floor, a 90-degree abduction. If in the course of setting down the tablet after the exercise is defined, the patient turns their body so that they are 90-degrees from their initial position, despite still having their arm by their side and therefore considering themselves still in the start position, the IMU sees this as a difference as great as moving the arm to the final pose, as the patient is 90-degrees from the start pose recorded in the initial directional frame of reference. Therefore, the POME reads at a 90-degree error, telling the patient they are severely off track and potentially greatly confusing them. The patient should always have a POME and ROM of 0-degrees in the start position if their arm is by their side in that pose regardless of their direction. In short, the quaternions must be transformed to place the poses of an exercise into the personal frame of reference that provides intuitive and therefore meaningful feedback to the patient.

The initial method described below in First Approach: Reference Sensor Method attempts to change the frame of reference via a reference IMU affixed to the patient's body. The second method, described below in Second Approach: Set Start Position Method, attempts to change the frame of reference via an adjustable start position the patient sets while performing the exercise. The reasons for adopting the second approach over the first one for the application are based on the issues discussed at the end of the First Approach section, and both are worth discussing as this first approach was the basis of the project and the second approach followed from the first.

4.1 First Approach: Reference Sensor Method

The original design for the system involves two IMU sensors. The system is designed to deal with differences between the world reference frame and the frame relative to the patient by relating the IMU around the limb being tracked to a fixed reference IMU. For a shoulder exercise, the sensor tracking the patient's exercise movement is placed around the patient's forearm, and the stationary reference sensor is placed around the patient's chest, as shown in Figure 2. By taking the difference between the quaternion describing the reference and the quaternion describing the patient's arm position, all exercises are moved out of the world reference frame and into the reference frame of the stationary quaternion, a process described mathematically in Eq. 4.

$$ {}_{e}\mathbf{q}(t) = {}_{w}\mathbf{q}(t_{reference\_IMU})^{-1}\ {}_{w}\mathbf{q}(t_{moving\_IMU}) \qquad \text{Eq. 4} $$

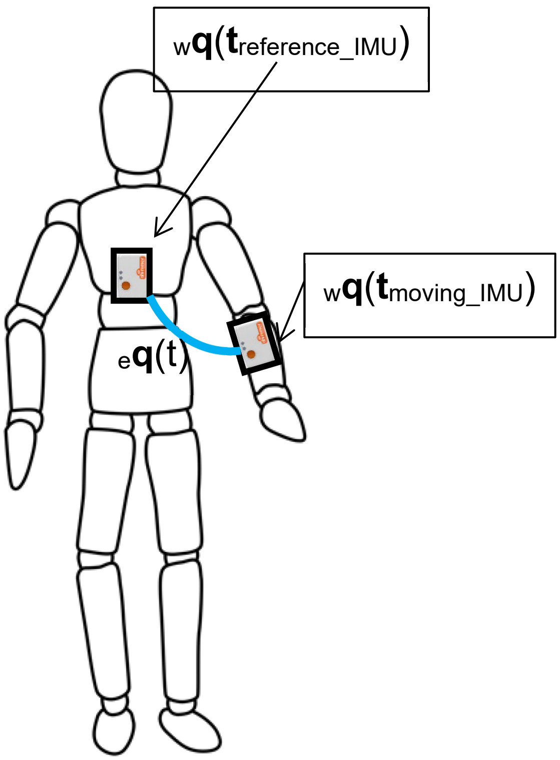

Figure 2: IMU sensor placement and exercise declaration for two-sensor method

The motion of the exercise is now described in terms of the difference between the patient's arm and center, denoted by the e as the exercise frame of reference as opposed to w, the world frame. The **t** denotes time dependence and the continual updating of this measurement as the patient moves. This time dependance contrasts with saved static quaternions such as the one used to define the exercise arc that will be discussed next. The new frame of reference is easier to think about than translating the units for the exercise's arc of motion in the larger world reference frame. It also solves the issue of slight movements of the patient throughout the exercise, for example going to get a drink between exercises and coming back to a slightly different position, causing large errors in the exercise as initially defined from the original orientation. As long as the patient keeps the sensors fixed in the same locations, they remain in the correct reference frame regardless of their direction, which is not true in the world reference frame.

4.1.1 Exercise Capture and Tagging

To create the exercise, the difference between the start and target position is recorded as the exercise arc.

$$ {}_{e}\mathbf{q}_{start} = {}_{e}\mathbf{q}(t_{at\_moment\_user\_is\_at\_start}) \qquad \text{Eq. 5} $$

$$ {}_{e}\mathbf{q}_{target} = {}_{e}\mathbf{q}(t_{at\_moment\_user\_is\_at\_end\_pose}) \qquad \text{Eq. 6} $$

$$ {}_{e}\mathbf{q}_{exercise\_arc} = ({}_{e}\mathbf{q}_{start})^{-1}\, {}_{e}\mathbf{q}_{target} \qquad \text{Eq. 7} $$

Once this exercise arc in Eq. 7 is defined and stored, the patient can go to the start position and begin to go through the exercise motion. As the quaternions are streamed from the IMUs, the transformation in Eq. 4 continuously moves them from the world reference frame to the reference sensor frame. Calculating the distance from this current position to the target quaternion in Eq. 8, this quaternion describes the arc of motion for the orientation of the patient relative to the target pose. The exercise arc quaternion in Eq. 7 describes the orientation of the patient relative to the target pose for the ideal exercise.

$$ {}_{e}\mathbf{q}_{arc\_to\_target}(t) = ({}_{e}\mathbf{q}(t))^{-1}\, {}_{e}\mathbf{q}_{target} \qquad \text{Eq. 8} $$

These two quaternions describe the same arc of motion if the patient is following the correct exercise arc and differ if the patient is diverging from the path established as the correct arc. By comparing the current arc of motion in Eq. 8 to the ideal one in Eq. 7, and quantifying how far off path the patient is, correct feedback can be expressed to help the patient correct their exercise form.

4.1.2 Detecting Plane of Motion, Range of Motion, and Counting Repetitions

To get this feedback in an intuitive form, both arcs of motion are converted to angle-axis form. Eq. 7 yields Eq. 9 and Eq. 8 yields Eq. 10. If these two axes around the arc of rotation are aligned on top of one another, the arc of motion the patient is currently performing is following the exercise defined. If they are not aligned, that means the current path the patient is following differs from the correct exercise motion. Taking the angle of the dot product between these two axes gives the difference between the correct POM and the current POM, which is the POME in Eq. 11. This error in degrees communicates to the user that they need to change their current pose until the error in degrees is close to zero. The error increases proportionally if the patient continues to move off-path.

$$\vec{\boldsymbol{e}}_{\text{arc\_to\_target}} = \text{axis}({}_{\text{e}}\mathbf{q}_{\text{arc\_to\_target}}) \qquad \text{Eq. 9}$$

$$\vec{\boldsymbol{e}}_{\text{exercise\_arc}} = \text{axis}({}_{\text{e}}\mathbf{q}_{\text{exercise\_arc}}) \qquad \text{Eq. 10}$$

$$\theta_{\text{POME}} = \text{acos}(\text{dot}(\vec{\boldsymbol{e}}_{\text{exercise\_arc}}, \vec{\boldsymbol{e}}_{\text{arc\_to\_target}})) \qquad \text{Eq. 11}$$

The ROM the patient is currently positioned at is the distance from the start position to the current position which is equal to the total ROM of the exercise minus how far the exercise has yet to go. This can be calculated by comparing the angle of the current position to the target (Eq. 12) and the angle of the total exercise ROM (Eq. 13) for a final current ROM in degrees as calculated in Eq. 14.

$$\theta_{\text{arc\_to\_target}} = \text{angle}({}_{\text{e}}\mathbf{q}_{\text{arc\_to\_target}}) \qquad \text{Eq. 12}$$

$$\theta_{\text{exercise\_arc}} = \text{angle}({}_{\text{e}}\mathbf{q}_{\text{exercise\_arc}}) \qquad \text{Eq. 13}$$

$$\theta_{\text{ROM}} = \theta_{\text{exercise\_arc}} - \theta_{\text{arc\_to\_target}} \qquad \text{Eq. 14}$$

This angle is how far from the initial start pose the user has moved. The patient uses this to track how close to the target pose they are, and in conjunction with the angle for POME, can help the user move along the correct POM and reach the target position, avoiding motions in an incorrect direction via POME feedback and overextension or under extension via ROM feedback.

The primary issue with this method is finding a stationary location on the body for the reference sensor. A slight movement of the sensor can lead to considerable error because both sensors have an unknown and changing bias with respect to the world reference frame and the exercise reference frame, so it’s hard to quantify error for that relative measurement. And correcting it requires realigning the sensors to be in the same agreement they originally were when the exercise was defined, which is hard to do. This is a source of frustration during exercise, as the sensor often moves slightly on the chest mid-performance, especially when positioned over the shirt. Different reference points such as the thigh or ankle were tested as well, but slight unconscious foot movements during the exercise yield similarly inaccurate results. And if the sensor has moved and cannot be placed directly back in the original position, redoing the entire exercise definition is currently the only solution. This issue leads into the method described in the next section, the development of a method that makes it easier to account for movements of the reference by saving a reference position at the start position that can be reset if the patient adjusts that position and finds the measurements to be incorrect, instead of relying on the continuous stream of quaternions from a reference sensor. This has the added benefit of removing the need for the reference sensor altogether, although adjustments to the ROM and POME calculations are needed to work with this new method as discussed in the next section.

4.2 Second Approach: Set Start Position Method

4.2.1 Exercise Capture and Tagging

In the new single sensor method, the difference quaternion between start and target is calculated and represents the ideal range and plane of motion path that encapsulates the correct form of the exercise:

$$ {}_{e}\mathbf{q}_{\text{exercise\_arc}} = {}_{w}\mathbf{q}(t_{\text{ exercise definition start pose}})^{-1}\ {}_{w}\mathbf{q}(t_{\text{ exercise definition target pose}}) \qquad \text{Eq. 15} $$

$$ {}_{e}\mathbf{q}_{\text{target}} = {}_{e}\mathbf{q}_{\text{exercise\_arc}} \qquad \text{Eq. 16} $$

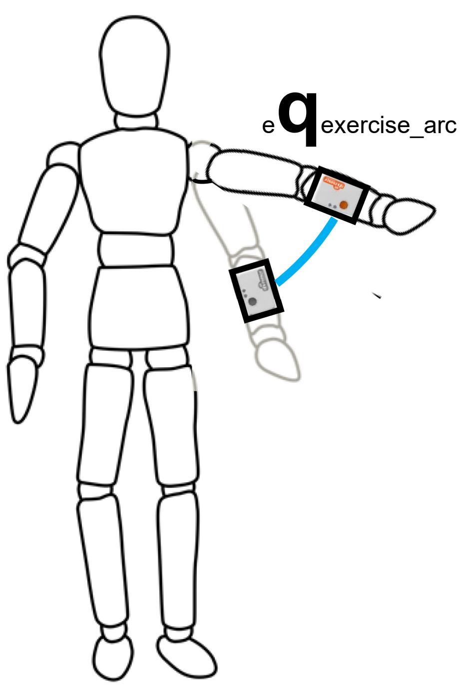

Figure 3: IMU sensor placement and exercise declaration for single sensor method

where ${}_{w}\mathbf{q}(t_{\text{ exercise definition start pose}})$ is the quaternion captured while the patient is standing in start pose in the world reference frame, and ${}_{w}\mathbf{q}(t_{\text{ exercise definition target pose}})$ is the target quaternion captured while the patient is standing in the final target pose, both defined in the world reference frame. The difference quaternion ${}_{e}\mathbf{q}_{\text{exercise\_arc}}$ is the difference quaternion between the two, which represents the target pose relative to the start pose as the reference frame. This effectively defines the exercise reference frame and ${}_{e}\mathbf{q}_{\text{target}}$ as the target pose in that frame which represents the ideal motion of the exercise in a single quaternion.

4.2.2 Detecting Plane of Motion, Range of Motion, and Counting Repetitions

Defining an exercise reference frame allows an account for differences in start position from when the exercise is defined to when it is utilized in tracking the motion during exercise execution. When the patient wishes to begin exercising, they need to stand in the new start pose and indicate this on the app to capture the exercise execution start pose:

$$_{w}\mathbf{q}_{start} = {}_{w}\mathbf{q}(t_{\text{ exercise execution start pose}}) \qquad \text{Eq. 17}$$

$$_{e}\mathbf{q}(t) = {}_{w}\mathbf{q}_{start}{}^{-1}\ {}_{w}\mathbf{q}(t) \qquad \text{Eq. 18}$$

$_{w}\mathbf{q}(t_{\text{ exercise execution start pose}})$ is the quaternion that the patient sets as the start pose upon beginning to perform the exercise which we define as the start pose $_{w}\mathbf{q}_{start}$. This new start pose $_{w}\mathbf{q}_{start}$ is used to transform the current pose of the sensor $_{w}\mathbf{q}(t)$ in the world reference frame to find $_{e}\mathbf{q}(t)$, which represents the orientation of the IMU in the exercise execution reference frame. This single sensor method is sensitive to changes in the patient's position in the world reference frame without the reference sensor. However, to adjust for the change in position, the patient can simply overwrite the start pose defined in Eq. 17 and continue performing the exercise. Contrast this to the method with the reference sensor where an issue in the position of either sensor resulted in the exercise having to be redefined to account for the new difference between the two sensors, which resulted in the need to restart the exercise completely, instead of simply resetting the start position as many times as needed.

It is now possible to calculate the exercise feedback variables based on the quaternions shown in Eq. 16 and Eq. 18. The method is based on conceptualizing a triangle of quaternions representing (i) the rotation from start pose to target pose $_{e}\mathbf{q}_{target}$, (ii) the rotation from the start pose to the current sensor pose $_{e}\mathbf{q}(t)$, and (iii) the rotation from the current pose to the target pose $_{e}\mathbf{q}_{error}(t)$ defined as:

$$_{e}\mathbf{q}_{error}(t) = {}_{e}\mathbf{q}(t)^{-1}\ {}_{e}\mathbf{q}_{target} \qquad \text{Eq. 19}$$

$$\theta_{ideal} = \text{angle}({}_{e}\mathbf{q}_{target}) \qquad \text{Eq. 20}$$

$$\theta_{current}(t) = \text{angle}({}_{e}\mathbf{q}(t)) \qquad \text{Eq. 21}$$

$$\theta_{error}(t) = \text{angle}({}_{e}\mathbf{q}_{error}(t)) \qquad \text{Eq. 22}$$

$$\text{ROM error} = \theta_{ideal} - \theta_{current}(t) \qquad \text{Eq. 23}$$

$$\text{POME} = \theta_{current}(t) + \theta_{error}(t) - \theta_{ideal} \qquad \text{Eq. 24}$$

Calculate the relative pose between $_{e}\mathbf{q}(t)$ and $_{e}\mathbf{q}_{target}$ to find $_{e}\mathbf{q}_{error}(t)$ which reflects the error between the patient's current pose and the exercise target pose which the patient should be in as defined in Eq. 19. Range and plane of motion information are converted from quaternion representation to the more intuitive angle-axis form. The angle of ${}_{e}\mathbf{q}(t)$ in angle-axis form (Eq. 21) represents the total angle by which the patient has moved from the start pose, without regard to the axis of rotation. This is the range of motion (ROM) as described by the system. Quaternion ${}_{e}\mathbf{q}_{error}(t)$ is the error in both range of motion and plane of motion relative to the target pose. Translating the quaternion to angle-axis form and taking the angle of ${}_{e}\mathbf{q}_{error}(t)$ (Eq. 22) represents the total angle by which the range of motion differs from the target pose. It is how many degrees the patient must move before they reach the target pose.

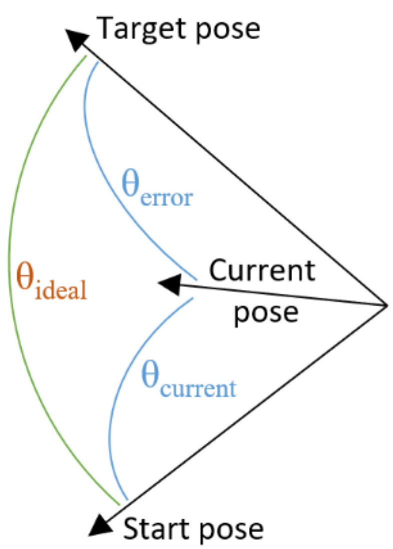

Figure 4. Illustration of angle measurements between the start pose, current pose, and target pose. The three are used to estimate the plane of motion error.

Figure 4 illustrates the angle measurements used to estimate the plane of motion error. If the patient moves perfectly in the correct arc of motion, the sum of $\theta_{error}(t)$ and $\theta_{current}(t)$ should equal θ_{ideal}, being the ROM from start to target expressed in degrees. But θ_{ideal} is the shortest path between the start and target poses along the POM, so if the patient is off-plane, the path in degrees from start pose to current pose to target pose will be a longer one than the optimal path. This can be visualized as a triangle between the start pose, target pose, and current pose. By subtracting this ideal angle from the angle of the total displacement in degrees, $\theta_{current}$ plus θ_{error}, the difference gives a measure of the error in the plane of motion. This value is reported back to the patient as the error by which they must adjust their current pose to once again be correctly following the ideal path of motion. This is defined as the plane of motion error (POME) in Eq. 24.

In summary, with the IMU reporting current orientation at a rate of approximately 50 Hz, the patient's progress from their start pose to their target pose and back again can be detected, as $\theta_{current}(t)$ starts at zero at the start pose increases until it matches that of θ_{ideal}. This method is an improvement over the two-sensor method and was used in the design of an application programmed using a simple state machine that tracks the patient's progress from start pose to target pose to back to start pose. This application will be described further in the next section and is the basis for the Results based on trials undertaken by both the PIs and patients in the pilot program.

4.3 The RehabBuddy Application

Given the above mathematical solution and the stated goal to introduce it to inform patients as they exercise and evaluate if it improves exercise adherence, it was necessary to build a user interface capable of this. The first project was built in MATLAB, but due to the overhead of a laptop and working with a GUI most users are going to be unfamiliar with, it was determined that switching to an Android application would be preferable. An Android application was selected as most patients are familiar with mobile apps, there is a lot of Android development support, and there are a wide variety of affordable tablets compatible with an Android app. University of Michigan-Dearborn undergraduate students Sarah Makki and Max Theisen helped to translate the original application from MATLAB to Android. The RehabBuddy application was designed to accomplish three primary tasks. One, have a setup method to allow a PT to create and store exercises performed correctly as quaternions using the method from the Single Sensor Method Section to define the exercises. Two, have a series of options to allow the patient to indicate they are attempting an exercise and either (i) received real-time feedback based on the ROM and POME calculated from their current positions they used to correct their exercise form while performing the exercise, (ii) received PT feedback, not application feedback or (iii) received no feedback at all and performed the feedback without any outside guidance. And three the application should be consistently capturing, tagging, and storing the time series quaternion data streaming as the patient performs the exercises for all three conditions so that the investigators can evaluate the effect of application feedback versus PT feedback or no feedback at all. These three main components, as well as session set up and conclusion, were accomplished in the following design.

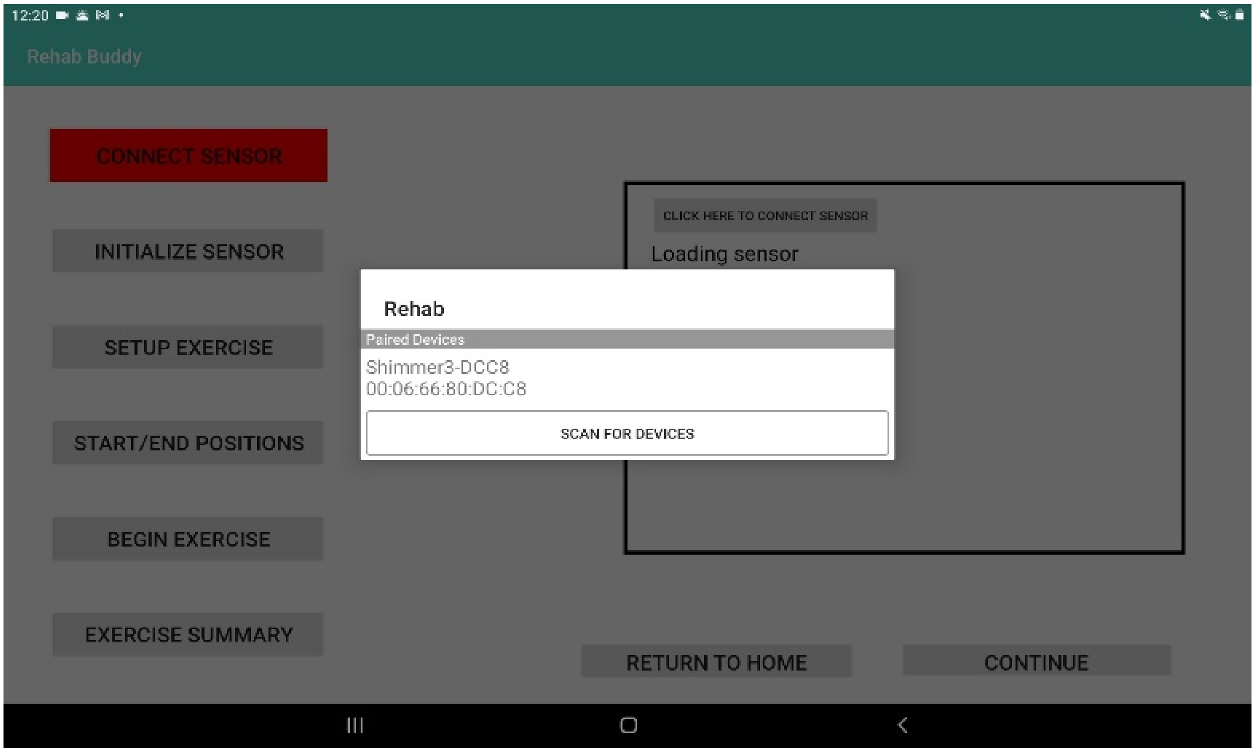

Figure 5: Screenshot of Bluetooth sensor connection interface

4.3.1 Initialization

The Shimmer sensors used for this project came with an Android API to connect the Shimmer to a phone or tablet sensor via Bluetooth. After a brief period of allowing the data to stream so that the AHRS system can being getting accurate data, the sensor could then stream the data shown in columns B through E below. This data is processed by the tablet via the Madgwick IMU-AHRS sensor fusion algorithm to compute the quaternions from the IMU data. This information was saved to the csv and used in the creation of the feedback that will be discussed in the Exercise Performance section.

A	B	C	D	E	F	G	H	I
exercise	qtw	qtx	qty	qtz	time	event	rep	set
flexion	0.282253	0.486726	-0.02441	0.826339	1.62161E+12	hold_top	8	0
flexion	0.28263	0.486687	-0.02475	0.826222	1.62161E+12	hold_top	8	0
flexion	0.282683	0.48638	-0.0255	0.826363	1.62161E+12	moving_dc	8	0
flexion	0.28279	0.486527	-0.0261	0.82622	1.62161E+12	moving_dc	8	0

Figure 6: Example of the RehabBuddy application data log

4.3.2 Exercise Setup and Definition

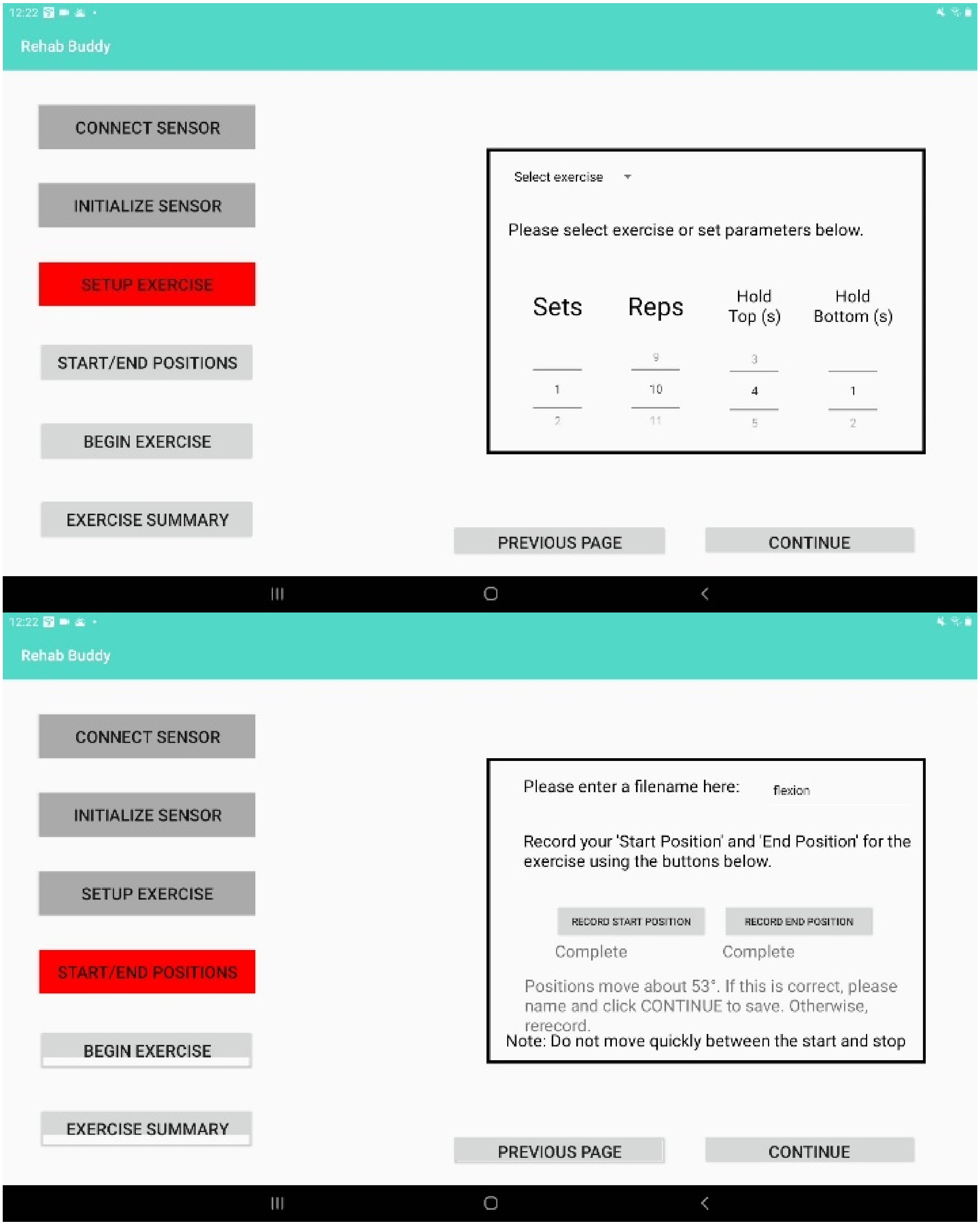

Figure 7: Exercise parameters (top) and tagging of start and target poses (bottom)

To create the exercise, first the healthcare provider names the exercise and sets the number of repetitions to be performed as well as the length of time the patient should hold the start and target poses while performing the exercise. Then, the healthcare provider moves the patient into the start pose and presses the record start button, at which point the app defines the start pose by taking the average of the quaternions captured while the patient is holding their arm still in this start pose. Next, the healthcare provider guides the patient through the motion of the exercise until their arm is in the stop pose and uses RehabBuddy to record the stop pose in the same way. The application then uses these two quaternions to calculate the "exercise arc" quaternion encompassing the trajectory of the exercise performed correctly as described in the above Section on the Single Sensor method. This ideal exercise quaternion is named and saved to a csv with the exercise's repetition and hold time parameters.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
name	qStartw	qStartx	qStarty	qStartz	qEndw	qEndx	qEndy	qEndz	qIdealw	qIdealx	qIdealy	qIdealz	angIdeal	holdTop	holdBotto	reps	sets
practice	0.464817	-0.50072	0.47328	-0.55608	0.133715	-0.64014	0.75487	0.049944	0.712172	-0.674	-0.09338	0.172584	1.556385	3	3	10	1
prone ext	0.429571	-0.52844	0.492536	-0.54186	0.118421	-0.66594	0.736212	0.020789	0.754129	-0.63266	-0.11391	0.134144	1.432861	3	3	10	1
flexion	-0.46456	0.658893	-0.31479	0.500842	0.296332	0.573052	-0.11203	0.755777	0.653709	-0.27966	0.356297	-0.60609	1.716507	3	3	10	1

Figure 8: Exercise definition file used to define and reconstruct PT recorded exercises

This saved exercise can now be selected from a menu and the patient can proceed to a page with a screen containing a line graph of the range of motion path of the exercise and a bar graph depicting the error in the plane of motion.

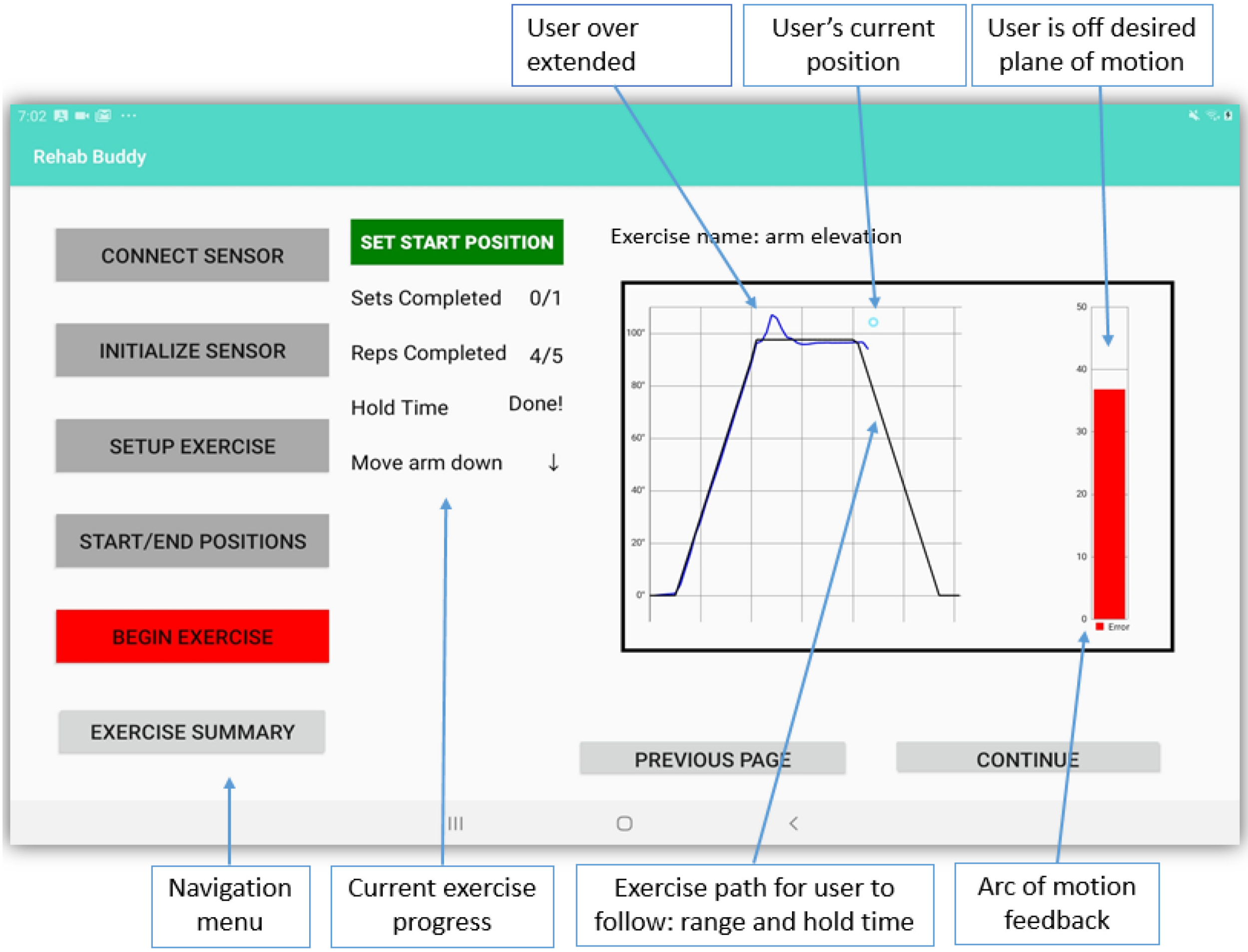

Figure 9: RehabBuddy exercise feedback screen

4.3.3 Exercise Performance

When the exercises are recorded in the application, the patient continues to the exercise feedback screen. Figure 9 shows this feedback system as it is currently designed in the app. The panel in the middle tracks the patient's sets and reps and has a countdown timer that helps the user track how long they should hold at the target pose. To the right of that is the guide path that shows the user their current range of motion and guides them to move to their target, the plateau at which they will then hold before following the range of motion path back down to the start pose. Providing reliable feedback about how long they have been holding their poses will encourage patients to hold those poses longer. The horizontal axis of the step function indicates the progress the patient has made towards completing an exercise repetition. If the user moves in a direction that indicates they are not making forward progress, the cursor halts and moves above or below the line, indicating the incorrect direction of movement, and the line fails to make progress. This feedback visually shows the patient to adjust the exercise. The vertical axis is a percentage scale from 0% ROM at the start position to 100% ROM at the target position. The path from start to target to start again is incremental and tied to them moving in the correct direction.

To the right of the guide path is the error bar, which shows the patient the magnitude of how far from the plane of motion their current pose is, which helps them adjust their current pose toward the plane of motion. Due to the freedom with which the sensor is placed and the exercise is defined by the PT, directions such as move "arm left to get into position" are not possible, but because the feedback is near real-time the patient can move their arm slightly forward or back and see if that decreases the error and the error bar goes down, indicating they are moving in the correct direction to get back on the correct plane of motion, or if that slight movement causes the error to increase, indicating the patient is moving in the wrong direction. Plane of motion is important as some patients, in particular, those who experience pain may perform exercises incorrectly to avoid pain by compensating with another joint.

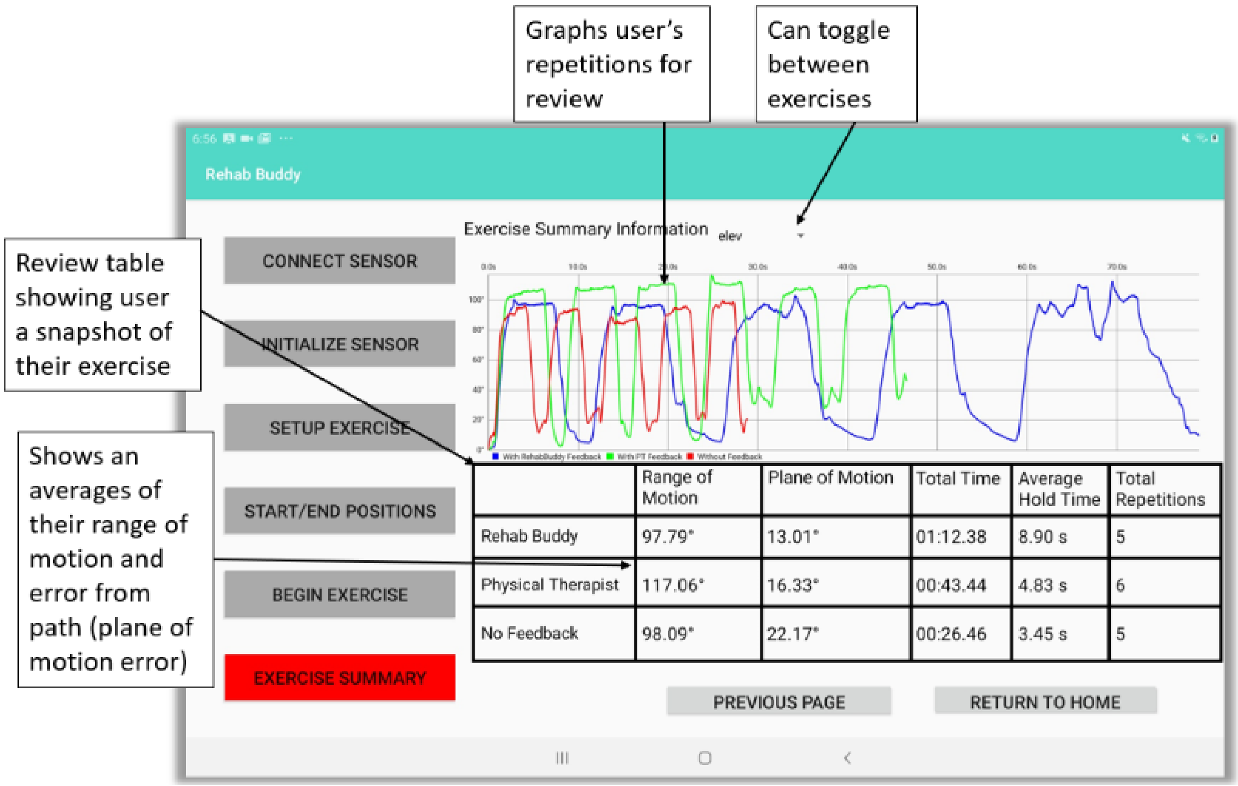

Figure 10: RehabBuddy application exercise summary screen

4.3.4 Exercise Conclusion

Once the patient has completed the total number of repetitions assigned to the exercise, they are free to use the Back button to go back to the exercise selection list and select another exercise from the list. Or they can hit the Continue button to go to an exercise screen, where they can review their overall performance as well as average ROM and POME. The graph also shows them comparisons of the repetitions they did with RehabBuddy assisting them and without, so they have a visualization of the aid the system provides and how accurate their exercise performance is with and without assistance.

4.3.5 Additional Software Update

After subject trials that will be introduced and discussed in the Evaluation section, it became apparent partway through testing that the small adjustments to the arm's position in the start pose create the appearance of a large POME. This POME was concerning to patients who complained about the RehabBuddy feedback being prone to error as a result. This complaint has merit as users were encouraged to see a POME of around 20-degrees to be a problem mid-exercise but not at the start of the repetition. To deal with this issue a gamma function was used to suppress POME at the start of the exercise which is shown in Eq. 25. All angles are in degrees, and the function is designed to affect the first 20 degrees the most as this was the point at which the POME caused by a slightly incorrect POME was most apparent. The 4th power is used because running the data from a series of trials that had this issue through a series of gamma functions with different powers from 1 to 10 with a step of 0.5 indicated this was the most acceptable solution. The issue was discovered after the start of subject trials, and this quick solution proved effective.

$$20\cdot\mathrm{minimum}(\theta_{current}(t), (\theta_{current}(t) /20)^4)/(\theta_{ideal}) \qquad \text{Eq. 25}$$

This implementation was used only in the feedback for the patient. The data presented in Evaluation is post-processed separately and the gamma function is not implemented.

Chapter 5: Evaluation

5.1 Experimental Procedure

Once a working application was built, a series of trials were undertaken to demonstrate the system's ability to guide the patient to perform exercises to the correct range of motion and hold times while detecting when they move out of plan. This section lays out the general procedure followed. It was first used in the lab with the principal investigators serving as test subjects and then later in the clinic with therapy patients recruited for a pilot study.

First, the Shimmer IMU is affixed to a limb of interest, typically directly below the elbow on the forearm but varying with exercise. Then, the application discussed in the section RehabBuddy is launched from a Samsung Galaxy Tab A Model SM-T510 with 32GB storage, Octa-core (2x1.8 GHz Cortex-A73 & 6x1.6 GHz Cortex-A53) CPU, and 2 GB RAM. Following the prompts by the app, the PT connects the IMU to the tablet via Bluetooth. They select Create New Exercise, type in an exercise name, and set the number of repetitions and the hold time they wish the application to use at the start pose and the target post. Then the PT guides the patient to stand in the start position, which they then tag by pressing "Set Start Position". The patient was then guided by the PT into their target pose, which is tagged by pressing "Set End Position".

This data collection process results in quaternions labeled as the definition of the exercise saved in the Exercises csv file, as well as time-series data of the quaternions streaming as the exercise is performed, labeled by the exercise, and saved in the Data csv file. This Data csv file log can then be processed with the equations discussed above to recreate the exercise as recorded by the IMU, from both the trials where RehabBuddy is providing feedback as well as the trials that are passively recorded for the comparison data without feedback. Clinical data is processed the same way as student trials, except there is a third condition where the patient is given PT guidance that is processed in the same manner as well.

5.2 Establishing a Ground Truth

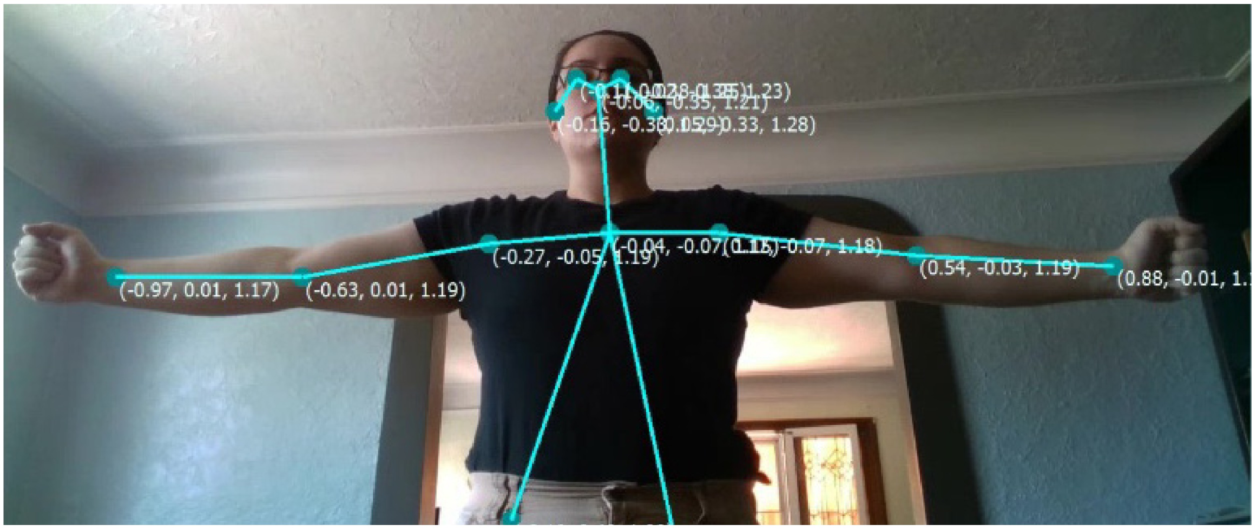

Figure 11. Demonstration of camera-based position reference using skeleton inference and an RGB-D camera.

To validate the IMU sensor output, we used an RGB-D camera as a reference sensor, namely the Intel RealSense. The reported images and depth measurements were processed by Skeleton Tracking software developed by Cubemos. This method was utilized to provide us with a secondary reference. The RGB-D camera frames are fed into the pose estimation software. There, each joint in the frame is detected and estimated in 3D space based on human pose inference and reported depth and RGB measurements. The result is a 3D map of the patient's position as shown in Figure 11. This skeleton, composed of reported joint positions, can be transformed into vectors describing the motion of the person at a given frame. Selecting a pair of joints that are of relevance to the exercise in question, a vector estimating the limb is formed. For instance, the forearm is a vector that can be created between the wrist and the elbow joints. By tracking this vector over time, exercise execution performance can be recorded in a way similar to that limb's motion as tracked by an IMU. To capture an exercise using the RGBD data, first, the shortest angle between the start vector and the end vector is calculated, denoted as $\theta_{start-end}$. Second, each frame's two joints of interest are used to create a limb vector. Third, the shortest angle between this limb vector and the start vector is calculated, denoted as $\theta_{start-limb}$. Fourth, the shortest angle between the limb vector and the end vector is calculated, denoted as $\theta_{limb-end}$. The range of motion θ_{ROM} is the angle between the start and current moving vector (the limb vector) $\theta_{start-limb}$. The plane of motion error $\theta_{POM\ error}$ is the sum of the angles between the start and the current limb position and that limb and the end position, minus the ideal angle between start and end.

$$\theta_{ROM} = \theta_{start-limb} \qquad \text{Eq. 26}$$

$$\theta_{POM\ error} = \theta_{start-limb} + \theta_{limb-end} - \theta_{start-end} \qquad \text{Eq. 27}$$

The ROM and POME calculated using this alternative RGB-D method are graphed on top of the ROM and POME calculated using the IMU data to get a second reference for comparison. We found general agreement between the pose estimates from the IMUs compared to the RGB-D skeleton inference. Figure 12 shows an example recording comparing the two methods for five repetitions of an exercise.

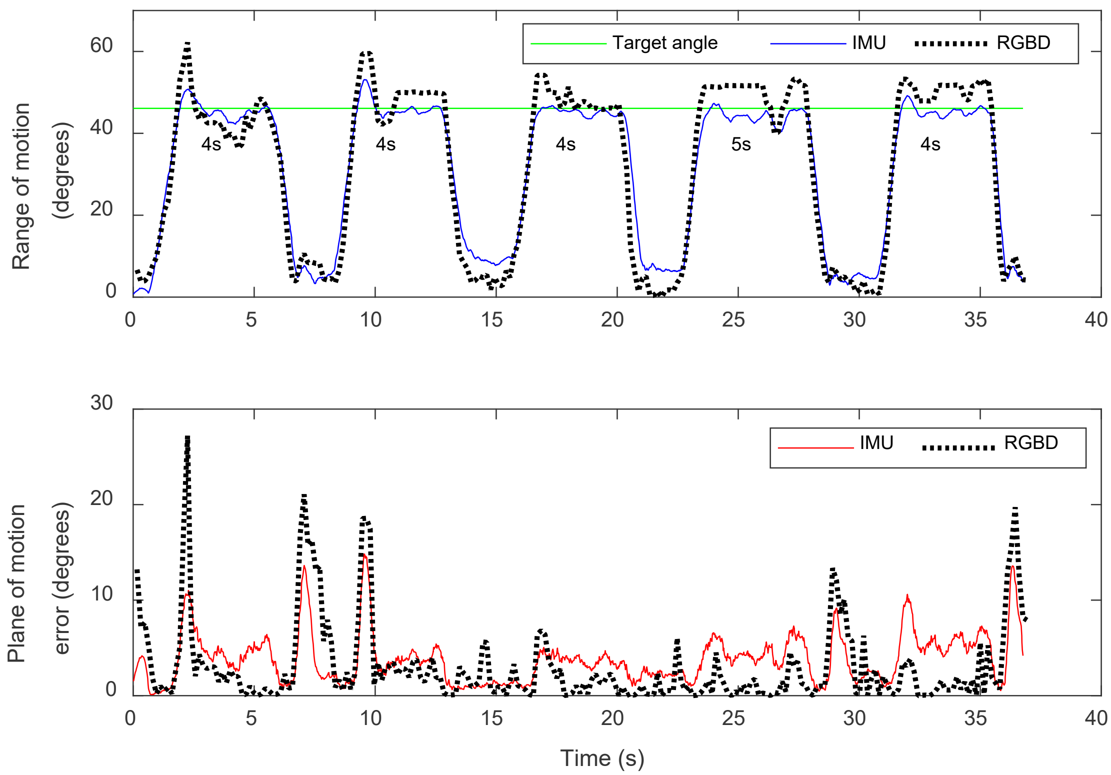

Figure 12. Exercise execution performance comparing RGB-D and IMU estimates. The general agreement provides confidence in the IMU-estimate accuracy.

5.3 Preliminary Student Trial Results

Once the feedback seemed to be working in short informal trials and the ground truth established basic accuracy, the system was tested in a longer series of formally recorded trials to demonstrate its ability to guide the patient to perform exercises to the correct range of motion and hold times while detecting when they move out of the plane of motion. The test subject in the trials is the student researcher for the project. This introduces a bias in that one of the people who would most benefit from the Application performing well is the one testing it. However, with knowledge that clinical trials were already being planned, setting up a formal IRB and recruiting human subjects for the proof-of-concept phase was deemed a prohibitive overhead. The trials were conducted with just the student as a subject to avoid a lengthy approval process in the summer of 2020, with knowledge that this is a trial run for formal trials to begin in fall of 2020. These initial results are described and discussed next.

5.3.1 Demonstration of the Application

Displayed in Figure 13 is an arm elevated into abduction, a common exercise that is defined by the start pose with the arm at the side and the correct target pose as shown in Figure 13b. These are the two poses used to calculate eqexercise_arc as described in the Single Sensor Method a Section IV.B. The exercise describes a forward elevation of around 85 degrees. For demonstration purposes, Figure 13c and Figure 13d also show deliberate incorrect execution of the exercise for demonstration purposes, where the arm is moved out of the desired plane of motion, too far forward, and too far back.

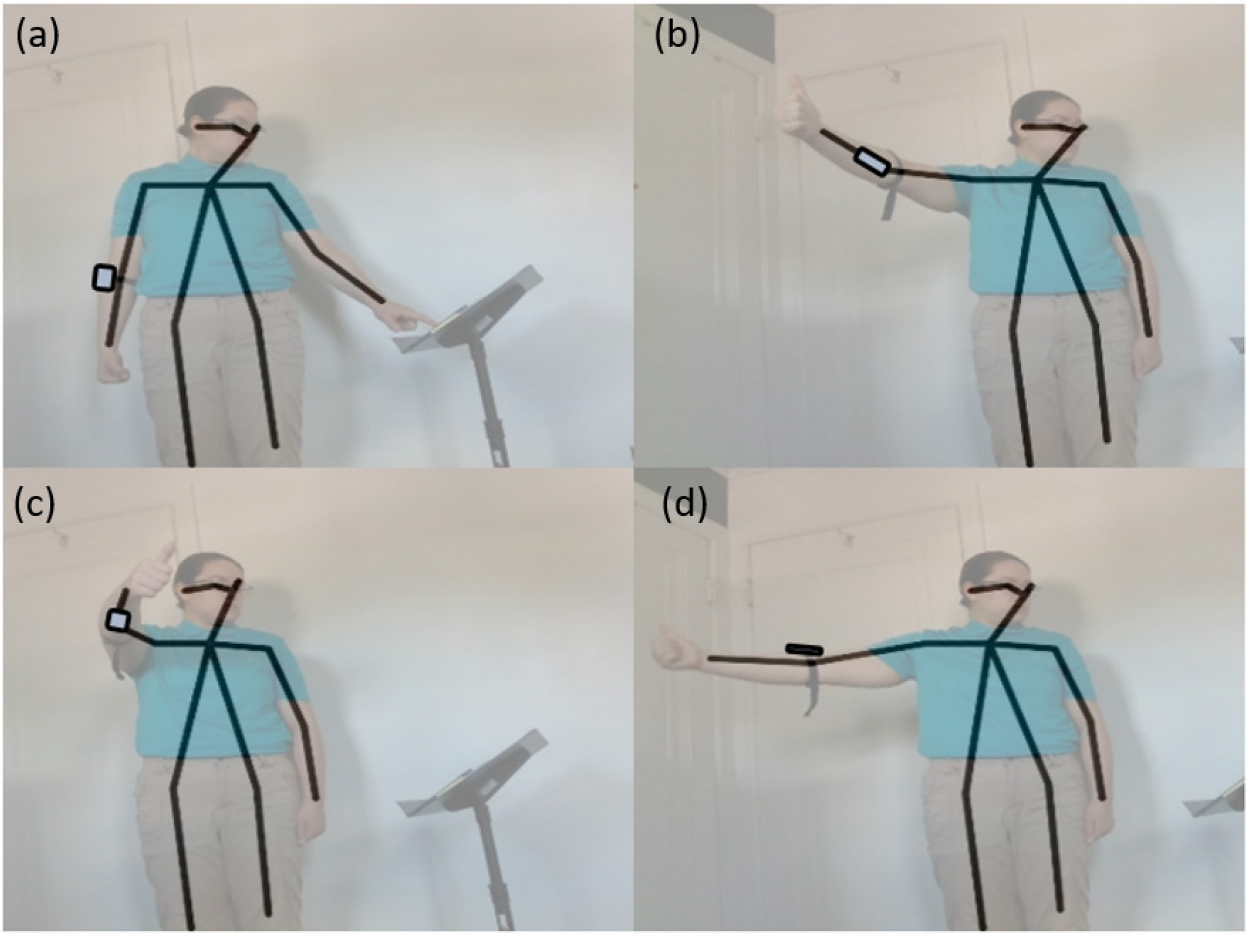

Figure 13. Arm abduction exercise, (a) start pose, (b) target pose, (c) arm too far forward, (d) arm too far backward.

As shown in Figure 14, the feedback error bar reflects the difference between a correct intermediate pose and an incorrect one, and is used as feedback to guide the student to adjust to a pose like that in Figure 13b.

For this demonstration trial, the student performs six repetitions of the exercise highlighted in Figure 13. The student receives feedback for the entirety of the test. The first two repetitions are done as close to correct as possible, the second two are done moving off-plane too far back, and the final two are done off-plane too far forward. Figure 15 shows the resulting range of motion (ROM) and the plane of motion error (POME) plots. The differences in the resulting plane of motion errors graphed in red on the bottom plot highlight the difference between a rep following the correct plane of motion and either of the two types of incorrect ones, despite each repetition achieving the same range of motion.

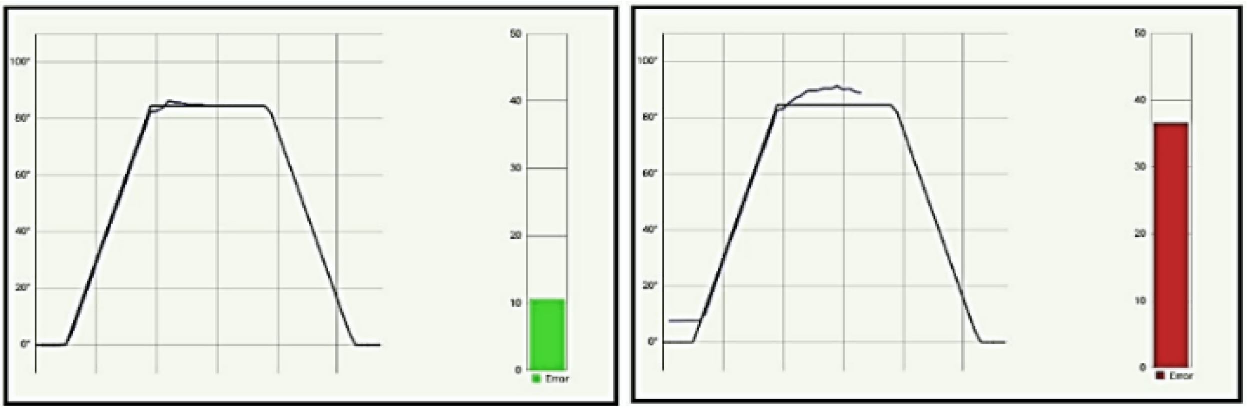

Figure 14. Left: App feedback when correctly holding target pose. Right: App feedback (with red bar plot) when arm is held too far back during target pose.

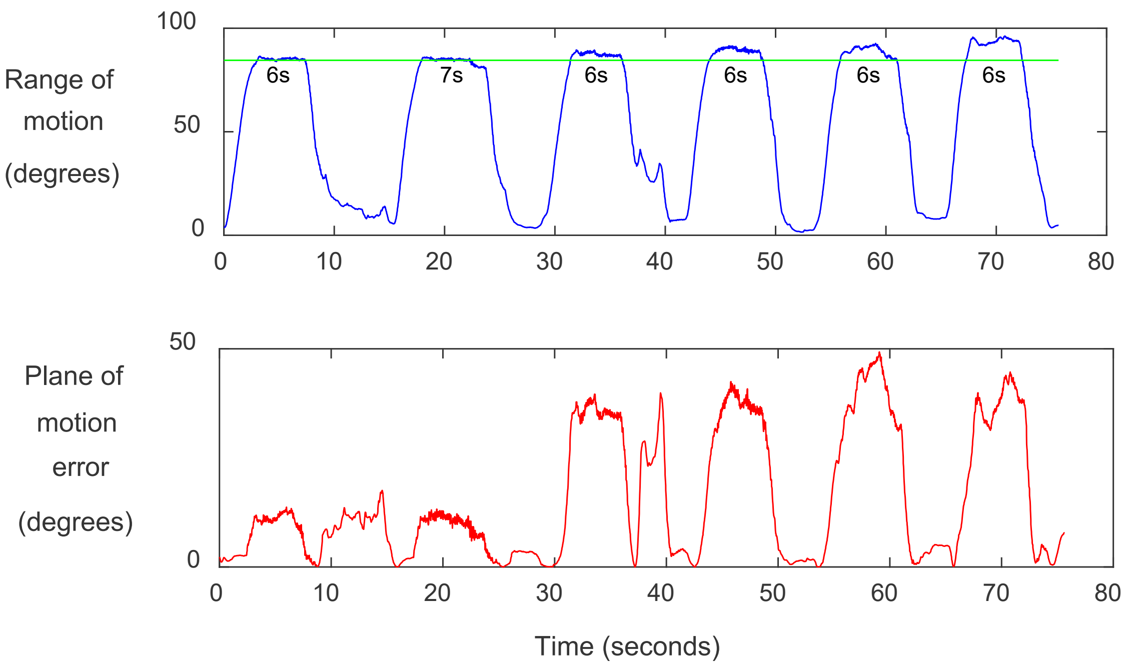

Figure 15. Graph of feedback for repetitions: first two were done correctly, the subject deliberately moved arm too far back for the second two repetitions, and too far forward for the final two repetitions

5.3.2 Trial 1: Arm Abduction

For trial 1, the quaternions are recorded from a trial calculating the ROM and POME while the student follows the exercise with the guide system providing feedback. Then for comparison, the student repeats the exercise again without being given this feedback. The exercise is the same as in the demonstration, a forward flexion of around 85 degrees defined in Figure 13. Figure 16 shows the four resulting graphs of 7 repetitions with and then without feedback. The exercise's range of motion is graphed in blue, and the error generated when moving off the plane of motion is given in red.

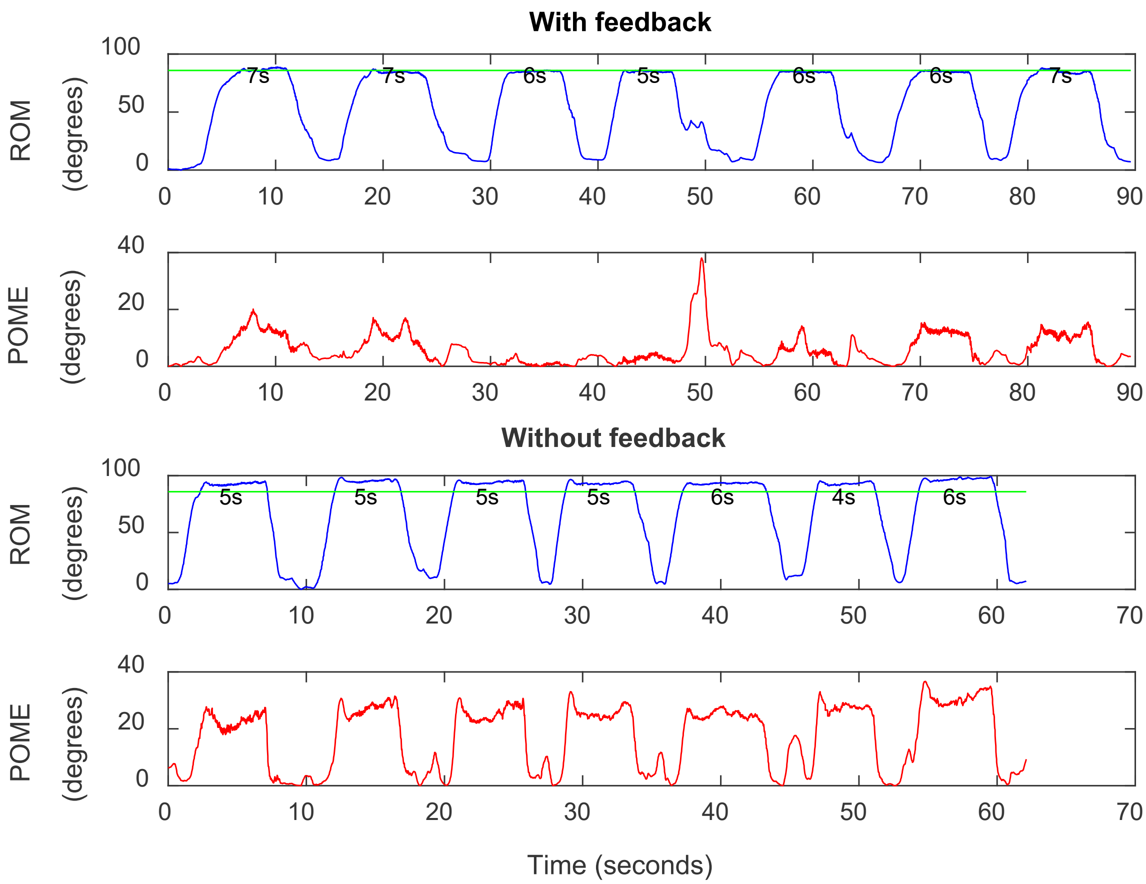

Figure 16. Range of Motion (ROM) and Plane of Motion Error (POME) over time during an elevation exercise

Table 1 below shows a summary of the results for Trial 1. For the range of motion graphed in Figure 16, the average, standard deviation, and the percent error are calculated at a per-repetition basis based on the average range of motion when the user is near the target pose for each of the seven repetitions. This is achieved by taking all values above a certain threshold calculated by taking the average of the highest 90th percentile of the range of motion points recorded. When the exercise was done without feedback, the average range of motion was about 10% higher than it was when the exercise was done with feedback. This shows that the 85-degree target ROM was hard to hit and, in this case, the subject routinely overestimated. In cases where over extension could lead to re-tears, this feedback could be helpful.

For the plane of motion error graphed in red above, the mean and standard deviation are calculated over the entirety of the exercise. The ideal plane of motion error is zero throughout the exercise. When the exercise was done without feedback, the average plane of motion error was more than double the error recorded with feedback. This shows that the feedback system does help keep the user closer to the desired exercise plane of motion by helping them gauge their current success.

Average hold time was calculated as well, based on the length of time the user held each repetition's target pose. In this exercise, the outcomes were similar, although the user did hold about a second longer when using the feedback system.

Table 1. Results for forward elevation exercise with and without feedback. The feedback prevented over-extension, reduced range of motion (ROM) error, and plane of motion error (POME).

Condition	ROM mean (deg)	ROM standard deviation (deg)	ROM error	POME mean (deg)	POME standard deviation (deg)
With Feedback (84.9° target)	83.42	3.71	1.74%	5.72	5.45
Without Feedback (84.9° target)	93.55	2.73	10.19%	17.16	11.32

5.3.3 Trial 2: Diagonal Motion

The first trial was a linear exercise of arm abduction which involves a single plane of motion for the shoulder. For trial 2, we demonstrate the system's capability of allowing clinicians to use any plane of motion with a diagonal proprioceptive neuromuscular facilitation diagonal pattern of flexion/abduction/external rotation. The motion resembles drawing a sword. The exercise's start and target poses are shown in Figure 17. Again, the quaternions are recorded from a trial calculating the ROM and POME while the student follows the exercise with the guide system providing feedback. Then for comparison, this was followed by the student performing the exercise again without being given this feedback.

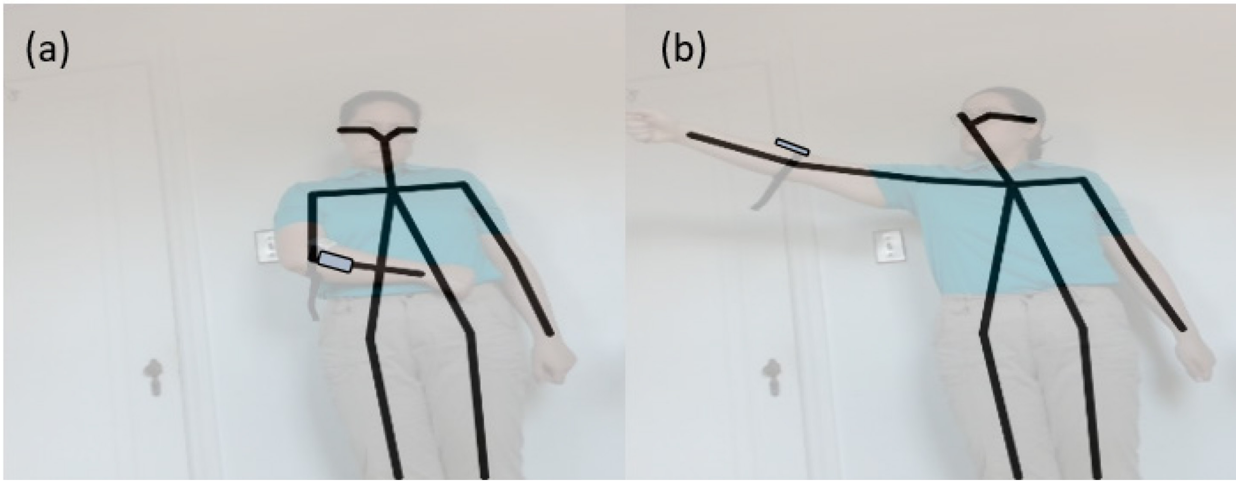

Figure 17. Sword draw exercise, (a) start pose, (b) target pose

Figure 18 shows the four resulting graphs of five repetitions with and without feedback. Table 2 is a summary of the ROM calculated in the same manner as described for trial 1. This time the student is close to the desired ROM of 146 degrees graphed in green with and without feedback. However, the average hold time is about 50% longer when using the system feedback. For the POME, without feedback, the student has about twice as much average error as they did when they were following the guided feedback reference.

Table 2. Results for sword draw exercise with and without feedback. The feedback prevented over-extension, reduced range of motion (ROM) error, and plane of motion error (POME).

Condition	ROM mean (deg)	ROM standard deviation (deg)	ROM error	POME mean (deg)	POME standard deviation (deg)
With Feedback (146.1° target)	145.6	8.94	0.34%	11.2	7.3
Without Feedback (146.1° target)	148	14.5	1.3%	19.2	13.1

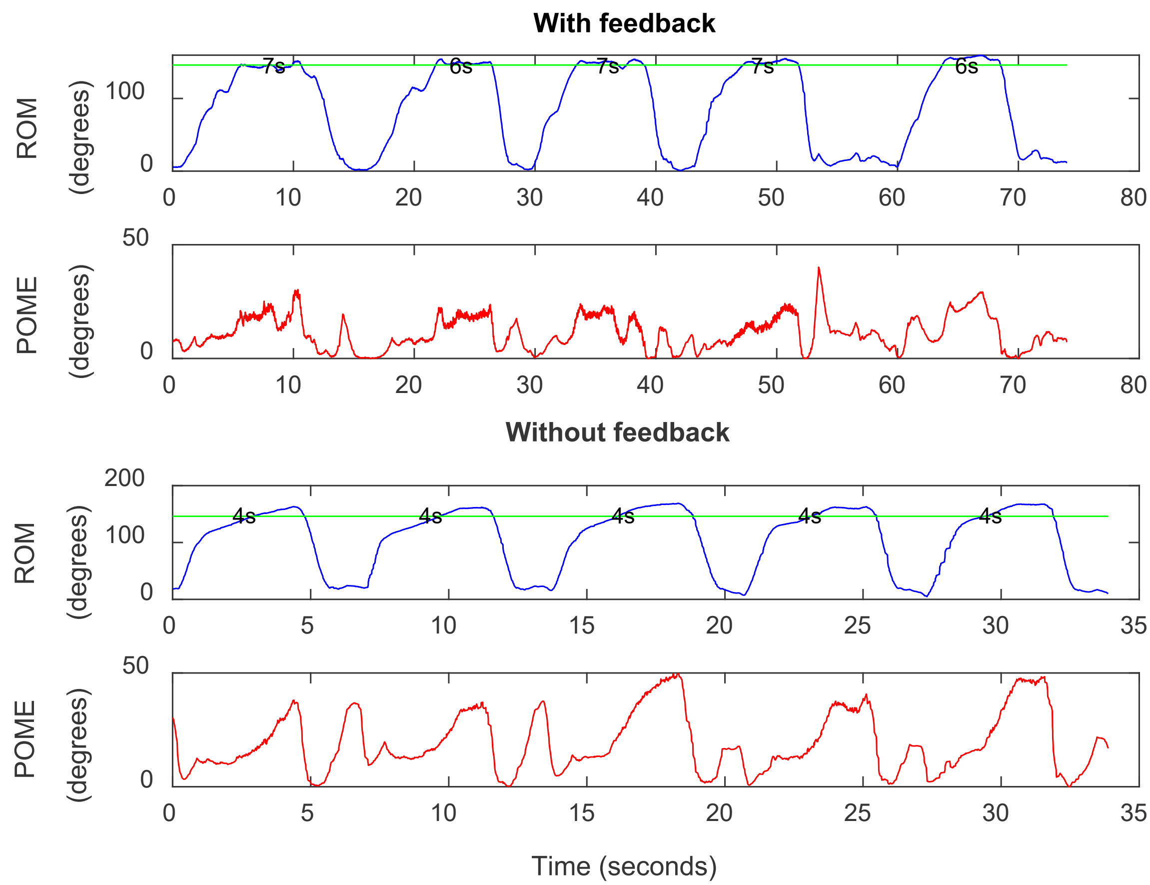

Figure 18. Range of Motion (ROM) and Plane of Motion Error (POME) over time during a sword draw exercise.

5.4 Clinical Trial Results

With preliminary student trials experiments showing promise, clinical trials were undertaken with PI Dr. Timothy Uhl from the College of Health Sciences at the University of Kentucky. The goal of this study was to evaluate RehabBuddy on real patients and collect data of Dr. Uhl's PT feedback, to compare RehabBuddy's guidance to that of the professional the system is trying to emulate. The trial designed was given IRB approval on February 19th, 2019 and assigned IRB number 46074.

5.4.1 Subject Recruitment and Trial Design

The subjects recruited to the trials are patients attending physical therapy at a University of Kentucky outpatient physical therapy clinic.

The inclusion criteria are:

- Attending physical therapy for rehabilitation following shoulder surgery.
- Has started their physical therapy at a UK outpatient physical therapy clinic.
- Plans to follow up with physical therapy at UK outpatient physical therapy clinic for the duration of their care,
- Is between the age of 18-99.
- Has undergone an informed consent procedure to ensure complete understanding of what being a subject will entail.
- Has given permission to have the trial results collected published without identifying information.

Participants are excluded from participation for any of the following criteria:

- Before surgery patient reports having arm weakness due to a neurological disorder (stroke, Multiple sclerosis, spinal cord injury, other)
- Started physical therapy after surgery at another physical therapy location.
- The patient is planning to seek care at another rehabilitation facility.
- Is outside of the age range for inclusion,
- Cannot speak or comprehend English.

This study will include approximately 40 patients who have undergone shoulder surgery and is currently ongoing. A total of 31 patients have been subjects in the study so far. For this paper, preliminary results will be presented based on 25 of these patients, as some trials were discarded for reasons discussed later in this section. Each patient is requested to perform two different 2 exercises, time permitting, and these exercises vary based on their current rehabilitation plan. Most exercise trials involved the patient completing a set of 10 repetitions, although it did vary according to patient needs. Exact records of the repetitions performed by each of the 25 subjects with useable results are in the Appendix. Together they performed a total of 39 exercises.

Under PT guidance, the patients followed the RehabBuddy setup procedure outlined in the RehabBuddy Application Design Section and demonstrated in the student trial results above. After having each subject fill out a consent form, an IMU is affixed to their arm, where it remains for the entirety of the exercise session. Then the PT goes through the process of defining the two exercises the patients will be performing in RehabBuddy, including an additional exercise called practice. The practice exercise has a few repetitions and is typically a simple exercise motion such as a wave. This practice exercise is used to get the patient comfortable with using RehabBuddy and allows them to point out major concerns before the trials start, where the PT is not in the room for the RehabBuddy feedback and no feedback conditions so as to not bias the results of these conditions.

The trials are set up so that the patient was randomly assigned one of the three conditions, either RehabBuddy feedback, no feedback, or PT feedback. They are told to perform the exercise with the IMU recording data regardless of whether they are receiving feedback or not. Once the first condition is complete, they are given an 8-minute rest period. This is partially done so that there is enough time between conditions that patients no longer rely on the routine they have established in the previous condition. Once the break is complete, the patient is randomly assigned a second condition. The patient then does the second and the third conditions in the same manner as the first.

5.4.2 Individual Subject Details and Results

The Appendix shows the full results of the trials undergone thus far. The first 5 trials were omitted because there was an issue with the start position that was corrected with a gamma function as discussed in the RehabBuddy Application section. Subjects 17 and 26 each recorded only a single exercise. Subjects 12, 21, and 30 had one or more exercises omitted due to a failure to capture all 3 conditions, for example missing the no-feedback condition, which would mean their inclusion imbalanced the number of trials for each condition. Subjects 9, 11, 18, 22, 24, and 27 had one or both exercises omitted due to data collection issues that created errors in the collection method that left data in one or more of the conditions unusable. An example of this is in Figure 19 where the RehabBuddy and no feedback cases indicate an issue with either forgetting to set a start position, moving the IMU mid exercise, or some other error during the trial that causes the data to be incorrect to the degree the data is discarded.

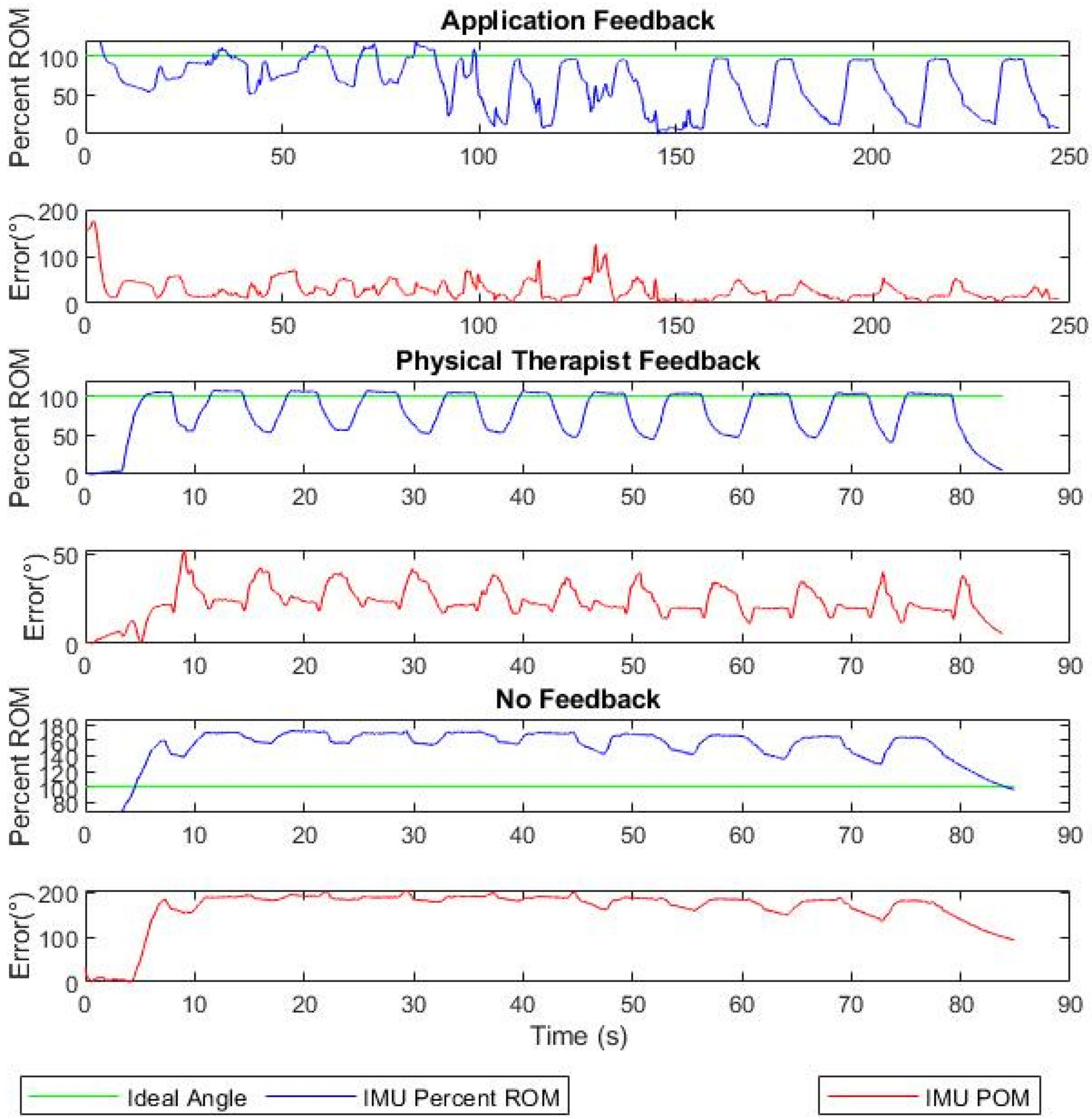

Figure 19: Example of error in data collection in RehabBuddy and no feedback conditions

A notable difference to the data collected on the student is that instead of degrees, ROM is measured as a percent of 100, where 0% is at the start position and 100% is at the target position. This is because each exercise had a unique ROM, anywhere from 30 degrees to 150 degrees. By converting ROM from degrees to a percent scale, the data can be more easily aggregated and compared.

5.4.3 Summary of Results

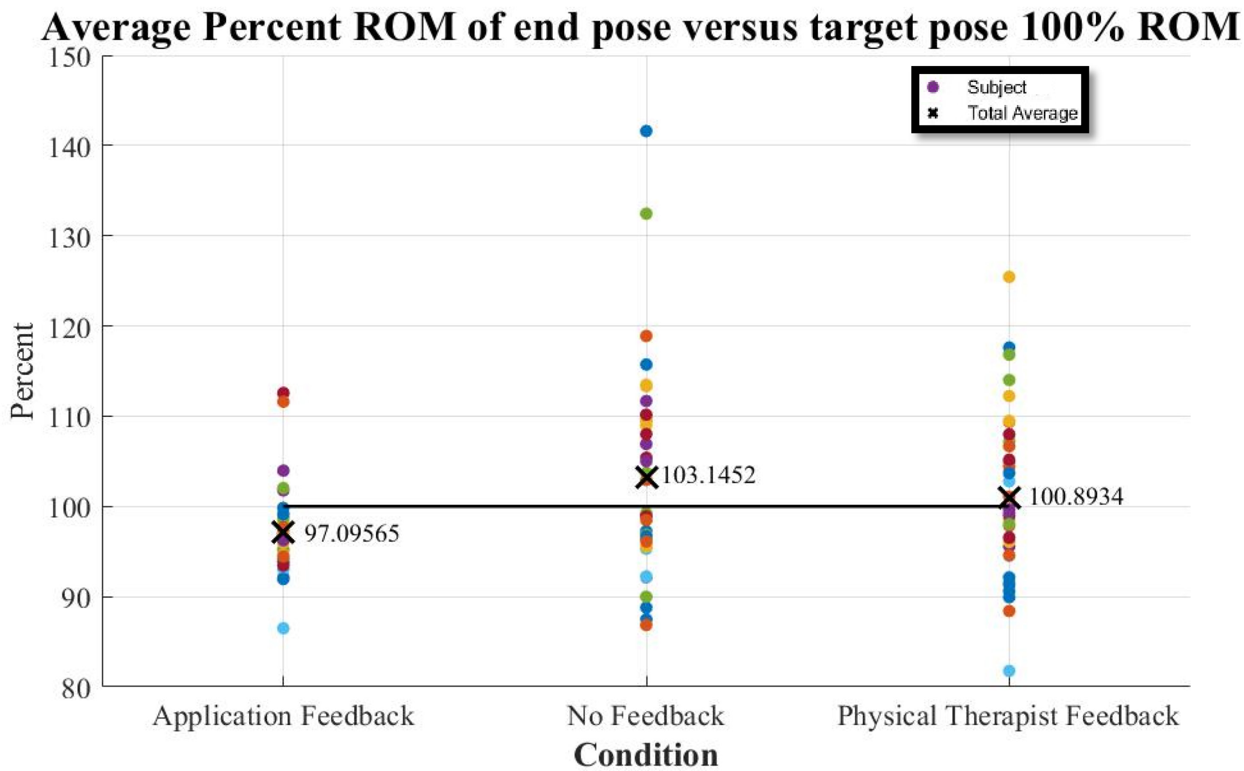

Figure 20: Average target pose ROM results for patient trials

Figure 20 shows the results of Percent ROM for all three conditions. The average ROM is taken at 80% of the 100% target where everything above this line is counted as being at the hold position. The 80% target was chosen because most repetitions, even those with underextensions or without user feedback, hit this point even if the repetition did not hit 100% ROM. The data above this line is considered the hold position for a given repetition. The ROM reached is the average of these points above the threshold for a given repetition and the hold time of each repetition is the time that passes. The average of the 8 middle repetitions is taken for an exercise where the user performed 10 repetitions. If less than 8 repetitions are performed, data from two conditions is trimmed to match the condition with the least amount of repetitions for a fair comparison. The repetitions trimmed were the first repetition if only one is missing and the first and the last repetition if two or more are missing. This pattern of taking a starting repetition and an ending repetition continues until all three conditions have an even number of repetitions. This is done as the first and last repetitions were often outliers, regardless of the condition, likely due to user inexperience or fatigue. The average ROM for each repetition is itself averaged across the exercise to get a single value representing the average ROM achieved during the trial. This is plotted separately for each exercise in Figure 20. The total average is the mean of these plotted exercise points. RehabBuddy has the lowest average ROM and is about 3% below the 100% target. However, the distribution is more tightly clustered, indicating RehabBuddy's ability to help users reach a more consistent final pose. No feedback had the worst average and the largest spread, but on average was only 3% higher than the 100% target position. PT feedback had a similarly wide spread to no feedback, but the average ROM was closest, differing 1% on average from the target position. The results of these 3 conditions were analyzed by Dr. Uh. The ANOVA used was not a traditional ANOVA, but a non-parametric version called Friedman's test with post hoc analysis using Wilcoxon Signed rank which is the non-parametric paired t-test. Due to lack of normal distribution, these are appropriate alternative management of data approaches. Significant differences found were further analyzed with Wilcoxon Signed Rank test with alpha set at ≤0.016 due to multiple comparisons. Median (interquartile ranges) were used to represent the data. The average range of motion during all exercises under the no feedback condition 99(97-109°) was significantly greater motion than with RehabBuddy feedback 96(94-99°, p=0.003) which was not significantly different from the PT condition 99(95-107°, p=0.08).

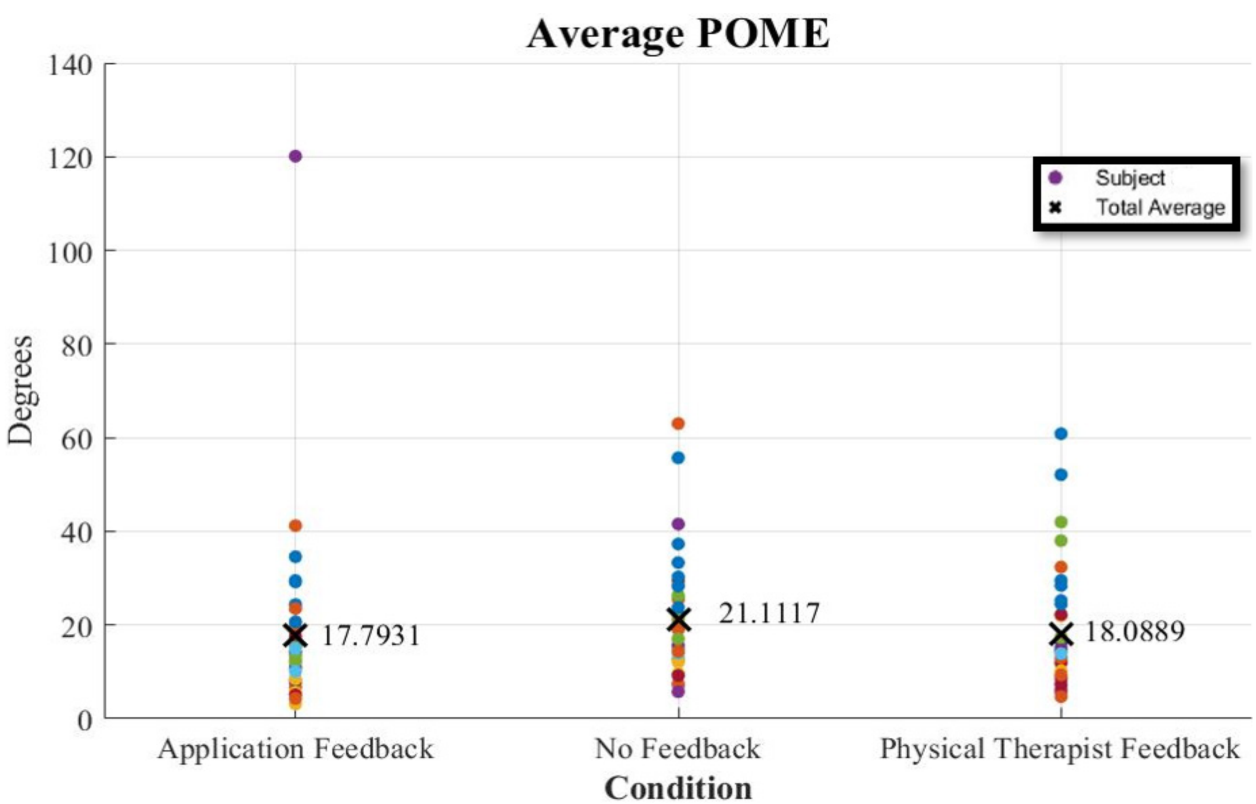

Figure 21: Average POME results across an exercise for patient trials

The POME, again averaged over each exercise, is measured in degrees off of the target POM. Instead of across the top of the repetitions, it is taken across the entire exercise, as POME should be minimized at the start pose, target pose, and on the transition between them. The error across all exercises was again averaged and can be found in Figure 21. Here RehabBuddy still has a tight cluster, disregarding the obvious outlier, but the differences are not as stark as with ROM. RehabBuddy also has the lowest average error, though PT feedback is close, with both at around 18 degrees. The no-feedback condition's error is on average 3 degrees higher, a percent difference of about 15%. According to Dr. Uhl's statical analysis, the average plane motion error was the greatest in the no feedback condition 18(12-27°) compared to the RehabBuddy condition 14(8-21°, p=0.002).

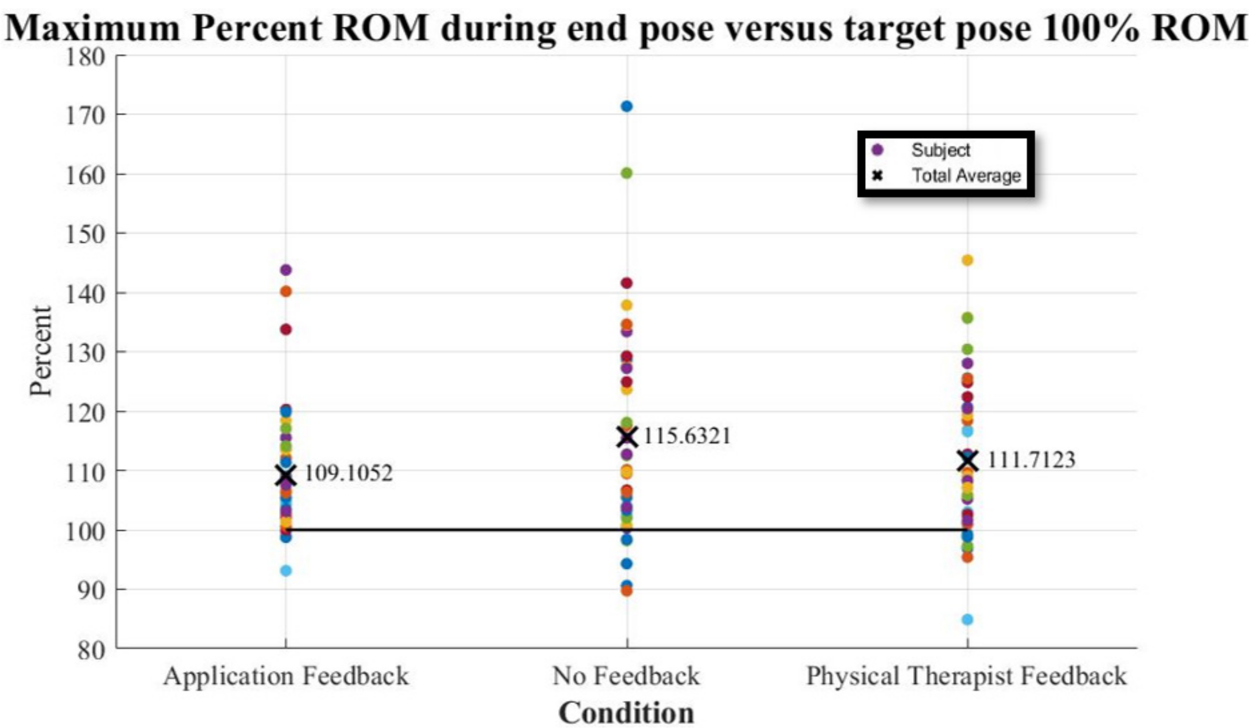

Figure 22: Maximum ROM for patient trials

While the average ROM across all exercises was close to 100% for all three conditions, the severity of undershooting and overshooting for both the PT feedback and no feedback conditions led to an exploration of the differences in maximum ROM for each condition. Here the metric used is the "point" maximum, the highest recorded ROM for each exercise, even if it was only reached momentarily. This was compared to see how common overextension was for all three conditions. The results show RehabBuddy has the lowest overextension, 2% below PT feedback and 6% below no feedback, as shown in Figure 22. This continues to indicate that the RehabBuddy feedback has a conservative effect on patients' ROM.

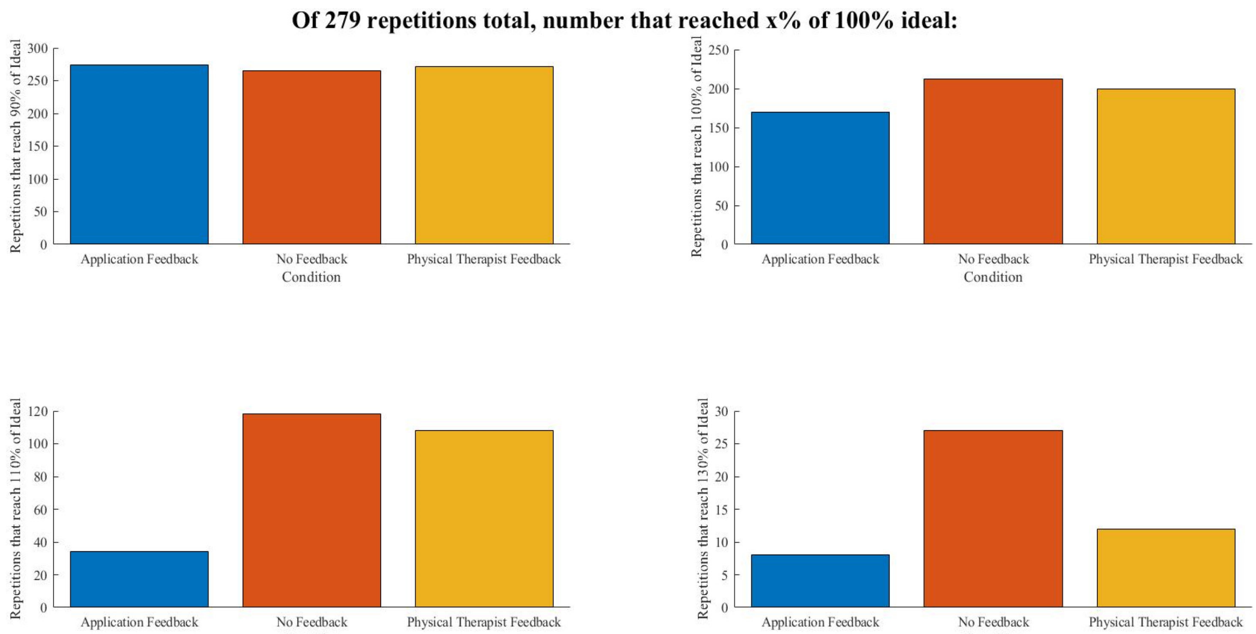

Figure 23: Number of repetitions that reach a certain % ROM clockwise from upper left-hand corner: 90% ROM, 100% ROM, 110% ROM, 130% ROM

Figure 23 is this maximum ROM described in a different way. A set of bar graphs showing how many exercises reach a specific ROM. The upper left-hand corner shows the number of exercises that reached 90% ROM, which was met across virtually all exercises, regardless of condition. This is confirmed by a chi-squared test measure of difference. The number of repetitions hitting 90% ROM under the RehabBuddy condition was compared with the number hitting 90% without feedback. Against the null hypothesis that the condition made no difference in the number of repetitions to hit 90% ROM, the p-value was 0.0357 which rejects the null hypothesis with alpha 0.05 for criteria. This was repeated to test the number of repetitions hitting 90% ROM under the RehabBuddy condition compared with the number hitting 90% with PT feedback. Here the p-value was 0.559, indicating not significant difference between the number of repetitions hitting 90% ROM for PT and RehabBuddy conditions. This means there was significant difference between the number of repetitions without feedback that failed to hit 90% compared to when the subject was using PT or RehabBuddy assistance. Since the latter two conditions got closer to the 279/279 repetition goal, this indicates that RehabBuddy encouraged uses to move past and underextended final ROM. But at 100% ROM RehabBuddy performed worse than the other cases, as a greater number of repetitions failed to reach this marker. This was confirmed by the chi-squared test where the p-value versus no feedback was 0.0001 and the p-value versus PT feedback was 0.0094. Since ideally all 279 repetitions should hit 100% ROM, the PT and no feedback conditions getting closer to that ideal than RehabBuddy indicates RehabBuddy feedback did encourage slight under-extension. Conversely, this also meant that at 110% ROM, RehabBuddy shows significantly fewer instances of overextension. Ideally 0 repetitions should reach a 110% ROM overextension. Only 34 out of 279 repetitions hit 110% ROM under the RehabBuddy condition, as opposed to the 108 and 118 repetitions with overextension of 110% for PT and no feedback respectively, both with p-values less than 0.00001 for the chi-squared test for both comparisons to RehabBuddy. As the ROM increases to 130% of ROM, only 8 exercise trials performed with feedback from RehabBuddy have this large overextension. This is slightly less than the PT condition's 12, but not significantly so (p-value 0.3884). But both are much lower repetition values than the no-feedback condition in which 27 of the 279 trials reach 130% ROM, which when compared with the RehabBuddy condition's 8 repetitions resulted in a p-value of 0.0009, indicating a significant difference. This indicates RehabBuddy helps keep a conservative ROM closer to the lower bound of the ROM target the PT prescribed, which is aids in preventing users from possibly re-injuring themselves by overextending, as this analysis indicates they occasionally would without feedback. However, it also means RehabBuddy was less likely to hit the exact target ROM, although users did reliably hit 90% of that ROM target.

This makes sense when considering the design choice to allow users to continue making progress at 90% ROM. Forcing them to hit and maintain 100% ROM led to frustration even in student trials but it is suspected that because the subject saw the cursor continue to make progress on the graph at 90% they were content to stay put instead of extending their arm more, despite the patients' PT feedback and no feedback conditions indicating they were generally capable of this greater ROM. The clinical significance of this RehabBuddy's conservative effect had not yet been fully explored, but trials are still outgoing, and post exercise survey results are being collected as to the effect RehabBuddy has on these patients.

Hold times in general have yielded interesting results so far. As the ROM at the target pose is calculated at 80% of the ideal target pose (so that under extended repetitions are still detected), the hold times do bias longer than the patient was likely holding the final pose. RehabBuddy implements hold times via a timer function native to Android. Even so, patient hold times when using RehabBuddy are much higher than the number of seconds prescribed by the PT. The average hold time in the final position across all repetitions for an exercise, when compared with the PT set prescribed hold time as an absolute difference between the prescribed hold time and actual hold time is, for RehabBuddy, an average of 2.67 seconds different. Compare this to the average hold time for PT and no feedback conditions which are on average about half a second different than the prescribed hold time, 0.53 seconds for PT feedback and 0.60 seconds for no feedback. Given that a hold time for an exercise target pose is typically 2 to 4 seconds, holding on average 2.67 seconds longer than prescribed is a notable error. With PT feedback as well as with no feedback patient hold time tends to be slightly shorter or longer than the prescribed target. RehabBuddy always causes patients to hold the target position longer than prescribed.

There are a few suspected reasons for this. For one, understanding RehabBuddy feedback does have an acclamation period. While the interface is designed to be simple to follow and the subjects are given a practice period to get comfortable with the system, it is possible new users go slower as they adjust to monitoring and adjusting their exercise based on external feedback they must interpret. Another possible cause is that the hold timer for RehabBuddy stops making progress if the user moves their arm under 90% ROM before they have held for the whole time, and they cannot make progress unless they move their arm back up. Although the timer speeds up to account for the time they were not at full ROM, it still potentially confuses patients when they start moving back towards the start position while following the correct path, but the graph indicates they are off-path, and they realize they have to go back to finish the repetition because they were slightly too fast to start their descent. This is a function of the state machine and the design choice to tie the patient to a predefined path where they cannon make progress if their current position is over 10% off of what their position should be. Also, this path ties users to a specific pace that emphasizes slow steady progress, and that could mean more time is made progressing from 80% to 100% ROM, which would increase RehabBuddy hold times over hold times of trials passively recording PT or no-feedback conditions. Finally, all programmers who contributed to the RehabBuddy application were very new to Android studios and application design in general. It was a direction the team felt necessary to go in as in-clinic setup and existing user familiarity makes an Android application much simpler for both the PT and the patients, but this inexperience may mean RehabBuddy has undiagnosed software bugs. The timer function is an API provided by

Android Studios basic libraries, but how it interacts with the other threads running in the application is unknown. Ultimately, this hold time difference remains in the current application as there are concerns that changing the application partway through testing could greatly affect trial results, especially if the change has unanticipated effects on application functionally, and this is an area that still needs further exploration.

Additionally, while the average POME error is similar for both RehabBuddy and PT feedback, there is an extreme outlier that affects RehabBuddy's average. There is no justification for discarding this trial, so it remains, despite greatly affecting the average. A graph of the exercise in question is shown in Figure 24. All three conditions reach the correct ROM, and the PT and no feedback cases do it with a typical level POME. Yet in the RehabBuddy condition, the patient frequently reaches an improbable 200-degree POME. Why this occurred and only affected the RehabBuddy case is unknown, but it is suspected there was an issue with the user setting an incorrect start position when beginning the exercise, that due to chance did not affect ROM and was therefore not detected. The POME bar would have been completely red, indicating an error of greater than 50 degrees throughout most of the exercise, but the user is not penalized for being off the POM, so they likely ignored this.

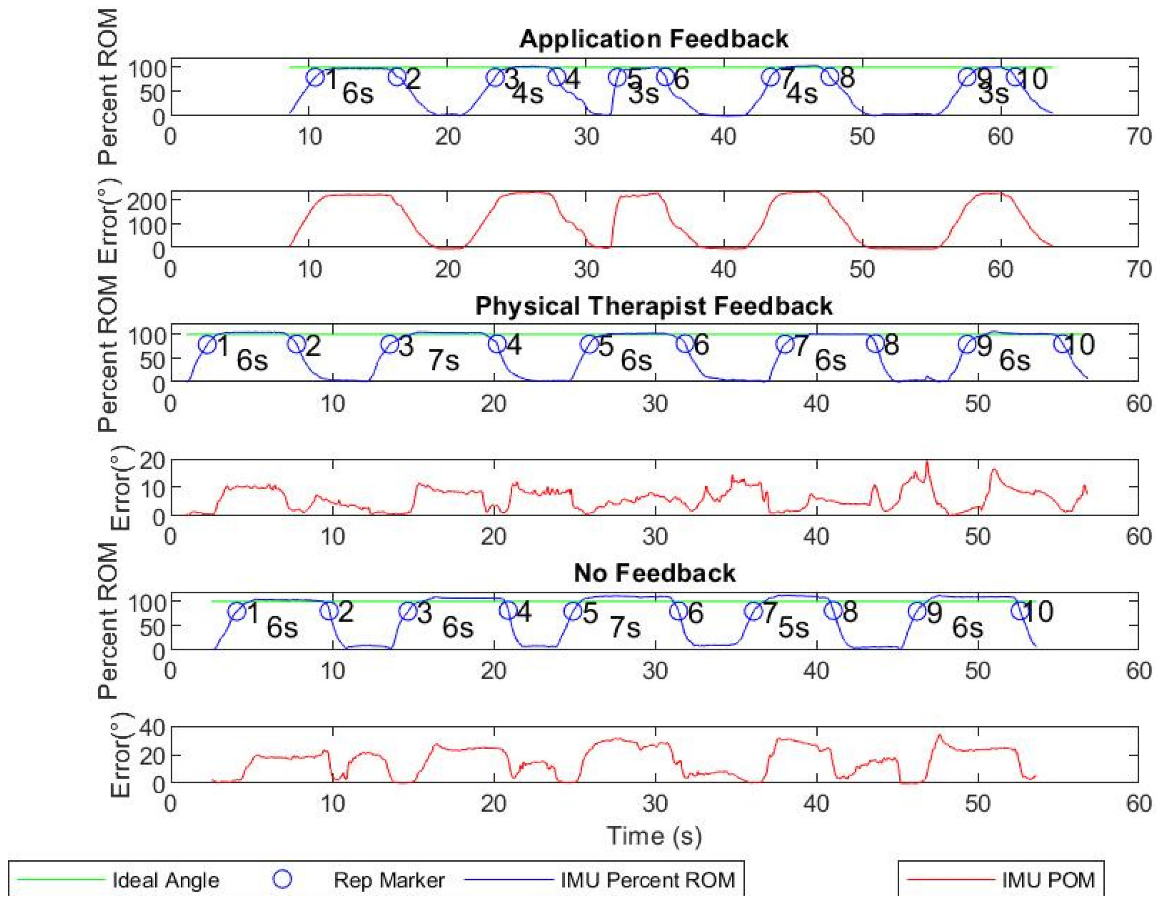

Figure 24: Subject 23 RNG Exercise with high POME for the RehabBuddy condition

Cases such as this one are rare however, and the aggregated results across all trials shown in Figure 21 indicate this was an atypical event.

Chapter 6: Conclusion

Presented in this thesis is the implementation of an application that utilizes IMUs to provide real-time feedback for patients performing exercises during physical therapy. The system requires a single IMU and an Android tablet that does not need a lot of processing power. This means RehabBuddy is simple and cost-effective, providing feedback that is fast, accurate, and can work with cheap devices, unlike other state-of-the-art methods. Saving and recalling an exercise is straightforward and allows the PT complete control of creating exercises that are tailored to the patient.

The approach demonstrated above can be extended to be versatile enough to allow a rehabilitation professional to prescribe any limb motion from any posture. This approach allows healthcare providers to individualize the exercise prescription in response to pain and a variety of disabilities. In addition, it removes the need for the standard written illustration that can lead to confusion and non-adherence. Also, the system potentially decreases the risk of further injury by providing real-time feedback to notify the patient that exercises are performed incorrectly in either quantity or quality. The real-time positive feedback when the patient performs the exercises correctly simulates an at-home "physical therapist", promising to enhance patient confidence. Correct exercise performance with feedback has improved pain and outcomes [57] while empowering patient independence [10]. Finally, the system can provide an objective record of the number of exercises performed correctly, frequency of performance, and duration of exercise sessions which are valuable as well compared to self-reporting.

Trials were run first on the PIs where differences were seen between the exercises performed with RehabBuddy feedback as opposed to exercises without. These trials indicate that IMUs can be used to effectively interpret and display real-time user feedback. Providing subjects with this feedback during exercise execution results in a more accurate range of motion (ROM) adherence, less plane of motion error (POME) as the exercise is performed, and longer hold times. The system helped both subjects maintain proper form by providing feedback about the POM error. When performing the exercises with feedback, the subjects were more capable of correcting these specific issues, and offset the effort of simultaneously tracking repetition count, hold time, so that accurately performing the exercise could be the focus of the session.

This general trend held even for more complex exercises and this proof of concept led to a set of clinical trials. These trials are still ongoing, but the preliminary results presented indicate that with RehabBuddy feedback, patients on average achieve a POME very close to the error in the path they display with the guidance of a PT. This POME is 15% lower than the average error in performance when they are performing the exercise with no feedback. There is also a difference in ROM when using RehabBuddy. Subjects on average show a 3% under extension when compared to the 100% target, whereas trials of the exercises where patients did not have feedback showed an average overextension of around 3%. Further exploration of the maximum ROM achieved by the average subject shows that RehabBuddy's tendency to keep patients at a less ambitious end pose keeps them from the larger overextensions. Patients without any feedback were over 3 times more likely to reach 130% ROM, a very large overextension. PT feedback was on average the closest to the 100% ROM target. One notable issue with RehabBuddy was that it encouraged patients to hold the target pose for longer than the PT selected. While this was unexpected, and the underlying reasons have not been ascertained, given that RehabBuddy has proven adept at keeping the patient from overextension, the extra few seconds at the hold position are not of serious concern and could likely be adjusted with a bug patch to the Android timer function utilized for tracking hold time.

The subjects were assigned a wide variety of exercises, each one with a customized target ROM. These results demonstrate a system that is simple to utilize and flexible enough to work with a wide variety of shoulder exercises. It allowed the PT full control to set ROM and POM to tailor an exercise for a specific patient. Although not used with patients with severe limitations to motion in clinical trials, this flexible exercise definition can be used to modify exercises to suit a particular patient's recovery as they progress through their training regimen.

There are, however, limitations and compromises associated with the system as it currently exists.

6.1 Limitations

The IMU must be affixed in the exact position it was during the original exercise creation process. If not, this difference in sensor position creates a lot of error between the exercise as it was recorded. Solutions such as a sensor embedded in a glove or brace would ensure the same placement of the sensor each time the patient put it on, but this is theoretical, and as is the system is not ready for take-home use.

There are tradeoffs associated with the design choice to keep RehabBuddy general enough for most exercises as opposed to being specifically designed to work with a predetermined list of exercises. First, acceptable error varies by exercise and for certain exercises, can be more severe along a specific plane. Even for a single patient, there can be injury-specific concerns such that particular arm rotations place the arm in a position that threatens injury retear, while other incorrect movements are not as high risk. RehabBuddy makes no such distinctions, and all error is treated as equally problematic as indicated by an absolute value on the error. This is especially noticed in exercises with large ROM, for example, a 150 side abduction, where the broad range means errors of even 20 degrees are not concerning in terms of exercise form. Compare this to a recently post-surgery patient performing an exercise with ROM of 30 degrees but that same 20-degree error means the patient is twisting their arm into a motion that risks retear.

Second, there are differences in how an IMU registers POME versus how it is perceived by the patient. For example, a 15-degree rotation of the wrist as measured by the IMU is perceived by the patient as a minuscule turn. If this motion causes a 15-degree error on the POME bar, it is seen as a "system malfunction" that could potentially lead to patient frustration or mistrust. Additionally, this slight wrist rotation often poses no real risk to the patient, if they are performing an exercise targeted at an elbow injury, for example. However, to ignore incorrect rotations on specific planes irrelevant to the exercise requires RehabBuddy to be tailored to such exercise, because this same rotation on the same plane can be a meaningful error for a different exercise, especially one where the sensor has been repositioned.

Finally, the error can only be reported back as an absolute measure of how far off the POM the patient is. No directional advice can be diagnosed from this POME, to get the patient back on the correct POM such as move left or move right, as this would require registration of the sensor's location on the body relative to these unfixed directions.

6.2 Future Work

The limitations listed above are all functions that, if implemented, can improve RehabBuddy's feedback system. Most crucially, setting up an IMU calibration or device embedding method would be necessary for take-home use. Without solving this first limitation this system will not fulfill its intended use case of monitoring exercises outside of the clinic. The PT would need to set the exercise to reflect the change in sensor position at the start of each session, which defeats the purpose of a system intended to act as a stand-in for the PT during at-home exercise sessions. Tailoring for specific exercises is a lesser concern that could nonetheless be an interesting and useful problem to tackle.

Appendix

SUBJECT	EXERCISE	CONDITION	MINIMUM REP (%)	MAXIMUM REP (%)	AVERAGE REP (%)	MAXIMUM ROM (%)	AVERAGE HOLD (SECONDS)	HOLD PRESCRIBED (SECONDS)	MAXIMUM POME (DEGREES)	AVERAGE POME (DEGREES)	REPS COMPLETED	REPS PRESCRIBED
6	no monies	RehabBuddy	92.01	97.37	94.23	100.42	6.74	4	19.08	7.63	10	10
6	no monies	PT Feedback	100.69	108.12	104.92	120.67	4.84	4	32.34	12.29	12	10
6	no monies	No feedback	129.66	148.57	141.60	171.33	4.32	4	78.68	33.33	10	10
6	pnfdiagonal	RehabBuddy	91.09	92.89	92.10	100.48	6.66	2	93.86	34.60	10	10
6	pnfdiagonal	PT Feedback	89.37	92.83	90.60	96.91	2.57	2	121.05	52.09	10	10
6	pnfdiagonal	No feedback	87.41	90.42	88.78	94.29	2.51	2	127.26	55.71	10	10
7	scaption	RehabBuddy	94.41	97.64	95.21	101.88	4.80	3	20.04	6.61	10	10
7	scaption	PT Feedback	103.50	105.88	104.42	109.02	4.27	3	22.48	8.34	10	10
7	scaption	No feedback	103.23	112.22	109.52	117.56	4.14	3	41.97	12.39	9	10
7	er90	RehabBuddy	94.87	98.25	96.80	112.06	4.92	2	60.21	19.49	10	10
7	er90	PT Feedback	97.49	103.65	101.07	109.63	3.82	2	37.08	17.32	9	10
7	er90	No feedback	100.71	104.96	102.93	112.69	3.56	2	41.30	19.00	10	10
8	scaption	RehabBuddy	86.28	104.65	96.03	114.17	6.84	3	36.79	13.45	7	10
8	scaption	PT Feedback	93.98	103.63	98.56	109.03	5.45	3	22.51	9.22	10	10
8	scaption	No feedback	109.87	116.75	113.32	123.64	5.62	3	42.29	21.87	12	10
8	horizabd	RehabBuddy	89.05	107.83	98.34	118.44	5.16	3	33.72	11.98	8	10
8	horizabd	PT Feedback	110.11	113.96	112.23	135.77	5.28	3	39.44	13.74	10	10
8	horizabd	No feedback	104.84	119.77	109.66	137.84	6.51	3	48.81	20.21	12	10

9	flexion	RehabBuddy	97.20	119.39	103.96	143.77	7.28	3	54.08	14.43	8	8
9	flexion	PT Feedback	95.31	102.82	99.65	128.03	5.33	3	52.52	14.57	8	8
9	flexion	No feedback	98.54	118.50	106.91	133.39	4.35	3	44.98	22.31	8	8
10	wexercise	RehabBuddy	90.83	96.98	93.06	104.79	4.32	2	33.08	5.75	10	10
10	wexercise	PT Feedback	102.38	110.23	107.19	116.72	3.56	2	33.20	13.10	10	10
10	wexercise	No feedback	85.51	92.73	89.99	98.19	1.69	2	47.48	21.16	10	10
10	rows	RehabBuddy	91.80	97.72	95.26	104.34	3.70	2	41.62	16.02	10	10
10	rows	PT Feedback	108.47	118.88	114.01	135.64	2.50	2	44.17	14.11	10	10
10	rows	No feedback	100.35	106.94	103.72	118.07	1.62	2	42.90	17.04	11	10
11	scaption	RehabBuddy	92.45	96.37	94.45	104.71	5.23	2	62.01	24.14	9	10
11	scaption	PT Feedback	92.63	96.97	94.51	103.02	4.40	2	14.85	5.38	10	10
11	scaption	No feedback	94.01	96.81	95.30	102.44	3.85	2	33.89	7.02	10	10
12	lowrows	RehabBuddy	91.64	96.26	93.84	102.32	5.53	3	31.32	8.16	11	10
12	lowrows	PT Feedback	88.29	112.97	98.97	122.38	3.88	3	37.43	11.93	11	10
12	lowrows	No feedback	92.37	119.60	105.40	141.56	4.02	3	39.76	12.11	14	10
13	flexion	RehabBuddy	91.83	97.55	94.18	108.99	5.91	2	25.18	8.42	6	10
13	flexion	PT Feedback	114.39	119.76	117.61	125.56	5.01	2	55.43	29.52	6	10
13	flexion	No feedback	113.84	118.63	115.73	128.72	3.75	2	64.56	28.45	6	10
13	abduction	RehabBuddy	92.19	99.78	96.95	105.44	4.53	2	29.26	12.50	6	6
13	abduction	PT Feedback	89.44	92.56	91.34	96.85	3.46	2	27.50	15.25	6	6
13	abduction	No feedback	86.76	88.02	87.48	90.60	2.56	2	31.51	7.45	6	6
14	flexion	RehabBuddy	95.89	98.01	96.68	106.26	3.02	2	14.90	4.31	10	10
14	flexion	PT Feedback	95.52	99.45	97.86	105.68	2.43	2	16.75	6.21	10	10
14	flexion	No feedback	94.74	101.79	99.11	110.11	2.19	2	21.37	7.33	8	10
14	er	RehabBuddy	95.88	98.53	97.27	102.68	2.91	2	55.46	13.57	10	10
14	er	PT Feedback	107.87	110.86	109.37	118.41	2.66	2	37.35	12.99	10	10
14	er	No feedback	85.14	88.28	86.85	89.73	1.88	2	73.29	25.54	10	10
15	horizontal abduction	RehabBuddy	92.17	98.27	95.99	113.53	3.43	2	39.55	8.49	10	10

15	horizontal abduction	PT Feedback	121.42	128.89	125.43	145.41	3.35	2	85.33	21.95	11	10
15	horizontal abduction	No feedback	98.64	119.72	109.01	134.50	2.92	2	60.96	9.72	9	10
15	ER	RehabBuddy	94.20	100.16	96.84	106.57	3.45	2	11.70	3.15	10	10
15	ER	PT Feedback	108.47	111.23	109.49	119.33	3.33	2	31.30	10.24	10	10
15	ER	No feedback	111.57	117.32	113.48	127.57	3.36	2	44.03	14.76	10	10
16	prone rows	RehabBuddy	100.05	103.13	101.77	108.66	4.98	3	41.23	14.21	10	10
16	prone rows	PT Feedback	91.67	101.04	96.58	108.28	4.73	3	53.28	16.37	10	10
16	prone rows	No feedback	109.66	114.58	111.68	127.21	5.14	3	74.19	41.56	10	10
16	IR	RehabBuddy	94.36	105.01	99.83	115.53	5.65	3	44.88	10.84	8	8
16	IR	PT Feedback	91.53	98.58	95.56	105.19	4.96	3	50.86	8.75	8	8
16	IR	No feedback	84.07	96.30	92.14	100.32	4.11	3	30.42	5.77	8	8
17	prone extensions	RehabBuddy	95.75	103.91	98.70	114.09	5.21	3	61.21	12.24	8	8
17	prone extensions	PT Feedback	89.92	94.75	91.62	97.28	3.96	3	123.03	38.02	8	8
17	prone extensions	No feedback	92.51	104.14	99.22	112.52	3.39	3	33.61	12.72	9	8
18	pronation-supination	RehabBuddy	91.74	93.71	93.02	98.93	5.70	3	41.84	10.15	9	8
18	pronation-supination	PT Feedback	81.09	83.01	81.77	84.87	1.86	3	28.48	5.89	8	8
18	pronation-supination	No feedback	94.21	98.02	96.19	104.08	4.14	3	26.62	9.24	7	8
19	sh flexion	RehabBuddy	93.62	109.45	97.67	120.26	4.89	3	42.09	15.72	12	12
19	sh flexion	PT Feedback	100.10	108.49	105.18	112.73	4.91	3	34.11	14.21	13	12
19	sh flexion	No feedback	106.86	116.95	110.16	124.93	3.36	3	58.20	29.51	12	12
19	ER	RehabBuddy	100.74	118.07	112.57	133.76	6.46	3	38.65	17.52	12	12
19	ER	PT Feedback	99.41	117.16	107.99	124.83	3.86	3	42.75	22.25	11	12
19	ER	No feedback	86.51	121.80	108.01	129.25	3.43	3	36.53	14.37	11	12
20	flexion	RehabBuddy	91.06	92.59	91.95	98.74	6.70	2	79.20	20.70	6	6
20	flexion	PT Feedback	90.04	93.23	92.13	99.27	5.70	2	80.64	28.42	6	6
20	flexion	No feedback	91.33	93.02	92.22	98.40	4.94	2	79.94	30.29	6	6
20	scaption	RehabBuddy	91.99	94.61	93.51	103.50	4.69	2	79.25	29.52	10	10
20	scaption	PT Feedback	87.64	94.40	91.35	98.81	4.54	2	69.14	24.49	10	10

20	scaption	No feedback	95.94	98.54	97.25	106.30	3.88	2	87.77	37.30	10	10
21	scaption	RehabBuddy	97.79	122.73	111.61	140.16	7.74	3	142.69	41.22	8	8
21	scaption	PT Feedback	101.50	115.30	106.67	125.47	4.47	3	127.11	32.38	8	8
21	scaption	No feedback	111.41	123.00	118.89	134.63	5.22	3	139.38	63.01	9	8
22	supination	RehabBuddy	93.41	95.38	94.61	100.60	3.65	2	22.49	5.63	5	5
22	supination	PT Feedback	94.56	98.35	96.06	102.15	2.91	2	28.48	5.48	5	5
22	supination	No feedback	93.87	97.93	95.54	100.74	3.50	2	29.32	12.06	5	5
23	rng	RehabBuddy	95.02	98.11	96.24	103.09	4.33	1	234.20	120.10	6	5
23	rng	PT Feedback	97.61	100.85	99.26	105.81	5.93	1	19.33	5.94	5	5
23	rng	No feedback	100.61	107.12	105.02	112.74	5.97	1	34.13	15.61	5	5
25	scaption	RehabBuddy	96.75	101.47	99.80	106.58	3.04	2	31.43	13.24	5	6
25	scaption	PT Feedback	96.30	100.86	98.05	105.82	3.18	2	28.52	17.40	6	6
25	scaption	No feedback	96.18	98.26	96.87	102.00	2.79	2	28.82	17.08	6	6
25	ER	RehabBuddy	95.48	106.48	102.03	117.06	3.17	2	33.46	15.29	7	6
25	ER	PT Feedback	114.28	120.28	116.82	130.41	3.04	2	57.65	41.99	6	6
25	ER	No feedback	126.31	145.71	132.44	160.09	3.89	2	69.68	26.32	6	6
26	pronet	RehabBuddy	82.64	89.98	86.49	93.12	5.80	5	37.76	14.97	8	8
26	pronet	PT Feedback	99.74	108.01	102.78	116.54	8.37	5	49.13	13.92	8	8
26	pronet	No feedback	87.11	96.78	92.20	103.97	7.14	5	89.64	14.00	7	8
27	biceps curl	RehabBuddy	82.79	95.46	93.43	99.98	3.28	2	13.82	5.06	10	10
27	biceps curl	PT Feedback	94.28	97.90	96.52	102.58	2.81	2	21.61	7.29	10	10
27	biceps curl	No feedback	97.82	100.80	98.89	106.68	2.70	2	28.51	9.23	17	10
28	elbow ext	RehabBuddy	94.39	106.67	99.79	119.87	18.60	10	80.36	24.38	6	5
28	elbow ext	PT Feedback	101.07	105.63	103.68	112.25	19.33	10	67.26	25.22	5	5
28	elbow ext	No feedback	95.41	98.22	96.69	103.30	14.10	10	58.42	23.73	5	5
28	elbows ext lb	RehabBuddy	94.63	101.64	99.14	111.35	12.23	5	89.60	29.20	5	5
28	elbows ext lb	PT Feedback	87.78	92.74	89.93	100.98	9.65	5	132.21	60.85	5	5
28	elbows ext lb	No feedback	95.33	97.19	96.42	105.50	12.06	5	60.00	28.32	5	5

29	skates	RehabBuddy	93.37	96.80	94.45	100.60	6.11	5	17.74	4.32	9	8
29	skates	PT Feedback	86.43	90.99	88.41	95.40	6.18	5	22.22	4.71	8	8
29	skates	No feedback	90.68	100.66	96.10	109.48	8.18	5	33.27	14.36	7	8
29	active elbow flexion	RehabBuddy	96.81	99.39	97.63	106.31	6.42	5	51.50	23.52	8	8
29	active elbow flexion	PT Feedback	92.80	95.57	94.58	100.92	6.33	5	30.57	9.38	8	8
29	active elbow flexion	No feedback	97.52	99.11	98.50	106.31	8.46	5	47.20	20.14	6	8
30	flexion	RehabBuddy	93.02	96.39	94.37	101.38	5.69	3	33.29	8.01	10	10
30	flexion	PT Feedback	96.75	101.23	98.74	107.11	3.54	3	21.32	7.38	10	10
30	flexion	No feedback	97.55	102.92	100.51	109.73	3.06	3	27.87	8.54	10	10
31	prone ext	RehabBuddy	91.17	100.38	96.02	107.58	4.59	3	34.85	10.39	11	10
31	prone ext	PT Feedback	111.65	113.66	112.45	120.42	4.53	3	34.82	13.73	10	10
31	prone ext	No feedback	102.30	109.67	105.50	115.47	4.12	3	52.95	29.87	11	10
31	flexion	RehabBuddy	95.45	97.83	96.82	103.09	4.90	3	34.23	15.60	10	10
31	flexion	PT Feedback	95.98	98.16	96.61	101.55	4.40	3	46.93	20.39	10	10
31	flexion	No feedback	95.08	100.10	98.19	103.79	4.52	3	63.20	26.83	11	10

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