Exploring In-Home Monitoring of Rehabilitation and Creating an Authoring Tool for Physical Therapists

Kevin Huang
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Human Computer Interaction Institute
School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213

khhuang@cs.cmu.edu
http://www.kevinhhuang.com

COMMITTEE
Sara Kiesler (Co-chair), Carnegie Mellon University
Daniel P. Siewiorek (Co-chair), Carnegie Mellon University
Asim Smailagic, Carnegie Mellon University
Anind Dey, Carnegie Mellon University
Patrick J. Sparto, University of Pittsburgh

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Abstract

Physiotherapy is a key part of treatment for neurological and musculoskeletal disorders, which affect millions in the U.S. each year. Physical therapy treatments typically consist of an initial diagnostic session during which patients' impairments are assessed and exercises are prescribed to improve the impaired functions. As part of the treatment program, exercises are often assigned to be performed at home daily. Patients return to the clinic weekly or biweekly for check-up visits during which the physical therapist reassesses their condition and makes further treatment decisions, including readjusting the exercise prescriptions.

Most physical therapists work in clinics or hospitals. When patients perform their exercises at home, physical therapists cannot supervise them and lack quantitative exercise data reflecting the patients' exercise compliance and performance. Without this information, it is difficult for physical therapists to make informed decisions or treatment adjustments. To make informed decisions, physical therapists need to know how often patients exercise, the duration and/or repetitions of each session, exercise metrics such as the average velocities and ranges of motion for each exercise, patients' symptom levels (e.g. pain or dizziness) before and after exercise, and what mistakes patients make.

In this thesis, I evaluate and work towards a solution to this problem. The growing ubiquity of mobile and wearable technology makes possible the development of "virtual rehabilitation assistants." Using motion sensors such as accelerometers and gyroscopes that are embedded in a wearable device, the "assistant" can mediate between patients at home and physical therapists in the clinic. Its functions are to:

- use motion sensors to record home exercise metrics for compliance and performance and report these metrics to physical therapists in real-time or periodically;
- allow physical therapists and patients to quantify and see progress on a fine-grain level;
- record symptom levels to further help physical therapists gauge the effectiveness of exercise prescriptions;
- offer real-time mistake recognition and feedback to the patients during exercises;

One contribution of this thesis is an evaluation of the feasibility of this idea in real home settings. Because there has been little research on wearable virtual assistants in patient homes, there are many unanswered questions regarding their use and usefulness:

Q1. What patient in-home data could wearable virtual assistants gather to support physical therapy treatments?

Q2. Can patient data gathered by virtual assistants be useful to physical therapists?

Q3. How is this wearable in-home technology received by patients?

I sought to answer these questions by implementing and deploying a prototype called "SenseCap." SenseCap is a small mobile device worn on a ball cap that monitors patients' exercise movements and queries them about their symptoms. A technology probe study showed that the virtual assistant could gather important compliance, performance, and symptom data to assist physical therapists' decision-making, and that this technology would be feasible and acceptable for in-home use by patients.

Another contribution of this thesis is the development of a tool to allow physical therapists to create and customize virtual assistants. With current technology, virtual assistants require engineering and programming efforts to design, implement, configure and deploy them. Because most physical therapists do not have access to an engineering team they and their patients would be unable to benefit from this technology. With the goal of making virtual assistants accessible to any physical therapist, I explored the following research questions:

Q4. Would a user-friendly rule-specification interface make it easy for physical therapists to specify correct and incorrect exercise movements directly to a computer? What are the limitations of this method of specifying exercise rules?

Q5. Is it possible to create a CAD-type authoring tool, based on a usable interface, that physical therapists could use to create their own customized virtual assistant for monitoring and coaching patients? What are the implementation details of such a system and the resulting virtual assistant?

Q6. What preferences do PTs have regarding the delivery of coaching feedback for patients?

Q7. What is the recognition accuracy of a virtual rehabilitation assistant created by this tool?

This dissertation research aims to improve our understanding of the barriers to rehabilitation that occur because of the invisibility of home exercise behavior, to lower these barriers by making it possible for patients to use a widely-available and easily-used wearable device that coaches and monitors them while they perform their exercises, and improve the ability of physical therapists to create an exercise regime for their patients and to learn what patients have done to perform these exercises. In doing so, treatment should be better suited to each patient and more successful.

Glossary

Sagittal Plane – A vertical plane that passes from front to back, dividing the body into right and left halves.[1]

Coronal Plane – A vertical plane that passes through the side of the body and divides it into front and back sections.[2]

Transverse Plane – A horizontal plane that divides the body into upper and lower parts. It is perpendicular to the coronal and sagittal planes.

Flexion – A bending motion that *decreases* the angle between a segment and its connected segment. For example, bending the elbow or the knee are examples of flexion.

Extension – The opposite of flexion, describing a straightening movement that *increases* the angle between body regions. For example, when standing up, the knees are extended.

Abduction – A motion that pulls a body region away from the midline of the body. For example, raising the arms up, such as when tightrope-walking, is an example of shoulder abduction.

Adduction – A motion that pulls a body region toward the midline of the body. For example, dropping the arms to the sides, or bringing the knees together, are examples of adduction.

Internal Rotation – Rotating a body region towards the center of the body. For example, when arm wrestling, both persons are attempting internal rotation of the shoulder.

External Rotation – The opposite of internal rotation - rotating a body region away from the center of the body.

1. The term sagittal is derived from the Latin word Sagitta, meaning "arrow". An image of an arrow piercing a body and passing from front (anterior) to back (posterior) on a parabolic trajectory would be one way to demonstrate the derivation of the term.

2. The term coronal also means the frontal bone - a wide, side-to-side bone of the head – from which the definition of the plane was derived.

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Huang, K., Sparto, P.J., Kiesler, S., Siewiorek, D. and Smailagic, A. iPod-based in-home system for monitoring gaze-stabilization exercise compliance of individuals with vestibular hypofunction. Journal of NeuroEngineering and Rehabilitation, 11, 1 (2014), 69.

1. Introduction

Physical therapy is often part of current treatment methods for many neurological and musculoskeletal problems, including balance disorders, spinal cord injuries, and joint mobility disorders. These disorders affect millions globally. In the U.S., up to 25% of the population experience balance disorders [Agrawal, '09; Neuhauser, '08] and more than 20 million have knee osteoarthritis, suffer joint pain, weakening of quadriceps muscles, and restrictions in mobility [Shiel, '08].

Physical therapy treatment programs typically last several months and involve daily exercises at home and bi-weekly (or more) clinical visits with a physical therapist (PT) [Szturm, '94]. At the start of many treatment programs, the PT diagnoses the patient's condition and prescribes a home exercise regime. In follow-up visits, the PT assesses the patient's progress and makes a decision on how to adjust the patient's exercise prescription, deciding which exercises to add or remove and how to adjust the exercises' parameters, including frequency and difficulty.

1.1. Lack of Patient Home Exercise Information

Because patients' exercises are performed at home, PTs cannot supervise patients directly and do not have observable or quantitative exercise data indicating whether patients are compliant with the prescribed exercise frequency and whether they are performing the exercises correctly. Without this information, it is difficult for PTs to make informed decisions on treatment adjustments. When patients do not show expected improvement, it is difficult to deduce whether the cause is ineffectiveness of the exercise, patient non-compliance with the exercise prescription, a significant issue in physical therapy [Sluijs, '93], or incorrect patient performance of the exercises. To make informed decisions, PTs need to know how often patients exercise, the duration (or repetitions) of each session, the average velocities and ranges of motion in each session, the symptom levels (*e.g.* pain or dizziness) before and after exercise, and what mistakes patients make.

1.2. Virtual Rehabilitation Assistants

Many researchers have examined the use of computerized technology for supporting home physical therapy exercises, including infrastructure-based systems and mobile devices. Infrastructure-based systems include those that use built-in systems such as the Kinect and Wii in conjunction with an output device such as a television [e.g. Chen, '12; Su, '12]. However, research has shown that infrastructure-based technologies may not be suitable for many patients. Axelrod & Fitzpatrick [Axelrod & Fitzpatrick, '09] showed that many elderly patients dislike technology that is complex to set up and maintain. In addition, their study and a study by Balaam and colleagues [Balaam, '11] showed that many patients do not like technology tethered to the living room.

Small, easily placed and removed wearable technology could satisfy patients' preferences. Wearable devices are portable and self-contained, making them potentially easier to set up and configure. With the increasing ubiquity of mobile sensors, such as accelerometers and gyroscopes, wearable technology has the potential to accurately measure body joint movements, and may be able to track movements unobtrusively while patients engage in their activities of interest. It might entail simple devices with a single sensor or complex devices with multiple sensors and a body area network. Wearable, mobile devices are especially promising for supporting home physical therapy exercises. Sensors on these devices can be used to provide real-time analysis of physical movement and to record exercise metrics for patients and PTs to review. These metrics would allow PTs to make informed decisions regarding treatment adjustments. I call a system using this approach a "v*irtual rehabilitation assistant (VRA)*."

Researchers have begun to explore the use of VRAs for supporting physical therapy treatment [Brutovsky & Novak, '06; Melzi, '09; Milenkovic, '02; Taylor, '12; Taylor, '10; Tseng, '09], but their studies were conducted in controlled laboratory settings where researchers could oversee patient exercises and technicians could set up and monitor the technology. Using storyboarding, Chandra and colleagues [Chandra, '12] explored the needs of physiotherapy patients in the home. Deploying working systems into real patient homes could raise many issues not illuminated in a lab or hypothetical setting. We lack information on how a virtual rehabilitation assistant would work in patients' homes where therapists are not present, the context is uncontrolled, and patients have no professional support.

1.3. Two Research Gaps – Foci of Thesis

In addition to the lack of research on how s VRA, deployed in real patient homes, might aid PTs, there is also a lack of research on how PTs would obtain and adapt it for particular patients. There are many physical therapy domains, each having alternative exercises and parameters of those exercises. Today, a virtual assistant that could monitor an exercise does not exist, so should a PT want to use one, they would require engineers and programmers to develop, configure and deploy it. Because most physical therapists do not have access to an engineering team, this technology is mostly infeasible in a real clinical setting.

This dissertation aims to make progress in assessing the usefulness of a VRA in the home and in creating an application for PTs to adapt it for their own use. First, I assess the potential of a virtual rehabilitation assistant by designing and deploying a technology probe, SenseCap, to examine how PTs and patients would use such a system in a real context. Second, I explore the design, implementation and evaluation of a VRA authoring tool for allowing PTs to use their own familiar anatomical language to create and customize a VRA.

1.4. Thesis Overview

Chapters 2 and 3 describe the implementation and deployment of an application called SenseCap to explore how a VRA could be used by PTs and patients when in patients' homes. In this exploration, balance rehabilitation, which treats disorders affecting approximately 69 million Americans [Agrawal, '09], was used as the test domain.

Chapter 4 describes a second domain in which PTs frequently prescribe body movement exercises: orthopedic physical therapy. Orthopedic physical therapy is prescribed for arthritis patients, knee and hip replacement surgery patients, and many others. I used it as a test domain to explore the creation of an authoring tool with which PTs can create and customize a virtual rehabilitation assistant for various orthopedic exercises. Chapter 4 gives detailed information about this domain and chapter 5 presents the implementation details of the authoring tool.

Chapter 6 describes an evaluation of the authoring tool with nine PTs; chapter 7 describes an evaluation of the VRA created under this architecture and its accuracy in recognizing correct and incorrect exercise movements. Chapter 8 concludes the thesis and discusses future work.

2. SenseCap Techology Probe – Design, Implementation, Sensor Testing

Research with SenseCap differs from prior research in that it applied a common, ubiquitous, commercial device in a clinical patient home setting. The exercise of focus was a commonly prescribed balance rehabilitation exercise called the Gaze Stabilization Exercise [Tchain.com, '02]. Patients fix their eyes on a target, such as an "OK" sign or a business card, placed three feet in front of them, and rotate their head side-to-side (yaw direction) for typically 30 seconds. They repeat the exercise in the up-and-down (pitch) direction. These movements strengthen the vestibular function through neural stimulation [Whitney & Sparto, '11].

SenseCap consists of an iPod Touch 4G fitted into a baseball cap. Patients wear the hat when they exercise and take it off when they finish. SenseCap collects compliance and performance data and communicates them to PTs through an iPad-based PT Dashboard.

Figure 2.0. The SenseCap

2.1. SenseCap Prototype

SenseCap has three components: an iPod Touch 4G, a cap with a sewn-in sleeve to hold the iPod (Figure 2.0), and a custom software application. Patients wear the cap when they perform the head rotation exercises. Since the iPod has a capacitive touch screen, it can be operated through the see-through sleeve.

The iPod Touch 4G contains a 3-axis accelerometer and a 3-axis gyroscope. With these sensors, it is possible to measure head rotation velocity (degrees/sec), frequency (rotations/sec) and range of motion (degrees).

2.2. SenseCap Metrics

SenseCap gathers the following quantitative patient exercise data, used for metrics useful to PTs.

Times of exercise each day – The application automatically timestamps the start and end of each session and allows PTs and patients to see number of exercises performed each day.

Exercise duration – For this exercise, PTs use duration rather than number of repetitions because the latter can become high and cumbersome to count (100+). A simple difference between start and end time of sessions is used to record the duration. The durations were rounded to the nearest 10 seconds at PTs' request.

Average head-turn velocity – The iPod provides the rotation velocity about its own X, Y and Z axes. I transformed the data into earth-fixed velocities to accurately measure the yaw (side-to-side) and pitch (up-and-down) rotations of the head.

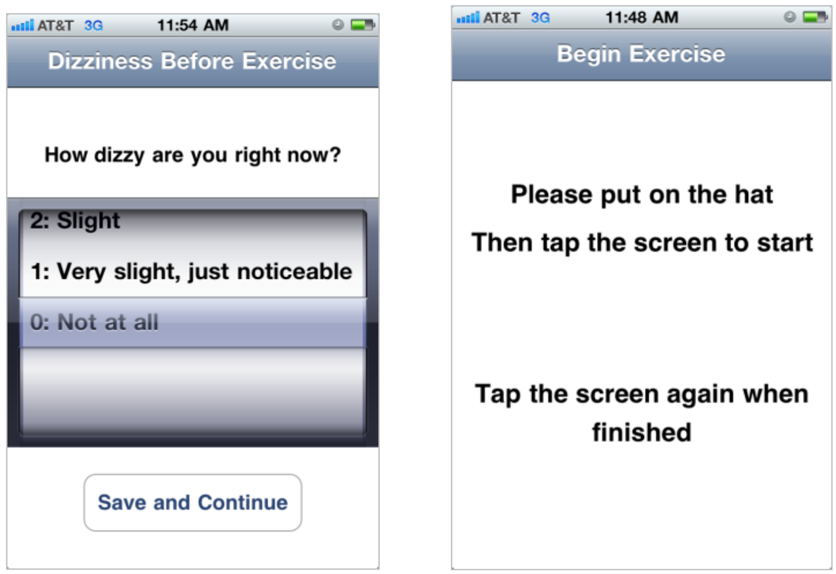
Turns-per-second – I segmented the data to calculate the number of repetitions, which was then divided by the exercise duration to create turns per second.

Average head-turn range of motion – I integrated the velocity data to calculate range of motion for each repetition and averaged them for each session.

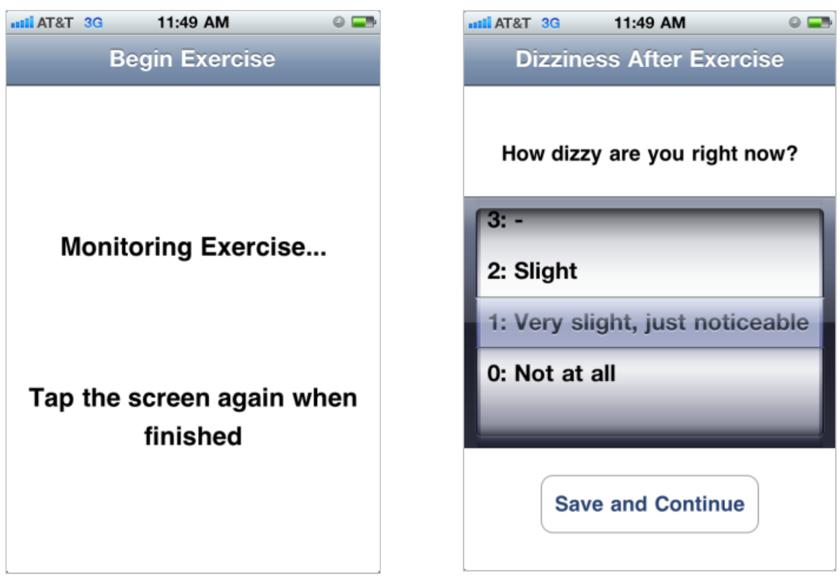
Dizziness before and after each session – Patients entered this dizziness rating (0 to 10) before and after each exercise (Figure 2.1). The scale was modeled after the paper rating scale used in the physical therapy clinic and requested by PTs. PTs want to know if patients are dizzy after exercising. For some conditions, the patients should be dizzier after the exercise to encourage recalibration of the patient's vestibular system.

2.3. SenseCap iPod User Interface

A series of simple displays on the iPod leads patients through the exercise (Figures 2.1 to 2.4). When patients first launch the SenseCap iPod application, they are prompted, via screen as well as voice prompt, to enter their current level of dizziness (Figure 2.1). Another dizziness rating is prompted after the exercise so that the difference can be measured.



Figures 2.1 and 2.2 – SenseCap iPod user interfaces



Figures 2.3 and 2.4 – SenseCap iPod user interfaces

After they enter their pre-exercise dizziness, patients put on the cap and tap the screen anywhere to start (Figure 2.2). Upon a tap, a voice announces “begin” and they begin their exercise. To assist with exercise timing, SenseCap announced, through audio, the time elapsed every 10 seconds for up to 60 seconds.

When they finish, they tap on the screen again and a voice announces “finished” (Figure 2.3). A voice then asks them to take off the cap and enter their post-exercise dizziness rating (Figure

2.4). Because some patients had hand tremors, I implemented a 3-second threshold after the starting tap before the system would recognize the finishing tap.

After entering the post-exercise dizziness rating, patients are then asked whether they need to perform another exercise or finish and return the iPod to its charger. Patients may tap "Perform Another Exercise" to begin a second exercise. Finally, a summary screen is also available to patients to reassure them that the system is working in recording the exercises.

2.4. iPad PT Dashboard

The patient exercise data are stored on a web server and presented to PTs through a PT Dashboard on the iPad, as shown in Figure 2.5.

Figure 2.5. The iPad Dashboard

2.5. SenseCap Sensor Validation

A technology probe will be of little value if the system's main function is defective. In this regard, SenseCap needed to capture patient exercise movements accurately. Therefore, it was necessary to validate this functionality of SenseCap.

Before conducting the in-home study with patients, I validated the head-referenced yaw and pitch velocity measurements of SenseCap against a commercially available magnetic field motion tracking system (Fastrak, Polhemus, Inc, Colchester, VT, RMS Static Accuracy 0.15 deg). Healthy control patients without a history of vestibular disease (six male, two female, age 18-50) performed head movements that are similar to those used in vestibular rehabilitation.

While performing the head movements, patients wore a plastic rock-climbing helmet to which the motion tracker and iPod were rigidly attached. The iPod was tested in three pitch inclinations from the horizontal (0, 45 and 90 degrees).

Each participant was asked to perform head movements for 30 seconds under varying conditions: orientation of iPod (0, 45, 90 degrees), frequency of head motion (0.25, 0.5, 1 Hz), direction of turning (pitch, yaw). The frequency of head turns was controlled by playing a metronome and asking the participants to move in synchrony with it. Each participant performed 18 trials to include all the combinations of the above, in randomized order. Each participant used one of three different iPods to test for consistency across iPods.

For each trial, a correlation coefficient was computed to determine the strength of association between the magnetic field motion tracker and iPod measurements of yaw and pitch velocity, using the entire time series. The correlations between the measurements were high and consistent across all experimental conditions. Across all patients and trials, the mean correlation was 0.99 (standard deviation 0.005). Furthermore, the average Root Mean Square error between the measurements was 3.4 deg/sec (SD 5.5 deg/sec), across a range of speeds from 58 to 178 deg/sec. It was concluded that SenseCap measurements were valid.

3. SenseCap User Study with Patients and PTs

After sensor validation, SenseCap was deployed for seven days in 10 clinical patient homes. Patients were recruited by vestibular rehabilitation PTs from the University of Pittsburgh Medical Center.

3.1. Patient User Study

3.1.1. Method

All patients were given the head-turn exercise prescription by their PTs. I did not intervene in the prescription process. They were briefly instructed in SenseCap in the clinic after they received the exercise prescriptions. The patients took the SenseCap hat home and used it for seven days.

At the end of the seven-day trial, patients returned SenseCap and completed a questionnaire on its usability. They also were interviewed briefly about their experience.

Columns 1 through 4 of Table 1 show the patient demographics and their prescriptions. For example, patient 1 was prescribed a set of side-to-side and up-and-down exercises three times a day (6 exercises total), with each exercise being 30 seconds long. The gender range in the patient sample reflects the actual vestibular patient distribution. As can be seen in the table, the prescriptions varied in exercise duration and daily frequency prescribed for patients.

The next section presents the patient home-exercise compliance and performance data captured by SenseCap.

3.1.2. Compliance Results

Table 3.1. Compliance data of patients during probe.

Patient	Gender	Age	Prescription	Direction	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1	F	59	3x30s	Yaw	1x60	1x60	1x60	1x60	1x60	1x60	Stopped *
				Pitch	0	1x60	1x60	1x60	1x60	1x60	
2	F	65	2x30s	Yaw	1x30	1x30	**3x30**	*2x30*	1x30	1x30	**3x30**
				Pitch	1x30	1x30	**3x30**	*2x30*	1x30	1x30	**3x30**
3	F	67	8x60s	Yaw	1x60	1x60	1x60	2x60	2x60	1x60	2x60
				Pitch	1x60	1x60	1x60	2x60	2x60	1x60	2x60
4	F	52	6x60s	Yaw	1x30	1x50	1x30	2x30	1x30	1x30	Returned early
				Pitch	0	1x50	1x30	0	1x30	1x30	
5	M	53	2x30s	Yaw	**2x60**	**4x60**	**4x60**	**4x60**	**4x60**	**4x60**	**4x60**
				Pitch	**2x60**	**4x60**	**4x60**	**4x60**	**4x60**	**4x60**	**4x60**
6	F	58	3x30s	Yaw	*3x30*	**6x30**	*3x30*	*3x30*	**5x30**	**6x30**	*3x30*
				Pitch	1x30	**5x30**	**4x30**	*3x30*	0	**6x30**	*3x30*
7	F	47	4x60s	Yaw	**5x60**	*4x60*	**4x90**	**4x90**	**4x120**	Returned early	
				Pitch	*4x60*	*4x60*	**4x90**	**4x90**	**4x120**		
8	F	28	6x60s	Yaw	**9x60**	**18x60**	**25x60**	**13x60**	iPod error **		
				Pitch	0	0	0	0			
9	M	54	3x30s	Yaw	2x30	*3x30*	*3x30*	1x30	2x30	2x30	1x30
				Pitch	0	*3x30*	*3x30*	1x30	2x30	2x30	1x30
10	M	36	5x60s	Yaw	4x60	**6x60**	**10x60**	*5x60*	*5x60*	iPod error **	
				Pitch	3x60	**7x60**	**10x60**	*5x60*	**7x60**		

Columns 6 through 12 of Table 3.1 show the actual exercise frequency of patients. Shaded cells are days where the patient was under-compliant, i.e. exercised less than prescribed. Unshaded cells with italic font are days where the patient exercised the same amount as prescribed. Unshaded cells with bold font are days were the patient was above-compliant, i.e. exercised more than prescribed. For example, patient 1 was prescribed 3 sets of exercises, 30 secs each (3x30s), but on day 1, she only did 1 exercise for 60 secs (1x60), so she was under-compliant for that day.

Some patients returned the iPod early – before 7 days – because of their scheduling constraints. For two patients, the iPod application crashed due to a bug towards the end of the trial. In confirmation of survey studies, approximately half the patients were under-compliant. Sluijs et al [Sluijs, '93] surveyed 300 PTs of various domains about their patients' compliance rates; these rates were measured by patient retrospective self-report. The study found that non-compliance rates might be as high as 70%. However, SenseCap gathered data that might not be captured in survey studies, e.g., that five of the patients exercised more than prescribed. One patient (#8) exercised significantly more, peaking at 25 sets of horizontal exercises in one day compared to the prescribed six sets.

3.1.3. Patient Performance Results

Head movement metrics (range of motion and velocity), showed substantial variability, both inter-subject and intra-subject. Inter-subject variability was shown with the mean values of head velocity ranging from 98 to 204 deg/sec in the yaw direction. Intra-subject variability is exemplified by patient #3 who showed a range of 113 to 222 deg/sec throughout the trial. Similar variability was seen among the patients for range of motion, ranging from 20 to 124 degrees for yaw direction and 5 to 71 degrees for pitch direction. Documenting such variation is potentially of considerable importance in customizing exercises and prescriptions to patient needs.

3.1.4. Symptom Level Results

Another metric recorded by the device was dizziness ratings before and after each exercise. These daily ratings are important to PTs because they show the subjective effects of exercise. Physical therapists conventionally ask patients to provide dizziness ratings in paper diaries. PTs interviewed reported that this approach has a very low compliance rate, although exact numbers have not been documented. However, researchers have documented paper-diary compliance rates in other domains such as for pain patients. A study by Stone et al. showed that paper diaries had only an 11% compliance rate [Stone, '03]. This study also showed that an electronic diary, such as the dizziness-rating logging function in our system, which can timestamp entries automatically, yielded a much higher compliance rate (94%). The study suggests that automatic time stamping discourages fake diary construction and motivates patients through accountability.

Patients in this study started with a low mean dizziness severity rating prior to performing the exercises, about level 2 (equated with "slight" dizziness). The lowest and highest values were 0.2 and 4.7. Immediately after the exercise was performed, yaw movements induced slightly more dizziness than pitch movements (increase of 0.6 points v. 0.3 points) on average.

3.1.5. Patient Critique

Comfort

When asked the question: "How comfortable was the cap to wear," with the options being: "Very comfortable", "comfortable", "neutral", "uncomfortable", and "very uncomfortable". Two patients reported "very comfortable", six patients reported "comfortable", and two patients reported "neutral".

One patient reported that he felt the weight of the iPod (101 grams, half the weight of a roll of quarters), though it did not interfere with the exercises.

Exercise Interference

For the question, “Did the hat interfere with your exercises,” five patients reported “not at all” and five patients (IDs 1, 2, 6, 8, 10) reported “a little”. Two types of interference were reported. The first type dealt with vision obstruction and the second type dealt with sizing and fit.

Some patients reported that when they performed the up-and-down exercises, the brim of the hat obstructed their vision of the OK sign in front of them. Some of these patients reported fixing this quickly by rotating the hat upwards so that the brim points higher. Others reported not being able to fix this particular issue and suggested a hat with a shorter brim or none at all.

Some patients reported that interference was caused by the cap being too loose, even at the tightest Velcro adjustment. This prompted them to hold on to the hat with one hand while doing the exercises. They suggested having different size hats for men and women to provide more accurate sizing.

3.1.6. Motivation Through Accountability

Patients reported an increase in their motivation and dedication during the interviews. Patients 2 and 8 stated:

“It was more motivating to do the exercise knowing that I was accountable…that it was going to record whether I did it or not. People should do it for all exercises; then they wouldn't skip so much.” – Patient 2

“I have a 2-year old… I’m running around all the time. With this, I felt more dedicated to doing it. I had to set aside time and be dedicated.” – Patient 8

3.2 PT User Study - Communicating Patient Exercise Data to Physical Therapists

PTs have limited time for each clinical session, and an increase in time spent deciphering data means a decrease in time spent with patients. Thus, the patient in-home exercise data presented to PTs should be quickly and easily comprehensible as well as useful for treatment decision making.

Patient in-home exercise data was presented to PTs using a series of charts (visualizations of the data) to gather their feedback on the data’s importance and comprehensibility.

3.2.1. Method

The following exercise data components were visualized on an iPad PT Dashboard: Patient compliance, performance metrics, and symptom levels. The visualizations were created with a PT collaborator.

These data and their visualizations were presented to four independent vestibular rehabilitation PTs who were not involved in the creation of SenseCap. They were shown hypothetical patient data as would be gathered with the system. This hypothetical patient data was created in order to intentionally insert problematic performances to see if the data and visualizations were effective in communicating these problems. Many of the inserted problems came from actual patient data. I named the hypothetical patient Sally.

3.2.2. Communicating Exercise Compliance

Compliance data are crucial as they quickly inform the PT if patients have adhered to the prescription. The key pieces of information are: how many times a day patients exercised and how long each exercise session lasted. (For other types of rehabilitation, such as knee osteoarthritis, repetition counts are often used instead of session duration.)

Since there are two types of exercises in this study (side-to-side and up-and-down), PTs also wanted to know the ordering of these exercises. Were patients doing all of the side-to-side exercises together or interleaving them with up-and-down exercises as instructed? To encode number of exercises, their durations, and the exercise order, I used a stacked bar chart as shown in Figure 3.1.

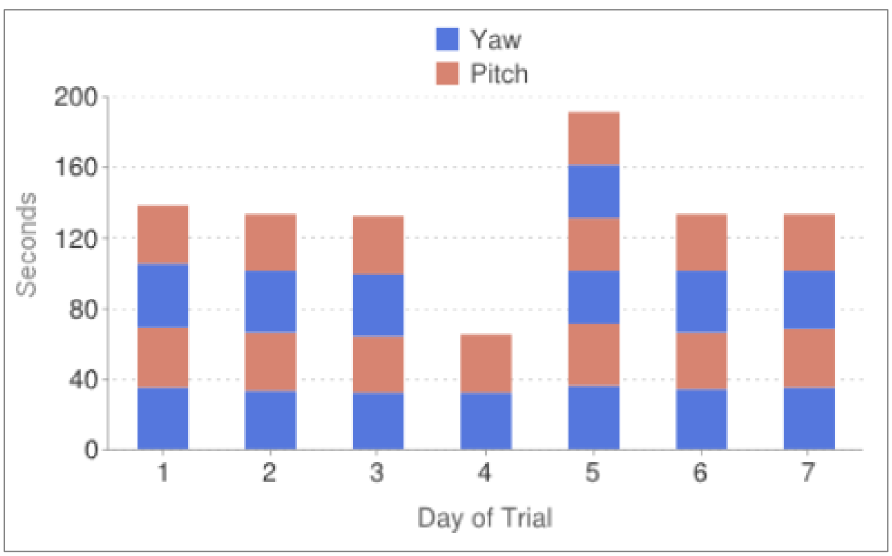


Figure 3.1. Patient Sally exercise compliance chart. Each block represents one exercise performed.

As can be seen from Sally's chart, the abnormality inserted was that the patient did four exercises on the first three days, but skipped two on the fourth day and then tried to make up for it by doing more on the fifth day.

PT Comments and Suggestions

PTs appreciated the concise nature of this data summary. They recognized the missing sessions on day four, but stated that it was an insignificant lapse and that the patient still showed good compliance overall. PTs found the compliance data to be important.

PTs suggested that they wanted to be able to see the time of day when patients were doing these exercises, e.g., were they doing them all in the morning, the evening, or more evenly spaced out (the last option being most beneficial). Thus, encoding exercise-time-of-day into the visualization would be important for future rehabilitation systems.

3.2.3. Communicating Exercise Performance Metrics

I presented data regarding head-turn velocity (degrees/sec), turns-per-second, and range of motion (degrees) to PTs. Figure 3.2 shows an example metric chart (range of motion).

Unlike the duration chart, I did not mix the two exercises into one since the blue and red dots may overlap and become indistinguishable. Thus, I separated the side-to-side and up-and-down exercises into a pair of charts, as shown in Figure 5. The dots are translucent and appear darker when overlapped by sessions with similar values.

PT Comments and Suggestions

PTs found the exercise metrics data valuable. One PT found the velocity metric, expressed in degrees per second, difficult to interpret. For example, she stated: “It’s hard to get a sense of how fast say 52 degrees per second is...” She suggested having categories of “slow”, “medium” and “fast.” All of the PTs found the turns-per-second and range of motion metrics helpful.

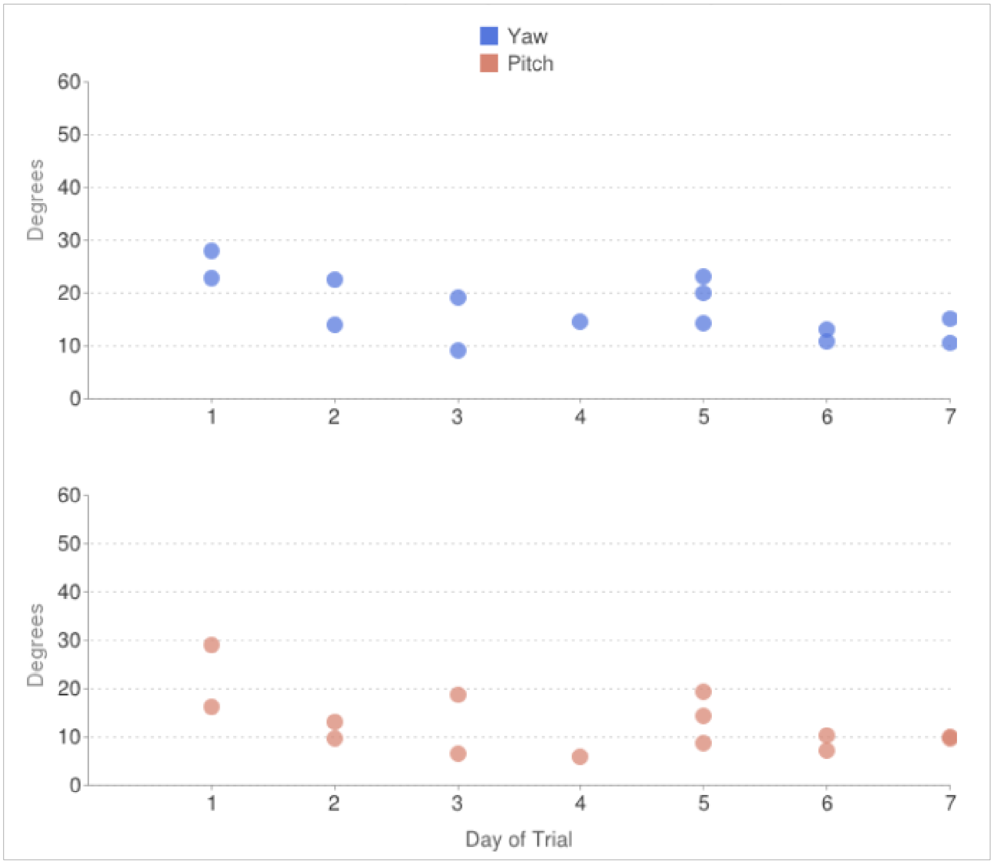


Figure 3.2. Patient range of motion chart. Each dot represents one exercise performed. Dots may overlap.

3.2.4. Communicating Pre-Post Exercise Symptom Levels

Pre and post exercise symptom levels are important information to PTs, whether they are dizziness ratings or pain ratings. They indicate the level of stimulation of the exercise. PTs usually try to find the right balance in prescribing exercises that are not too easy and not too difficult.

The pre and post exercise dizziness levels in this case posed unique challenges for summarizing in an easily interpretable format. PTs not only needed to know the exact ratings, but also to quickly understand their intra-session and inter-session patterns of change. I used a pair-point graph with connected lines, as shown in Figure 3.3. Each pair of points represent the before and after ratings of one session, and the line helps to connect them as well as visualize their direction of change (increase, decrease or plateau).

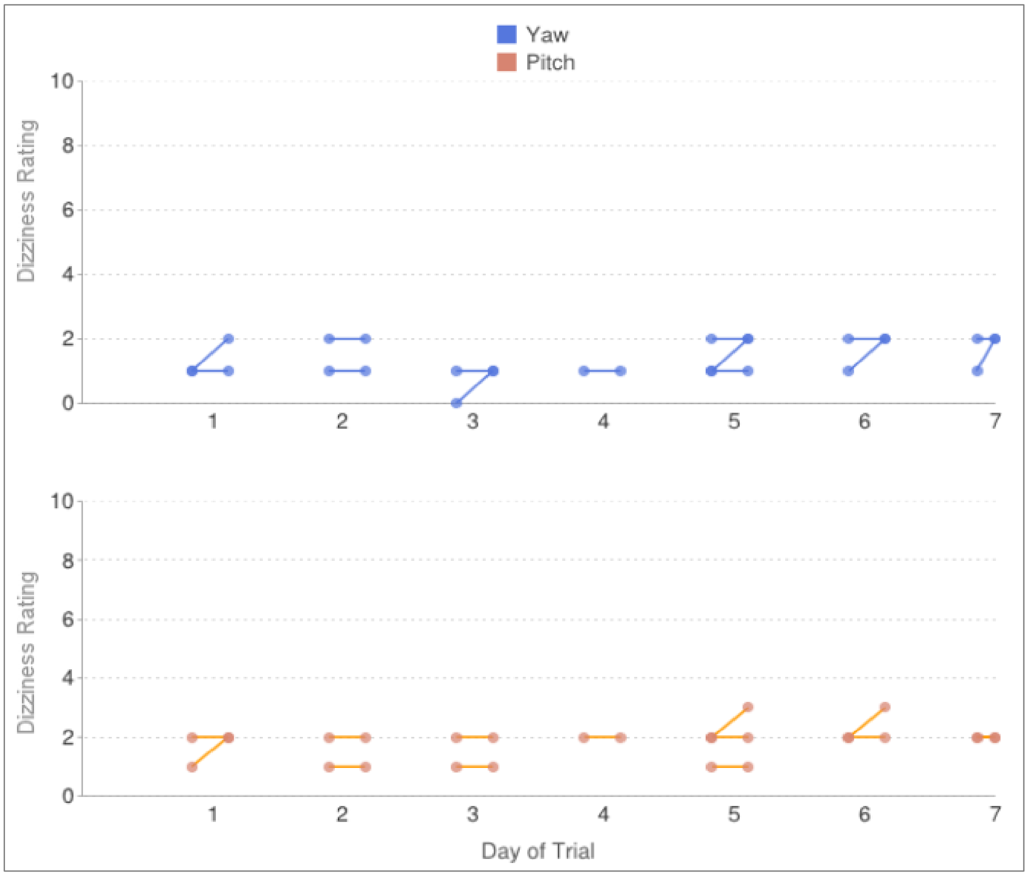


Figure 3.3. Pre and post-exercise dizziness levels. Each pair of dots, connected by a line, represents the pre- and post- dizziness of an exercise performed. Dots may overlap.

PT Comments and Suggestions

PTs appreciated this data component and recognized that many of the sessions involved plateaus in symptom levels. Given this information, PTs stated that they would increase the difficulty level by asking the patient to target faster turning speeds or a larger range of motion, or add more advanced exercises to the prescription.

PTs wanted more information regarding the reason for plateaus, increases, and decreases in symptom levels. They suggested having charts that allow them to easily see performances metrics associated with a certain dizziness rating. For example, if an exercise session were marked by a plateau in dizziness ratings, then they should be able to quickly check that session's average range of motion. If it is low, then it shows that the patient was not exercising rigorously enough to induce symptoms. If it is normal, then that suggests that the exercise has become too easy for the patient, and exercises that are more difficult should be introduced.

Because there are many components to patient home exercise data, PTs also reported a need for a summary screen. In our PT Dashboard, I provided the data components on separate screens, requiring the PTs to tap through them one by one. They stated that a summary screen which shows all of the metrics (exercise durations, range of motion, dizziness levels, and so forth) at once would allow for faster understanding of the big picture regarding patient home exercises. Errors and abnormalities can be highlighted here for more detailed investigation.

Although patients felt that SenseCap increased their motivation through accountability, the PTs interviewed about the patient data felt that SenseCap could increase patient motivation in another respect. They stated that one major reason for non-compliance in physiotherapy is pain and discomfort of the exercises. Vestibular patients are often debilitated by resulting dizziness after exercises. Not only is this uncomfortable but it can also be a major obstruction to their daily activities. To make the pain "worth it", they need to see benefits from the exercises. However, when progress is slow, it is difficult for them to see progress from day to day or at times week to week. This often leads to abandoning of exercise regime. Thus, PTs stated that being able to show incremental progress through SenseCap would be a significant motivating factor. PT 3 specifically states:

"That would be kind of helpful to me to be able to show them the differences, you know what I'm saying? I mean how much you couldn't move your head or how slowly you moved your head and now we are in week three and look how much better that is…Yes, motivational or you know what? Look at this week one and week three…"

3.3. Design Recommendations

This section synthesizes the findings, presents additional lessons learned, and provides design implications for creating wearable physical therapy home exercise support systems. The discussion centers on two main topics: (1) what to capture and communicate about patient in-home exercises, and (2) patients' special needs and preferences.

3.3.1. Patient Exercise Data to Capture and Communicate

Because PTs have limited session-time and need to make rapid patient assessments, systems should allow PTs to glean the following key pieces of information quickly:

Exercise Compliance and Timing

Prior work in capturing patient compliance data typically records repetition counts or session durations. For example, Balaam et al. described a system that counted daily repetitions of a hand exercise for a stroke patient [3]. While repetition and duration are key pieces of information, our findings showed that PTs sought detailed information on exercise timing as well. Specifically, they needed information on exercise time-of-day (morning, afternoon, evening), and exercise ordering (i.e. whether patients did all of the side-to-side exercises together or interleaved them with up-and-down exercises). This information conveys not only compliance but also the spacing of the exercises, which can impact their effectiveness.

It is thus recommended that visualization of compliance data also support rapid assessment of exercise time-of-day and ordering. A stacked bar chart can be used to visualize exercise duration and ordering together, as in Figure 3.2. When patients do the same exercise (e.g. side-to-side) several times in a row, a separator could be added to distinguish between contiguous bars of the same color. Exercise time-of-day could be encoded using patterns in addition to the colors, such as cross-stitch or horizontal lines for representing daytime and evening.

Above-Compliance of Exercises

Much focus of past physiotherapy-compliance research has been on non-compliance or under-compliance. For example, one survey by Sluijs et al. [14] asked patients "Did you manage to exercise regularly last week?" with the options of: "(1) not at all, (2) a little, (3) rather regularly, (4) very regularly."

However, our findings showed that five patients exhibited above-compliance, a phenomenon that has been less documented – perhaps partly due to the wording of questions such as the above which do not include an above-compliance option. PTs informed us that even though above-compliance can be a positive sign of motivation, excessive levels can worsen symptoms. Patient #8, peaking to 25 sets in one day (compared with her prescription of 6) was later asked to reduce her sets by her PT who was informed by the probe data.

It is recommended that above-compliance as well under-compliance data be highlighted in visualizations as both information are important to PT decision making. In addition, systems with real-time feedback can caution the patient accordingly when detecting significant above-compliance.

Exercise Performance and Symptom Levels

Prior work on quantifying exercise performances focused on movement metrics such as velocity, frequency (repetitions per second) and range of motion [7, 18]. Similar metrics were sought by the PTs in our study.

In addition to these metrics, however, I discovered that the PTs considered symptom levels (dizziness in this case) to be just as important for informing treatment decisions. PTs used pre- and post-excise symptom levels as the bottom-line measurement of an exercise's effectiveness. In the case of this exercise, dizziness levels would ideally increase after an exercise (intra-session), signifying that the exercise has a stimulating effect, but decrease over time (inter-session), signifying gradual neural strengthening and adaptation.

Thus, systems should support the assessment of this rehabilitative process by: (1) encouraging patients to log their symptom levels before and after an exercise, (2) provide visualizations to view intra-session trends, and (3) provide visualizations to view inter-session trends. Figure 6 shows an example of a possible visualization to show both intra- and inter-session trends together.

3.3.2. Patients' Needs and Preferences to Support

Patients' Spatial Preferences

Axelrod & Fitzpatrick and Balaam et al. reported that patients strongly prefer certain home locations where they do their rehabilitation exercises [2, 3]. Our observations support and extend this finding. Patient 4, who suffered nerve damage through a brain inflammation, was too dizzy to drive to the clinic and needed home-visits to receive and return SenseCap. When interviewed her at home, she explained that the kitchen was an ideal place to compensate for her level of dizziness because she frequently needed something to hold on to. With the OK sign posted on her refrigerator, she could conveniently use her chairs for support. Thus, in addition to room preferences based on aesthetics and space availability, as shown by prior studies, I also recommend that system designers consider room preferences based on patients' needs for exercise scaffolding.

Supporting Patients with Cognitive Challenges

Some patients face cognitive challenges, including disorientation and forgetfulness. Patient 4 reported that her nerve damage caused her to experience confusion and memory lapses such as where she last put her pencil, or where she is in a public place such as a store. As a result, she reports that she often forgets either some exercise sessions, or an entire prescribed exercise altogether when given multiple exercises. Her exercise compliance for this study shows that she is very much under-compliant.

Another patient showed similar forgetfulness (Patient 8). Though she was very motivated to improve (performing many more side-to-side exercises than prescribed), she forgot to do up-and-down exercises entirely.

SenseCap did not include exercise reminder features, but these data confirm that it would be an important part of a physical therapy support system.

Supporting Patients with Physical Challenges

To reduce reliance on fine motor control, I allowed patients to tap the screen anywhere to begin monitoring exercise and tap anywhere when finished. However, I discovered a usability obstacle experienced by patients with hand tremors. These patients sometimes accidentally tapped the screen twice in rapid succession, causing the system to say “begin” and “finished” before they started exercising. As a solution, I added a 3-second threshold after the starting tap before the system would recognize the finishing tap. After this implementation, subsequent patients did not report the problem.

It is recommended that similar considerations for future systems when the same interface area is used for both the starting and stopping functions.

Adapting to Patient Variations in Sensor-Positioning

Another challenge I discovered was a variation in how patients wore their caps. I learned that cap positioning can vary not only along the pitch-axis (how high or low the brim was tilted), but also along the roll-axis which occurred when patients held on to a loose cap with one hand, causing one side of the hat to droop.

I initially used an algorithm for velocity transformation -from iPod velocities to earth-fixed velocities - that accounted for variations in the pitch axis. However, the unexpected variations in the roll-axis (horizontal slanting of the cap) created false errors during data analysis. It appeared as if the patients were moving out of plane and doing the exercises incorrectly.

After discovering this phenomenon through patient interviews and an analysis of the gravity vector data, which shows the slanting of the cap, I created a more robust algorithm to account for roll-axis variations as well. The validation data was re-run with the new algorithm, which did not affect its results since the validation test-patients wore the magnetic tracking helmet under supervision with only pitch-axis variations. When I re-ran the patient data using the new algorithm, the false errors disappeared.

It is recommended that future systems take into account all possible shifting of position and orientation of worn sensors within and between exercise sessions so that data transformation produces consistent exercise metrics.

Motivating Patients

Motivation can play a significant role in a patient’s recovery. Patients in our study appeared to have increased motivation because they felt more accountable for doing their exercises. To support patient motivation further, future systems could also highlight improvements from session to session, day to day, and week to week. These visualizations and highlights should be available to patients at any time and not just during clinical visits with PTs so that patients can get immediate and continuous motivational benefits.

In addition, the system could support goal setting, done collaboratively between PTs and patients. Goal-setting and information visualization has been used to motivate behavioral change in other domains such as sustainability [8]. Since exercise performance parameters are quantifiable in this setting, weekly target goals can be set to further track and motivate progress.

3.3.3. Limitations

Although SenseCap can track head movements, it cannot determine if patients are keeping their eyes fixated on a target, as they are directed to do. Usually with a short duration of in-clinic instruction of the gaze stabilization exercise, patients are able to maintain gaze fixation on the target. A limitation of the in-home study is that the participant sample size of 10 is small and may not be fully representative of the people who would be prescribed the exercises. The time period of seven days is shorter than typically necessary for a full evaluation; our goal for the user study was to inform design and assess feasibility.

3.3.4. Summary of Clinical Relevance

The motivating factor for developing this application was to optimize the prescription of gaze-stabilization exercises so that individuals with vestibular dysfunction could progress and recover more quickly. Several important features of the application could facilitate this process.

First, having a record of the duration and number of exercise repetitions, and being able to correlate this information with dizziness severity ratings, will allow the physical therapist and patient to discuss this information and decide on the best treatment plan going forward. Referring back to Figure 6, I can surmise that the patient was tolerating the gaze-stabilization exercises. Upon seeing this information, the therapist would probably progress the prescription to increase the velocity or the number of repetitions. Furthermore, the therapist could inquire about other circumstances that might explain the increased symptoms on those days. This recorded information represents an improvement over patient recall, which is often inaccurate [Ainsworth, ‘12]. While the same information could be entered into an exercise diary, using the iPod device may relieve the patient of the burden of remembering to log the information.

Another benefit is that the velocity of head movement has heretofore been largely ignored as a part of the prescription process, primarily because there has been no easy way to measure it at home. It is important to note that in this study, velocity of head movement was not prescribed by the physical therapist. Rather, the physical therapist usually asked the patients to perform the exercise at a comfortable speed. The function of the vestibulo-ocular reflex is to stabilize images on the retina at velocities of up to 350 deg/sec [29], and frequencies up to 5 Hz [30]. It is therefore important for people with vestibular disease to perform exercises at a variety of speeds and frequencies, so that they recover their full range of function. The system can provide this critical information, and future versions may incorporate real-time feedback so that users know the velocity at which they are moving their heads with each repetition. Using this system, physical therapists and patients would be able to view and correlate dizziness severity with head velocity, and adjust head velocity accordingly. Therapists could also examine the data to determine whether users were performing an exercise incorrectly by checking for any out-of-plane movements, e.g. tilting the head side-to-side.

3.4. Conclusion

In this research, a technology probe is presented for wearable physical therapy support systems, SenseCap, which was deployed into 10 patient homes for seven days. SenseCap consists of a white baseball cap fitted with an iPod Touch 4G and a custom application. Patients wear the hat when they exercise and remove it when they finish. The data are visualized on an iPad Dashboard to assist PT decision-making during clinical sessions.

The exploration with the SenseCap probe garnered lessons and design insights from both patient and PT perspectives for creating wearable Virtual Rehabilitation Assistants. The lessons and design insights focused on data that are important to capture and communicate and patients' special needs and preferences to consider.

Chapter 4 describes a second domain to which I tried to generalize virtual rehabilitation assistants. This domain, orthopedic physical therapy, contains many body-movement exercises, which made it suitable as a test domain to explore an authoring tool for creating and customizing a virtual rehabilitation assistant rapidly, without requiring programming expertise. Chapter 4 gives the background details on orthopedic physical therapy and Chapter 5 describes the implementation details of the virtual assistant authoring tool.

4. Orthopedic Rehabilitation Context

Although my technology probe with SenseCap showed that a virtual physical therapy assistant could be helpful for balance rehabilitation, I wanted to explore whether it can be generalized to other rehabilitation domains, such as neurologic, integumentary (pertaining to the skin and related organs) and orthopedic (pertaining to the joints and muscles). I chose orthopedic because it is the most common type of physical therapy, and its focus on joint movements lends itself well to a wearable-sensor-based exercise monitoring system. This chapter provides background information on orthopedic physical therapy, and the next chapter describes generalizing the virtual assistant technology to this domain.

4.1. Orthopedic Physical Therapy

Orthopedic physical therapy treats injuries to the muscles, bones and other tissues in the body. Patients might have been injured from accidents or playing sports, or they might have difficulties resulting from surgery or a chronic disease.

Orthopedic physical therapy treats many types of musculoskeletal injuries, including knee and hip injuries, which result in restrictions in mobility for 20 million Americans each year, shoulder injuries, which affect 13 million Americans each year, and spinal cord injuries which affect 300,000 Americans each year [reference to be included].

Orthopedic physical therapy usually includes exercises that aim to increase range of motion and strength, relieve pain, and restore mobility.

Below, in Section 4.2, I describe the joints and movements that may be the focus of orthopedic physical therapy and define some of the anatomical language that clinicians use to describe movements precisely. In Section 4.3, I describe exercises that focus on improving these movements.

4.2. Human Body Movement

There are three planes of movement for the human body, shown in Figure 4.1: sagittal, coronal, and transverse. For example, when kicking a soccer ball, the leg is usually traveling in the sagittal plane forward. When doing jumping jacks, the legs are usually moving side to side in the coronal plane. When rotating or turning in place, the hip is rotating in the transverse plane.

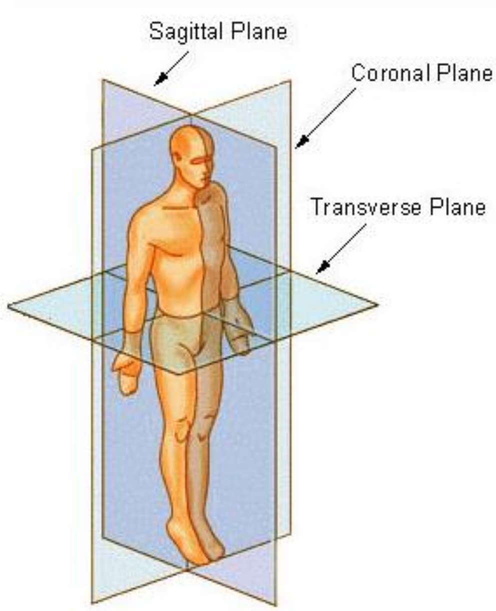
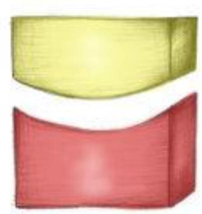


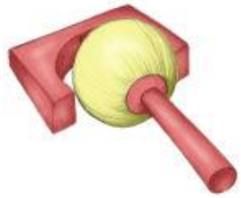
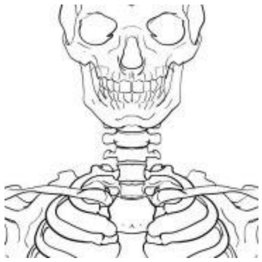
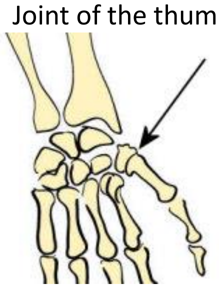
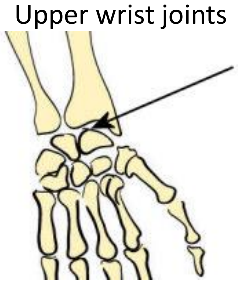
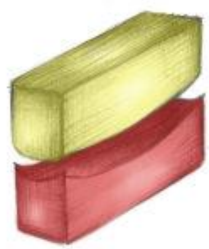
Figure 4.1. The three movement planes [Wikipedia.org, '15]

<u>Types of Joints</u>

Six types of joints in the body are commonly associated with movement. Table 4.1 shows these joint types, joints that belong to this type, and the movements of which they are capable. These movements are explained in Table 4.1.

Table 4.1. Types of joints, their structure, and their movements. [Images from TeachPE.com, '15]

Joint Type	Examples	Structure	Movement at Joint
Hinge	Elbow / Knee 		Flexion, Extension

Ball and Socket	Shoulder / Hip 		Flexion, Extension, Adduction, Abduction, Internal & External Rotation
Pivot	The neck 		Rotation of one bone around another
Saddle	Joint of the thumb 		Flexion, Extension, Adduction, Abduction, Circumduction
Condyloid	Upper wrist joints 		Flexion, Extension, Adduction, Abduction, Circumduction
Gliding	Lower wrist joints 		Gliding Movements

Types of Movements

As can be seen from the table above, the hinge and ball-and-socket joints cover the major movement joints of the body: Knee, elbow, shoulder and hip. The following section reviews the terms describing their movements: flexion, abduction and rotation. Table 4.2 provides illustrations for these movements.

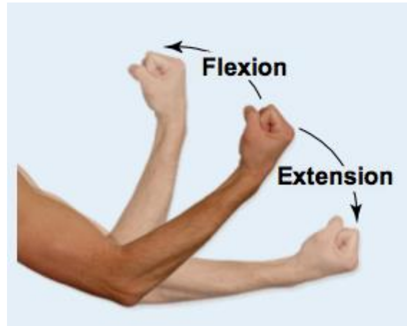
Flexion is the contraction of hinge joint such as elbows and knees. For ball-and-socket joints, flexion refers to the movement towards the anterior (front) side of the body. For example, an arm raise forward (along the sagittal plane) to being parallel to the ground would be described as shoulder flexion of 90 degrees. A movement in the opposite direction of flexion is called extension.

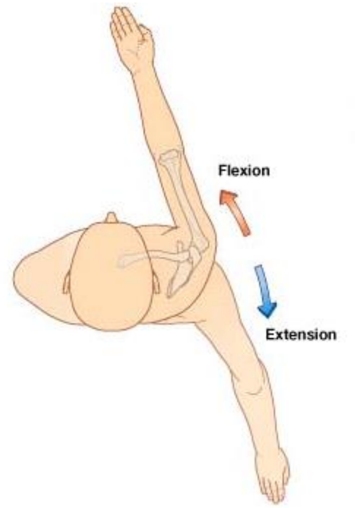
Abduction is the movement of a body region in the coronal plane away from the body's center. For example, when an arm is raised to the side (along the coronal plane) towards being parallel to the ground, it is described as a shoulder abduction of 90 degrees. The opposite of abduction is adduction.

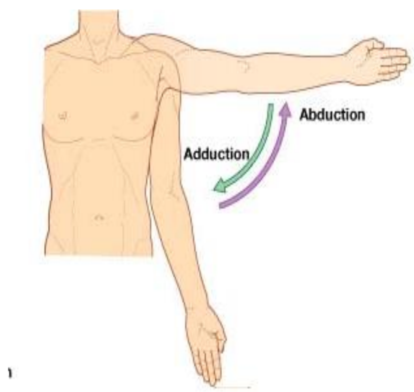
Rotation is the movement of a body region in the transverse plane. Lateral rotation is rotation away from the body's center and medial rotation is rotation towards the body's center. For example, when arm-wrestling, there is a strong component of medial shoulder rotation

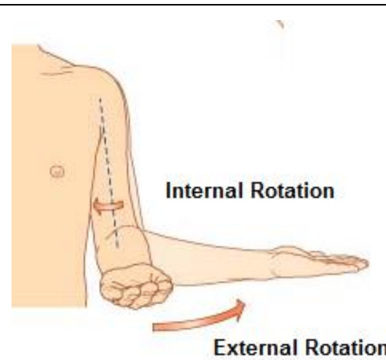
Table 4.2. Movements of the knee, elbow, shoulder and hip joints.

Joint	**Movement**	**Illustration**
Knee	Flexion / Extension	 [Quizlet.com, '15]

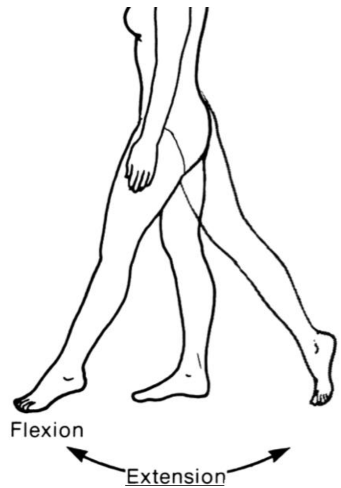
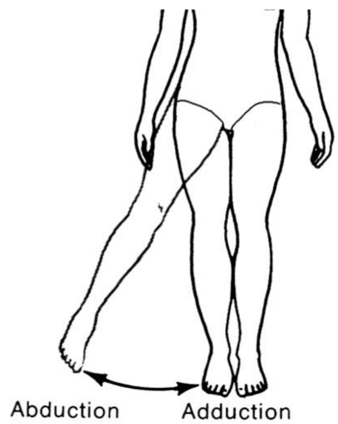
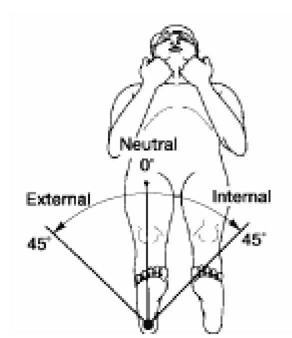
<table>
<tr><td>Elbow</td><td>Flexion / Extension</td><td>

[Quizlet.com, '15]</td></tr>
<tr><td rowspan="3">Shoulder</td><td>Flexion / Extension</td><td>

[Imgarcade.com, '15]</td></tr>
<tr><td>Abduction / Adduction</td><td>

[Imgarcade.com, '15]</td></tr>
<tr><td>Internal / External Rotation</td><td>

[Imgarcade.com, '15]</td></tr>
</table>

Hip	Flexion / Extension	 [Studyblue.com, '15]
	Abduction / Adduction	 [Studyblue.com, '15]
	Internal / External Rotation	 [Csmisolutions.com, '15]

4.3. Orthopedic Physical Therapy Exercises

As noted above, physical therapists will often prescribe exercises to rehabilitate a joint that has been injured or surrounding muscles that have atrophied, focusing on increasing the range of motion of the joint and the strength of the surrounding muscles. For example, when a patient has shoulder surgery and needs to rehabilitate that joint, physical therapists may prescribe an exercise called Shoulder Flexion (Figure 4.2). The instructions are: "Clasp hands together and lift arms above head. Can be done lying down (drawing A) or sitting (drawing B). Keep elbows as straight as possible. Repeat 10 times per set and do 2 sets per session. Do 3 sessions a day."

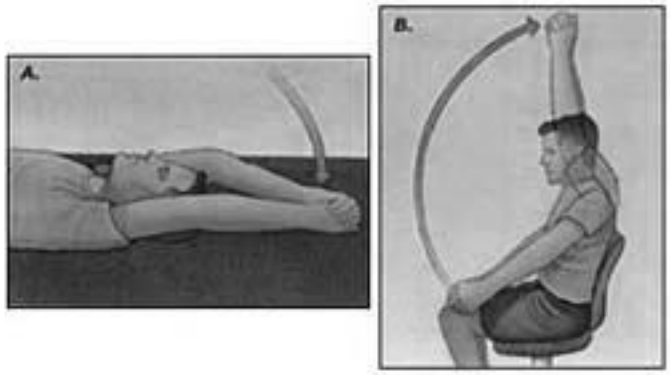


Figure 4.2. Shoulder Flexion exercise for strengthening and improving range of motion. [OrthoInfo.com, '07]

Another example is an exercise for a patient having a leg injury that results in weak knee and hamstrings. The commonly prescribed exercise is called *Standing Leg Curls* (Figure 4.3). In this exercise, PTs usually instruct the patients as follows: "While standing, bend the knee and raise the heel, but do not raise the leg. Perform this 10 times a day."

Figure 4.3. Standing Leg Curl exercise for rehabilitating the knee [VHI, '12]

It is common for exercises to have a correct and incorrect form. Usually, there is a general rule for performing the exercise, and an additional rule the patients should observe to do the exercise correctly. For the Shoulder Flexion exercise, the general rule is to "raise the shoulder" and the additional rule is to "keep the elbow straight". In anatomical terms, this translates to: "perform shoulder flexion while avoiding elbow flexion." For the Standing Leg Curl exercise, the general rule is to “curl the leg by raising the heel” and the additional rule is to “avoid raising the knee”. In anatomical terms, this translates to: “perform knee flexion while avoiding hip flexion.”

The next chapter describes the generalization of a virtual assistant to the orthopedic physical therapy domain by creating an authoring tool that understands anatomical language so that PTs can specify these exercise rules directly to the system to create a virtual assistant for their own use without needing a programmer or programming background.

5. Design and Implementation of Virtual Rehabilitation Assistant Authoring Tool

5.1. Overview

The goal of the VRA Authoring Tool was to create and customize a virtual assistant that a PT could use to instruct patients in a prescribed exercise and record the correct and incorrect movements. The tool is intended to be used without requiring the PT to have programming expertise; PTs should be able to use their familiar anatomical language. The system should translate this language into virtual assistant behavior for monitoring and recording the specified exercise movements and instructing the patient in the exercise. Ultimately, the tool could be extended to act as an in-home coaching aide that would include not just instructions, but also encouragement, corrections if needed, and visualizations for the PT, customized to the PT's specifications. This thesis covers the first steps in the process—the monitoring and instruction module.

The authoring tool prototype contains four main components: 1. A rule specification interface, with which the PT interacts to input the exercise specifications, 2. an exercise prescription database, where the specifications are saved, 3. a virtual assistant runtime environment, which loads and parses the specification file to generate the appropriate virtual assistant behavior during patient use, and 4. a patient interface where the corresponding visual and audio output is delivered to the patient. The four components and their interactions are shown in Figure 5.1.

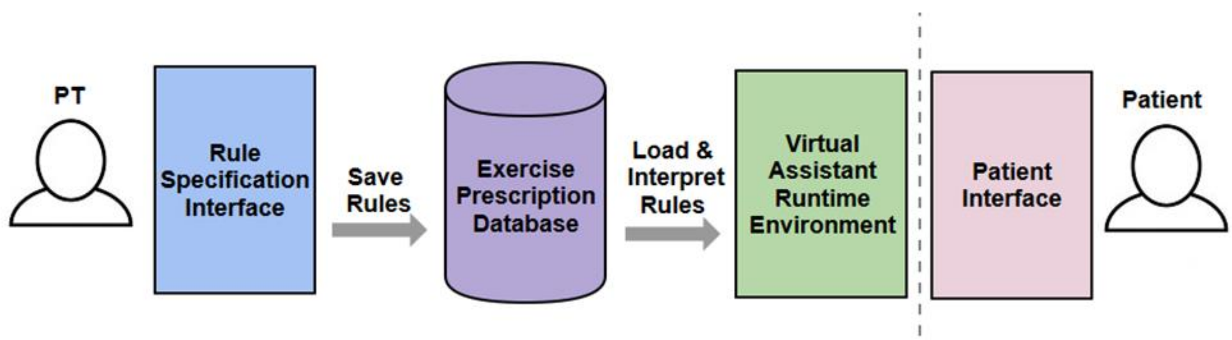


Figure 5.1. Four main components of the VRA Authoring Tool implementation: A rule specification interface, a data file for saving the specifications, a virtual assistant runtime environment, and a patient interface.

The following sections discuss each of these four components in detail.

5.2. Scoping

Body Regions of Focus

I explored physical therapy for the hip and knee with this authoring tool. These two joints represent two of the major joint-types in the human body, the hinge joint (knee) and the ball-and-socket joint (hip). More than 20 million Americans have knee and hip injuries, which result in restrictions in mobility. Focusing on these joints seemed to make sense; they are not only highly important to patients' quality of life and health, but often very responsive to physical therapy.

Focal Exercises

The exercises that I focused on were isolation exercises that are designed to strengthen the joints and increase their range of motion (RoM). These isolation exercises usually involve the movement of one or two joints in a controlled fashion, for example: Standing Leg Curls. These exercises are often prescribed to elderly patients with restricted mobility and to patients who recently underwent surgery. These exercises can be contrasted with complex, compound exercises, such as jumping jacks or lunges, which are typically prescribed to patients returning to sports or those who have recovered from surgery for some time.

5.3. Rule Specification Interface

Observing that most isolation exercises involve a primary motion by which repetitions are counted and one or more secondary motions that should be included or avoided, I created the prototype rule-specification interface shown in Figure 5.2. For example, with the Standing Leg Curl exercise, the primary motion is knee flexion, or bending of the knee. A secondary motion that should be avoided is hip flexion, or raising of the knee. As can be seen in Figure 5.2., Knee Flexion is selected as the primary motion, and "Avoid Hip Flexion" is selected as the additional rule. A feedback textbox would allow PTs to type in a vernacular feedback phrase, which could be spoken to the patient via text-to-speech when the associated rule is violated.

There are also options for specifying a target angle, a hold time if the exercise is one of stretching, in which case the virtual assistant can count with the patient to ensure proper stretch duration, and the speed of the repetitions.

Also, the PT can change the exercise quantity: repetitions per set, sets per session, and sessions per day. The virtual assistant can use these numbers to count reps along with the patient, ask them to take a break accordingly, and remind them to complete missing sessions.

Finally, there is a general textbox in which PTs can type free-form instructions to patients. PTs can specify exercise customizations such as asking the patient to use special equipment, e.g., resistance bands or ankle weights.

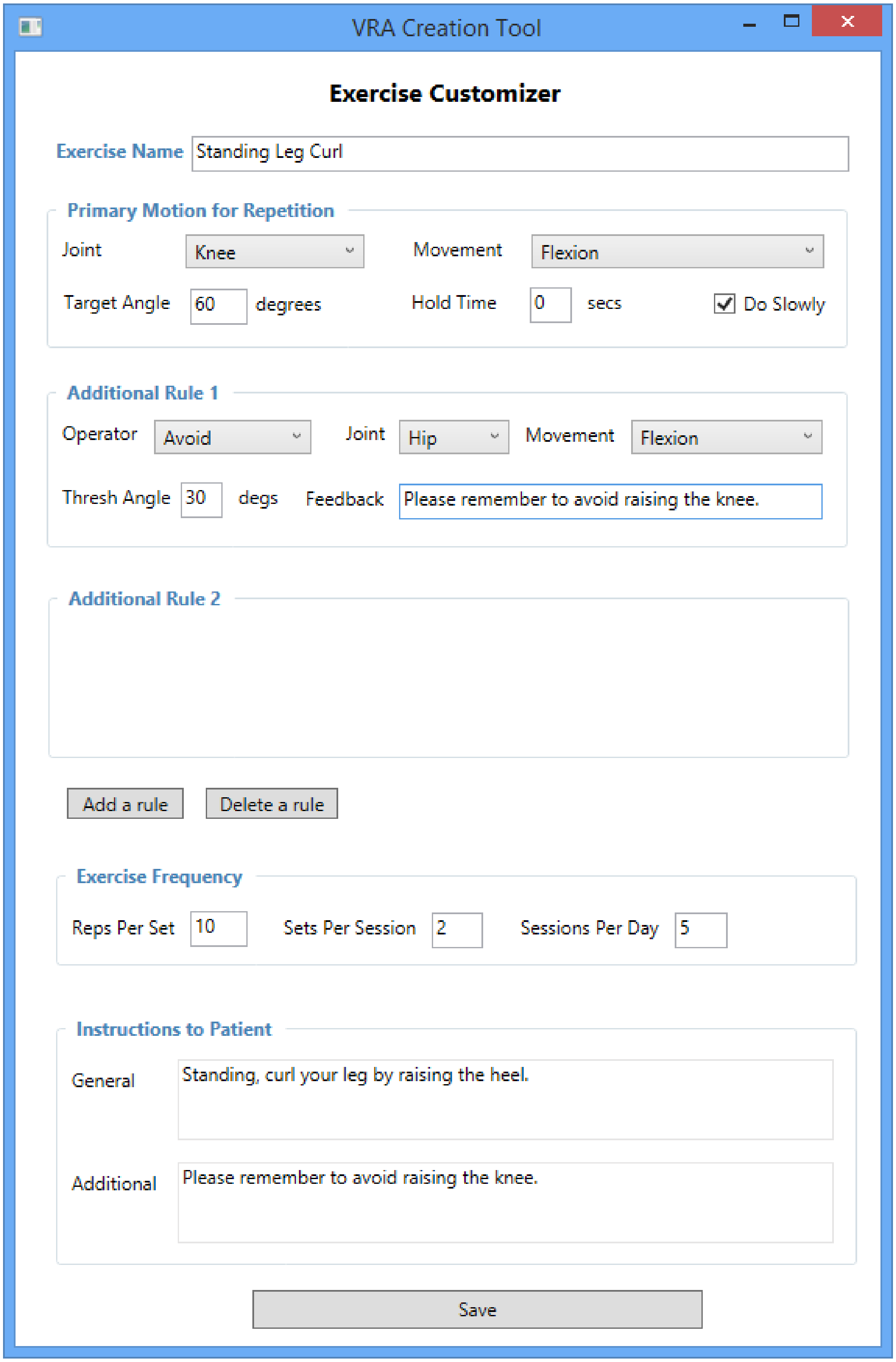


Figure 5.2. Rule specification interface of the virtual assistant authoring tool.

5.4. Exercise and rule specification file

Once the PTs' have input their specifications, they can press the "Save" button to save it. In this prototype, the specifications are saved to an XML file so that they can be loaded later. Figure 5.3 shows an example XML file for the Standing Leg Curl exercise with the specifications above:

```xml
<?xml version="1.0" encoding="utf-8"?>
<Exercise xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:xsd="http://www.w3.org/2001/XMLSchema">
	<exerciseName>StandingLegCurl</exerciseName>
	<bodyPosition>Upright</bodyPosition>
	<primaryJoint>Knee</primaryJoint>
	<primaryMovement>Flexion</primaryMovement>
	<startingAngle>0</startingAngle>
	<targetAngle>60</targetAngle>
	<holdTime>0</holdTime>
	<doSlowly>true</doSlowly>
	<repsPerSet>10</repsPerSet>
	<setsPerSession>2</setsPerSession>
	<sessionsPerDay>2</sessionsPerDay>
	<patientInstructions>
		Standing, curl your leg by raising your heel.
	</patientInstructions>
	<rule1>
		<op>Avoid</op>
		<joint>Hip</joint>
		<movement>Flexion</movement>
		<startingAngle>0</startingAngle>
		<targetThreshAngle>30</targetThreshAngle>
		<ruleFeedback>Please remember not to raise your knee.</ruleFeedback>
	</rule1>
</Exercise>
```

Figure 5.3. XML specification file for Standing Leg Curl exercise.

5.5. Virtual Assistant Runtime Environment

The Virtual Assistant Runtime Environment includes four main components that work together to produce the desired virtual assistant behavior according to the PT's specifications: 1. Motion sensors, which gather orientation data, 2. Physical motion widgets, which translate the orientation data to joint angles and movement events, 3. Rule engine, which checks to see which rules are adhered to and violated by the movement events and notifies the system to record this data accordingly, and 4. Patient interface, which delivers output based on rule adherences and violations reported from the rule engine. Figure 5.4 visualizes the interaction of these four components, and the following sections discuss each component in detail.

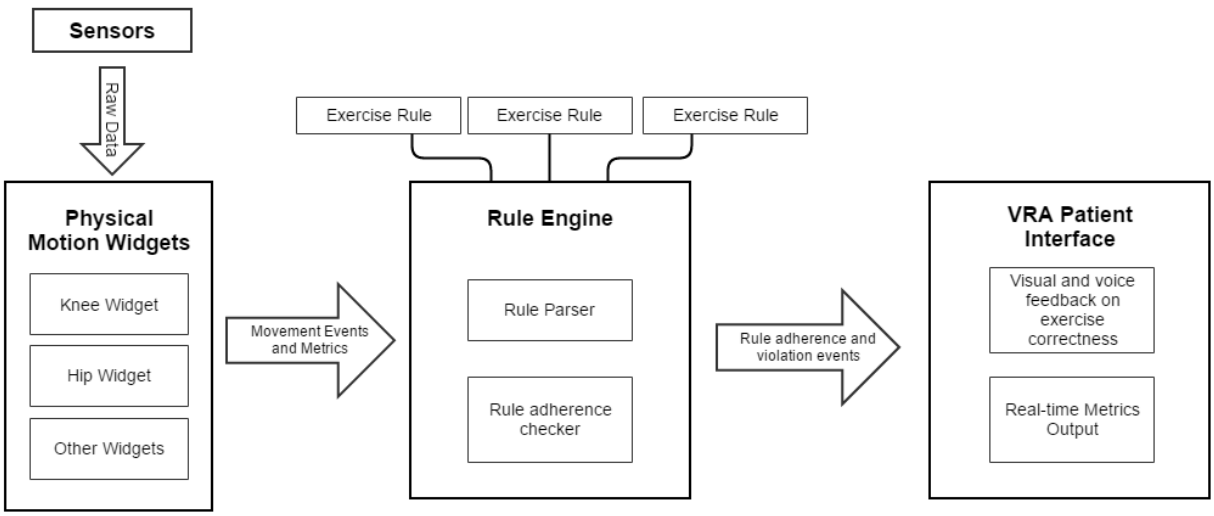


Figure 5.4. Four main components of the virtual assistant runtime environment: 1. Sensors, 2. Physical motion widgets, 3. Rule engine, 4. Patient interface

5.5.1. Motion Sensors

The sensors used for this prototype are wireless 9 degree-of-freedom inertial sensors from YEI Corporation. Figure 5.5 shows the specification details of the sensor.

5.5.1.1. YEI 3-Space Sensors

3-Space Wireless 2.4GHz DSSS - Hand-held Case (TSS-WL)		
	• USB 2.0, Wireless 2.4GHz DSSS, Rechargeable LiPO Battery • 60x35x15 mm, 28 grams • Communications: USB virtual COM port, 2.4Ghz Wireless • RGB status LED • Two input buttons • Hand-held case style • Click for Full Specifications	**Part:** TSS-WL **Price:** $251.00 Buy Now

Figure 5.5. YEI 3-Space Wireless Sensor

For the knee and hip exercises, two sensors are placed on the leg - one on the calf and one on the thigh. Figure 5.6 illustrates the positioning of the sensors.

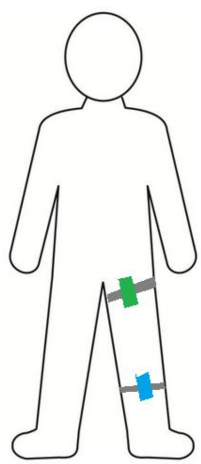


Figure 5.6. Sensor placements for the knee and hip exercises.

These sensors contain on-board Kalman filters and can return sensor-fused orientation readings at approximately 300 Hz. These orientation readings allow the application to determine how the thigh and shin bones, to which the sensors are strapped, are oriented. The orientations of the two bones can then be used to calculate the joint angle and movements of the knee and hip. The following section discusses the calculations in detail.

5.5.1.2. Sensor to Body Region Mapping

Each sensor has a unique ID. For example, the sensor worn on the thigh (colored green in Figure 5.6) is Sensor A and the one worn on the calf (colored blue in Figure 5.6) is Sensor B. In the Virtual Assistant Runtime Environment, a configuration table maps the sensor ID to the body region. Each data sample from a sensor includes its orientation values as well as its sensor ID. Thus, when each data sample arrives, the mapping table is used to convert the sensor ID to body region and inform the runtime environment that a new data sample for that body region has arrived. This data sample is then forwarded to a sample synchronizer to be synchronized with data samples from other body regions. This process is described in more detail in the next section.

Multi-Sensor Sample Synchronization

When there are multiple sensors responsible for providing data regarding a joint (for example, the knee joint requires two sensors, one for calf and one for thigh), data from these sensors must be synchronized before being processed together to provide motion information about that joint. A "SampleSynchronizer" class provides this function. When this class is instantiated, a list of body region that need to be synchronized are passed in the constructor; in this case, the list is "calf" and "thigh" for measuring knee angle. When a data sample arrives, this synchronizer class stores it and waits for data samples for the other required body region to arrive. Once data for all the body regions have arrived, this class creates a "frame" which is a new sample that includes data for all the body region necessary for updating information regarding a joint. This joint frame is then forwarded to a physical motion widget (discussed in the next section) that is in charge of processing data for that joint.

5.5.2. Physical Motion Widgets

Physical motion widgets are a set of software classes that transform low-level sensor orientation readings to high-level joint angles and movement events. They are currently implemented in C# using Microsoft Visual Studio. Figure 5.7 illustrates the data flow using physical motion widgets.

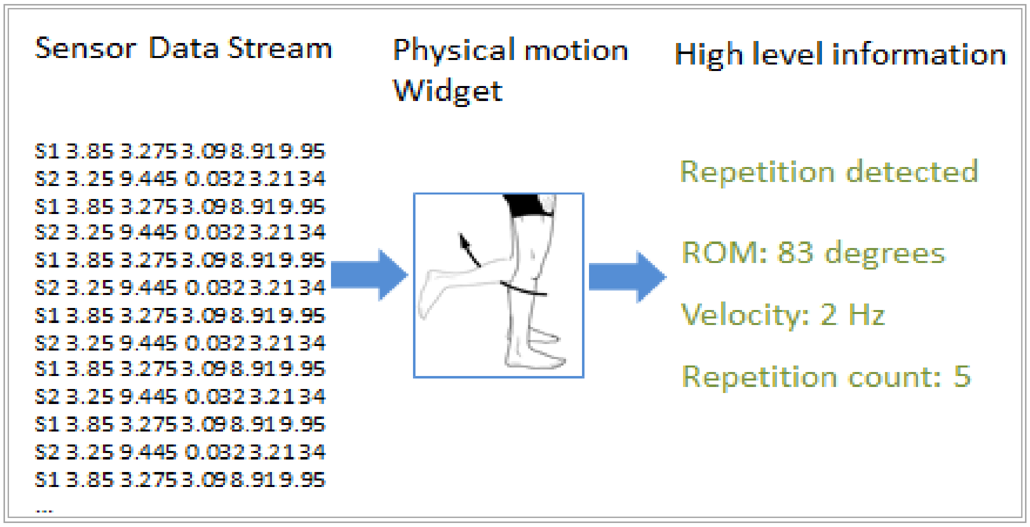


Figure 5.7. Physical motion widget: transforming raw sensor data to high level movement information.

5.5.2.1. Calculating Angles

Given the orientation of two sensors, and consequently the orientation of two bones to which the sensors are attached, joint angle can be calculated. The following is the C# code used for this calculation. “Quat” stands for quaternion, which is a format of storing orientation as a 4-tuple: (x, y, z, w). This code is part of the Knee widget.

Calculating hinge joint angles

```
private double getJointAngle(Quaternion calfQuat, Quaternion thighQuat)
{
    Vector3 calfDownVect = Vector3.Transform(deviceTrueDownVector, calfQuat);
    Vector3 thighDownVect = Vector3.Transform(deviceTrueDownVector, thighQuat);

    //This code compensates for wearing the sensor in different rotational alignments
    //Find angle from 0 position
    double calfAngle = Vector3.Dot(calfDownVect, deviceTrueDownVector);
    double thighAngle = Vector3.Dot(thighDownVect, deviceTrueDownVector);

    //Create new aligned vectors with the angles
    Vector2 calfAlignedVect = new Vector2((float) Math.Cos(calfAngle), (float) Math.Sin(calfAngle));
    Vector2 thighAlignedVect = new Vector2((float) Math.Cos(thighAngle), (float) Math.Sin(thighAngle));

    double dotProd = Vector2.Dot(calfAlignedVect, thighAlignedVect);
    double angle = Math.Acos(dotProd);
    double degrees = angle * 180 / Math.PI;
    return degrees;
}
```

Calculating ball-and-socket joint angles

Ball-and-socket joints, such as the hip, are more complex than hinge joints. While hinge joints can only move in the flexion/extension plane, ball-and-socket joints can move in three planes: flexion/extension, abduction/adduction, and rotation. The following C# code is part of the Hip widget and obtains joint angles along these planes.

Getting angle in the flexion/extension plane:

```
private double getFlexionAngle(Quaternion deviceOrientQuat) {
    Vector3 deviceRV = Vector3.Transform(trueVectors.GetRightVect(), deviceOrientQuat);
    //First get angle necessary to line up the right vectors
    double angle = getAngle(deviceRV, trueVectors.GetRightVect());
    Vector3 axis = Vector3.Normalize(Vector3.Cross(deviceRV, trueVectors.GetRightVect()));
    Quaternion qOffset = Quaternion.CreateFromAxisAngle(axis, (float)angle);
    Quaternion aligned_qt = Quaternion.Multiply(qOffset, deviceOrientQuat);
    //Then use quat to transform the forward vector such that the downvectors are aligned
    Vector3 aligned_FV = Vector3.Transform(new Vector3(0,1,0), aligned_qt);
    //Finally, calculate the angle of the transformed forward vector with the true forward
    //vector (or fv of trunk sensor if available)
    return getAngle(aligned_FV, trueVectors.GetForwardVect());
}
```

Getting angle in the abduction/adduction plane:

```
private double getAbductionAngle(Quaternion deviceOrientQuat)
{
    Vector3 deviceFV = Vector3.Transform(trueVectors.GetForwardVect(), deviceOrientQuat);
    double angle = getAngle(deviceFV, trueVectors.GetForwardVect());
    Vector3 axis = Vector3.Normalize(Vector3.Cross(deviceFV, trueVectors.GetForwardVect()));
    Quaternion qOffset = Quaternion.CreateFromAxisAngle(axis, (float)angle);
    Quaternion aligned_qt = Quaternion.Multiply(qOffset, deviceOrientQuat);
    Vector3 aligned_RV = Vector3.Transform(new Vector3(1, 0, 0), aligned_qt);
    return getAngle(aligned_RV, trueVectors.GetRightVect());
}
```

Getting angle in the rotation plane:

```
private double getRotationAngle(Quaternion deviceOrientQuat)
{
    Vector3 deviceDV = Vector3.Transform(trueVectors.GetDownVect(), deviceOrientQuat);
    double angle = getAngle(deviceDV, deviceTrueDownVector);
    Vector3 axis = Vector3.Normalize(Vector3.Cross(deviceDV, deviceTrueDownVector));
    Quaternion qOffset = Quaternion.CreateFromAxisAngle(axis, (float)angle);
    Quaternion aligned_qt = Quaternion.Multiply(qOffset, deviceOrientQuat);
    Vector3 aligned_FV = Vector3.Transform(new Vector3(0, 1, 0), aligned_qt);
    return getAngle(aligned_FV, new Vector3(0, 1, 0));
}
```

5.5.2.2. Determining Movement Phases and Repetitions

As the angles are calculated, their changes can be tracked indicating movement over time. For example, if the angle of the knee joint is increasing, that indicates flexion movement; if the angle is decreasing, that indicates extension. As these movements are tracked, repetitions can then be determined.

Repetition Detection and Positive / Negative Phases

Each motion defined as the "Primary Motion" in the exercise specification interface has positive and negative phases, which combine to make repetitions. For example, if the primary motion is "knee flexion", then the positive phase is when a knee is contracting (also called flexion) and the negative phase is when the knee is extending. Thus, a knee contraction followed by a knee extension is a repetition of a knee flexion movement.

Real-time Low Pass Filter

Because users may have tremors and jitters in their movement, a real-time low-pass filter is needed to prevent incorrectly detecting these jitters as repetitions. A filter was implemented using a thresholding algorithm based on time and angle change. The principle is that when a phase change is detected (for example, if the phase was previous positive and is now detected as being negative), this update should only be accepted if a certain threshold of time or distance has passed since the last phase change. Otherwise, it is considered jitter and ignored. The time threshold is currently set for 500 milliseconds and the distance threshold is currently set for 5 degrees. Thus, if the user exhibits a phase change, e.g., contracting and extending the arm, in less than half a second, the system will consider that a jitter and ignore it. In normal exercising, a leg movement repetition would not be done this quickly. Similarly, if the user exhibits a phase change in less than 5 degrees, the system will consider that as jitter because in normal exercising, a leg repetition should not have such a small range of motion.

These thresholds may need to be adjusted for other body regions. For example, for head rotation exercises, e.g., Gaze Stabilization Exercise for vestibular rehabilitation, it can be common for repetitions to occur in less than half a second if the patient is exercising vigorously to induce an effect.

When repetition events are detected, they are forwarded to the rule engine, which analyzes them further as described in the next section.

5.5.3. Rule Engine

When the rule engine receives a repetition event, it analyzes the exercises specifications (loaded from the XML file) and other movement parameters to determine whether the repetition is correct or incorrect.

For example, in the Standing Leg Curl exercise, the specification states that knee flexion is the primary joint movement and that the additional rule is that hip flexion should be avoided. When a repetition event is received, the rule engine checks to see if the repetition is a Knee Flexion. If it is not, then it ignores it. However, if it is a knee flexion repetition, then the rule engine proceeds to analyze the additional rule, which in this case is the avoidance of hip flexion. The rule engine then checks the max angle recorded in the hip flexion direction and if it is beyond the threshold specified by the PT, it considers the repetition incorrect. Otherwise, it considers the repetition correct. It then forwards this rule-adherence or rule-violation event to the patient interface, which can save the data and update the repetition display as well as speak the current count aloud to the patient.

5.5.4. Patient Interface

The patient interface potentially delivers both visual and auditory feedback to patients as they exercise. Figure 5.8 shows an example patient interface. It displays the instructions, current angle of both the knee and hip joints, current and prescribed repetitions, sets and sessions, hold time for stretching exercises, and feedback on exercise quality. This patient interface is a first step; its design is incomplete and not the emphasis of this thesis. Optimizing and testing it for patient use is part of future work.

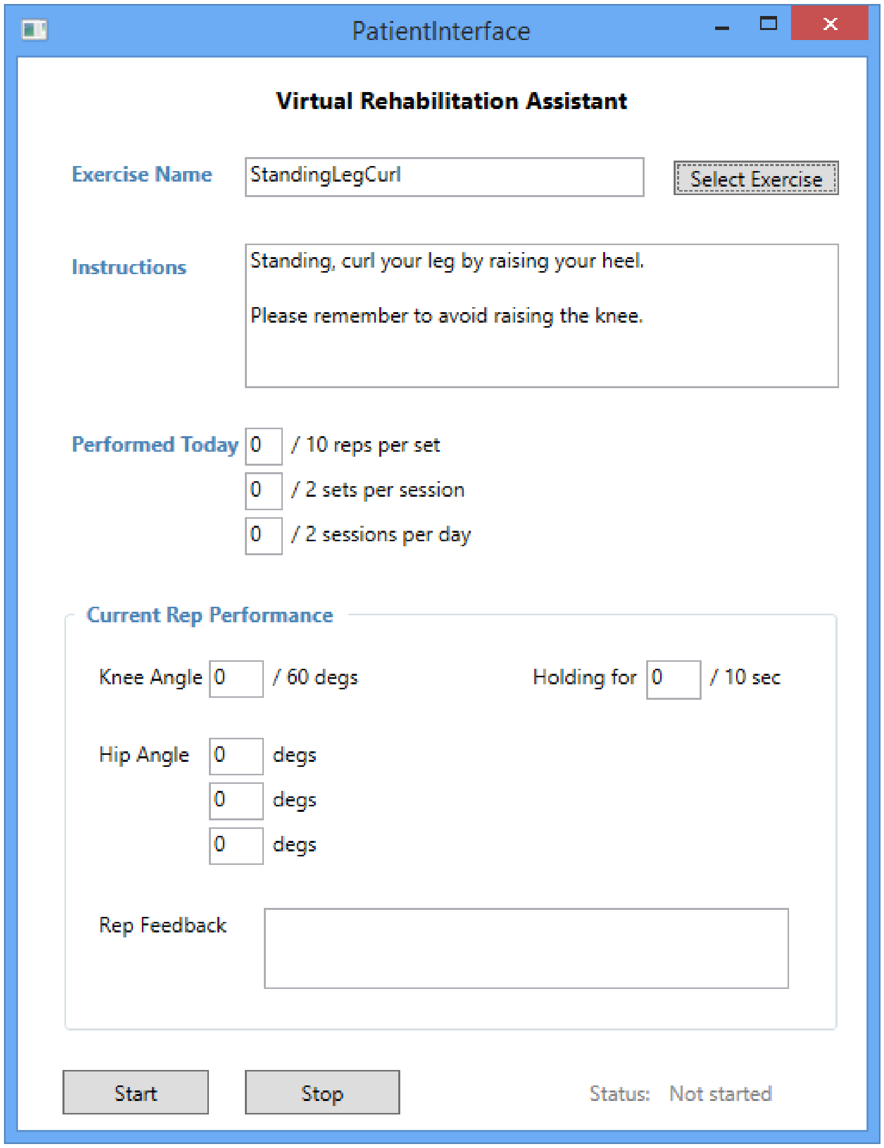


Figure 5.8. Example rudimentary patient interface that delivers exercise feedback to the patient.

The next chapter describes an evaluation of this system with PTs to assess its feasibility.

6. Evaluation of Virtual Rehabilitation Assistant Authoring Tool

I asked nine physical therapists from the University of Pittsburgh Medical Center to use the authoring tool to create and customize a virtual assistant for four exercises. During and after they completed the customization tasks, I interviewed the PTs about their experience. The study used an iterative process whereby I periodically modified the system according to PT feedback before I presented it to the next set of PTs. I conducted three iterations of testing and redesign: The first stage tested the initial prototype (Figure 6.1), presented to PTs 1, 2 and 3. The second stage tested modifications (Figure 6.2) presented to PTs 4 through 7. The third and final version (Figure 6.3) was presented to PTs 8 and 9.

6.1. Method

Nine Physical Therapists from the University of Pittsburgh Medical Center were asked to use the authoring tool to create and customize virtual assistants for four exercises. After the customization tasks, the PTs were interviewed for feedback. The study used an iterative process where the system was periodically modified according to PT feedback before being presented to next set of PTs. There were three iterations: The first was the initial prototype (Figure 6.1), presented to PTs 1, 2 and 3. The second (Figure 6.2) is a modification based on the PTs' feedback and it was presented to PTs 4 through 7. The third and final version (Figure 6.3) was presented to PTs 8 and 9.

6.1.1. Think Aloud Protocol and Interview Format

To assess interface usability, a think aloud protocol was used during the tasks. In this protocol, participants were asked to verbalize their thoughts continuously as they perform the tasks so that their mental processes could be observed. For example, if they were looking for a textbox to enter instructions, they were asked to say this aloud, e.g., "now I'm looking for the textbox for instructions…where is this textbox for instructions…" The purpose of think aloud is for the experimenter to be able to get direct observation of user-experience, both positive and negative. During this time, I noted utterances or facial expressions relating to significant emotions (termed "critical incidents" in usability analysis), including frustration and confusion. During these critical incidents, participants would often initiate discussion conveying what they liked or disliked and what improvements they would suggest. These points of interests often grew into longer and more in-depth discussions that led to new insights on their workflow and system feasibility. After the tasks were completed, participants were interviewed on their general impressions and thoughts for improvement. Sometimes they were asked to expand on comments made earlier.

While a traditional interview questionnaire may have a static set of questions, the exploratory and iterative nature of this study necessitated a more organic interview approach where the set of questions were dynamic and evolved as insights were discovered. For example, a question regarding what percentage of time the PT created new exercises as opposed to prescribing catalogued exercises was not posed to the first couple of PTs because I erroneously assumed that they prescribed new, uncatalogued exercises predominantly. It was not until I saw these initial PTs' frustration in using the system and their notifying me that this is not appropriate for their workflow did I begin to pose this question for the next set of PTs.

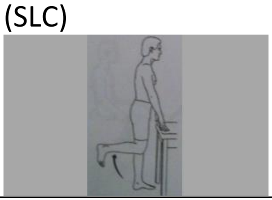
The following is the initial set of questions, which explored PTs' viewpoints and helped prompt new questions and discussions.

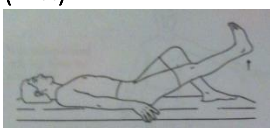
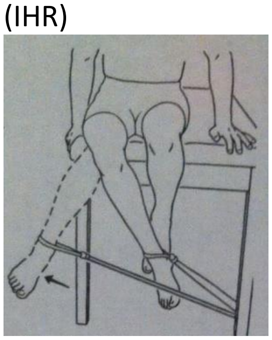
1. Sensors typically have a certain degree of error in measuring joint angles; what would be an acceptable range of error to you?
2. Are there other rules for these exercises that you would like patients to observe?
3. What do you think of the virtual assistant's real-time feedback, including the audio output?
4. When performing these leg exercises, would it be important for the system to monitor patients' body positions by having them wear a trunk sensor?
5. What do you think of the exercise specification interface? Would you prefer to specify exercises by demonstration to the system instead?
6. Are there other customization parameters or overall system improvements you would like to see?

6.1.2. Exercises Used for Evaluation

For the tasks, PTs used the tool to create four representative exercises, which together encompass all of the movements of the hip and knee. I obtained the exercises and common known mistakes from a catalog used by PTs. For each exercise, in turn, PTs were given a scenario whereby they prescribed an exercise and anticipated the patient would make a common mistake. PTs were asked to use the system to prescribe the exercise to the patient and create a virtual assistant that could monitor the exercise and detect the patient's mistake. During the first exercise, to familiarize PTs with the authoring tool, I walked the PTs through the task. I then asked the PTs to perform the other three tasks independently. The following table shows the exercises and the expected specification results.

Table 6.1. Exercised used for PT interface evaluation. Each exercise contained a scenario for which the PTs were expected to configure the interface according to the column on the right. (Images from [VHI, '12])

Exercise Creation Task	**Scenario Presented to PTs**	**Correct Virtual Assistant Specification**
Standing Leg Curl (SLC) 	"Suppose you want to prescribe the Standing Leg Curl exercise. Suppose you also notice that your patient tends to make the mistake of raising their knee when doing this exercise. Please use the tool to prescribe this exercise	Primary Motion: Knee Flexion Additional rule: Avoid hip flexion.

	and customize the virtual assistant so that it can monitor the exercise, recognize the mistake, and give vernacular feedback to the patient.”	Patient feedback: “Please remember to avoid raising the knee”
Lying Leg Raise (LLR) 	“Suppose you want to prescribe the Lying Leg Raise exercise. Suppose you also notice that your patient tends to make the mistake of bending their knee when doing this exercise. Also, suppose you want to increase the number of reps to 15. Please use the tool to prescribe this exercise and customize the virtual assistant accordingly.”	Primary Motion: Hip Flexion Additional rule: Avoid knee flexion Patient feedback: “Please remember to avoid bending the knee.” Additional setting: 15 reps.
Side-Lying Leg Raise (SLLR) 	“Suppose you want to prescribe the Side-lying Leg Raise exercise. Suppose you also notice that your patient tends to make the mistake of rolling on their butt slightly and moving their leg forward when doing this exercise. Also, suppose you want to increase the number of reps to 15. Please use the tool to prescribe this exercise and customize the virtual assistant accordingly.”	Primary motion: Hip Abduction Additional rule: Avoid Hip Flexion Patient feedback: “Remember to lay on your side and move the leg straight up and down”
Internal Hip Rotation (IHR) 	“Suppose you want to prescribe the Internal Hip Rotation exercise. Suppose you also notice that your patient tends to make the mistake of picking up the leg and sliding it across the chair rather than turning the hip. Also, suppose you want to ask the patient to use a green resistance band. Please use the tool to prescribe this exercise and customize the virtual assistant accordingly.”	Primary motion: Hip Internal-rotation Additional rule: Avoid Hip Abduction Patient feedback: “Remember to avoid sliding your thigh across the chair.” Additional setting: Add “Use green resistance band” to patient instructions.

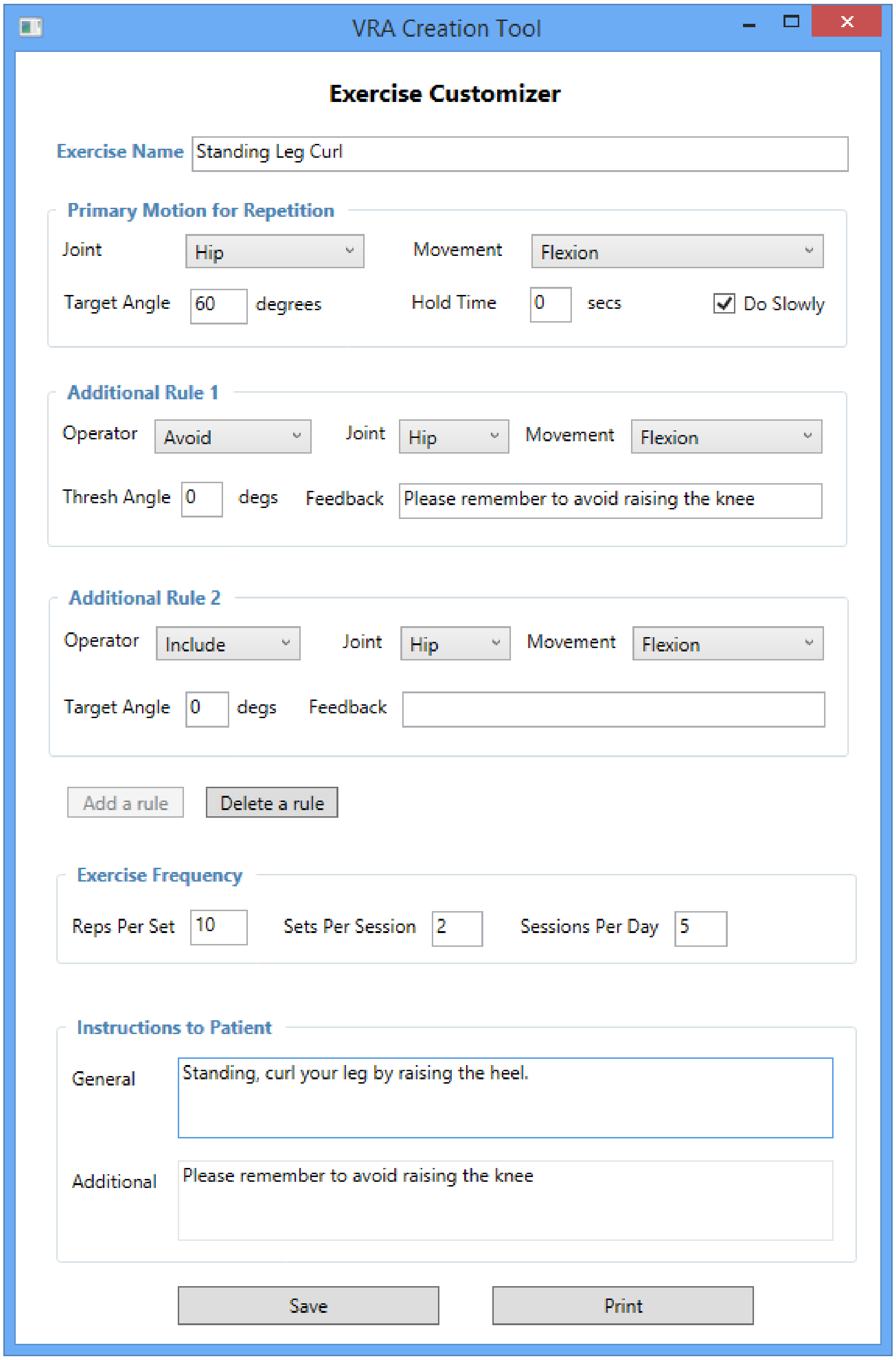


Figure 6.1. Initial interface for Virtual Assistant Authoring Tool – Evaluated with PTs 1, 2, and 3.

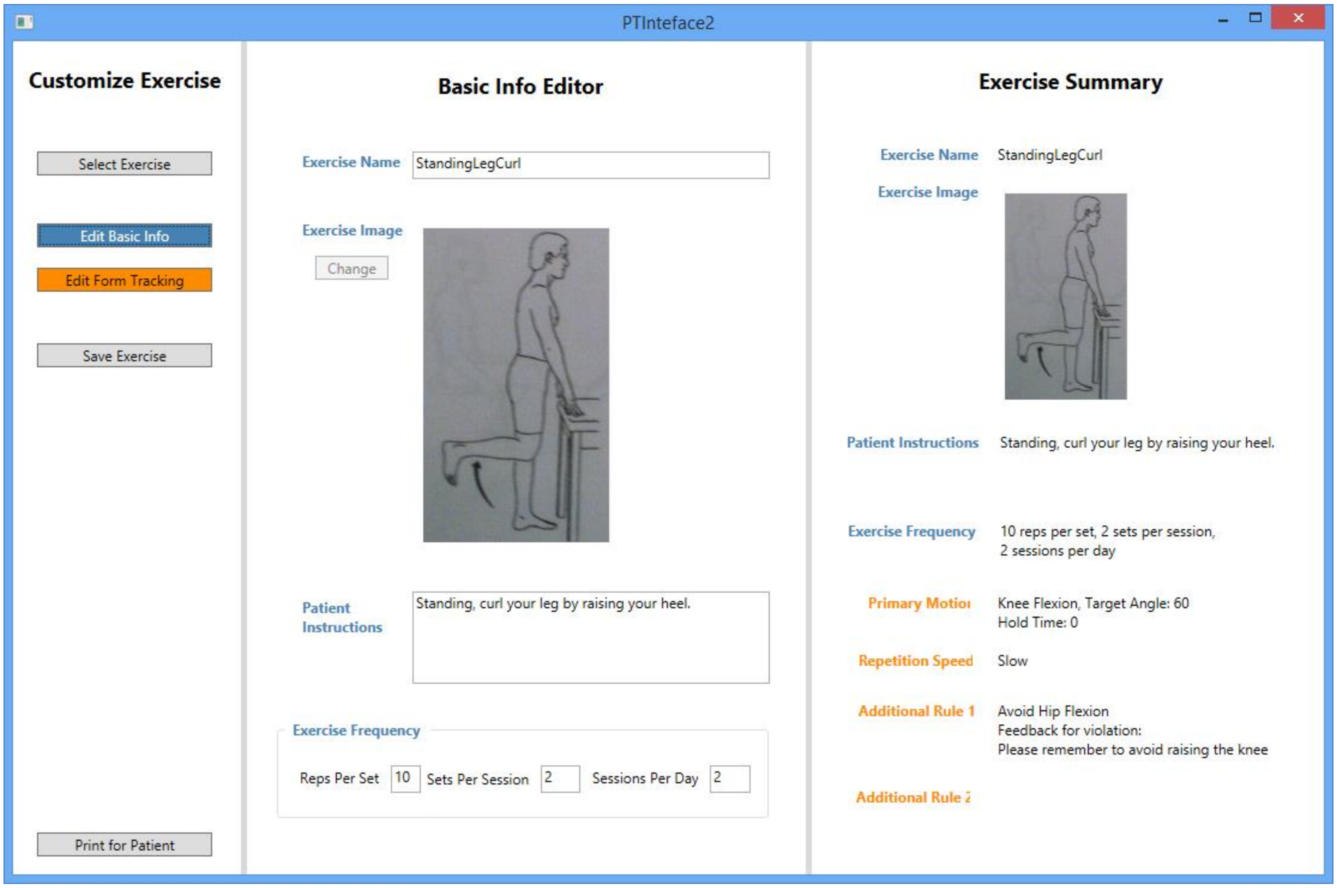


Figure 6.2. Second version of interface for Virtual Assistant Authoring Tool. Evaluated with PTs 4, 5, 6, and 7.

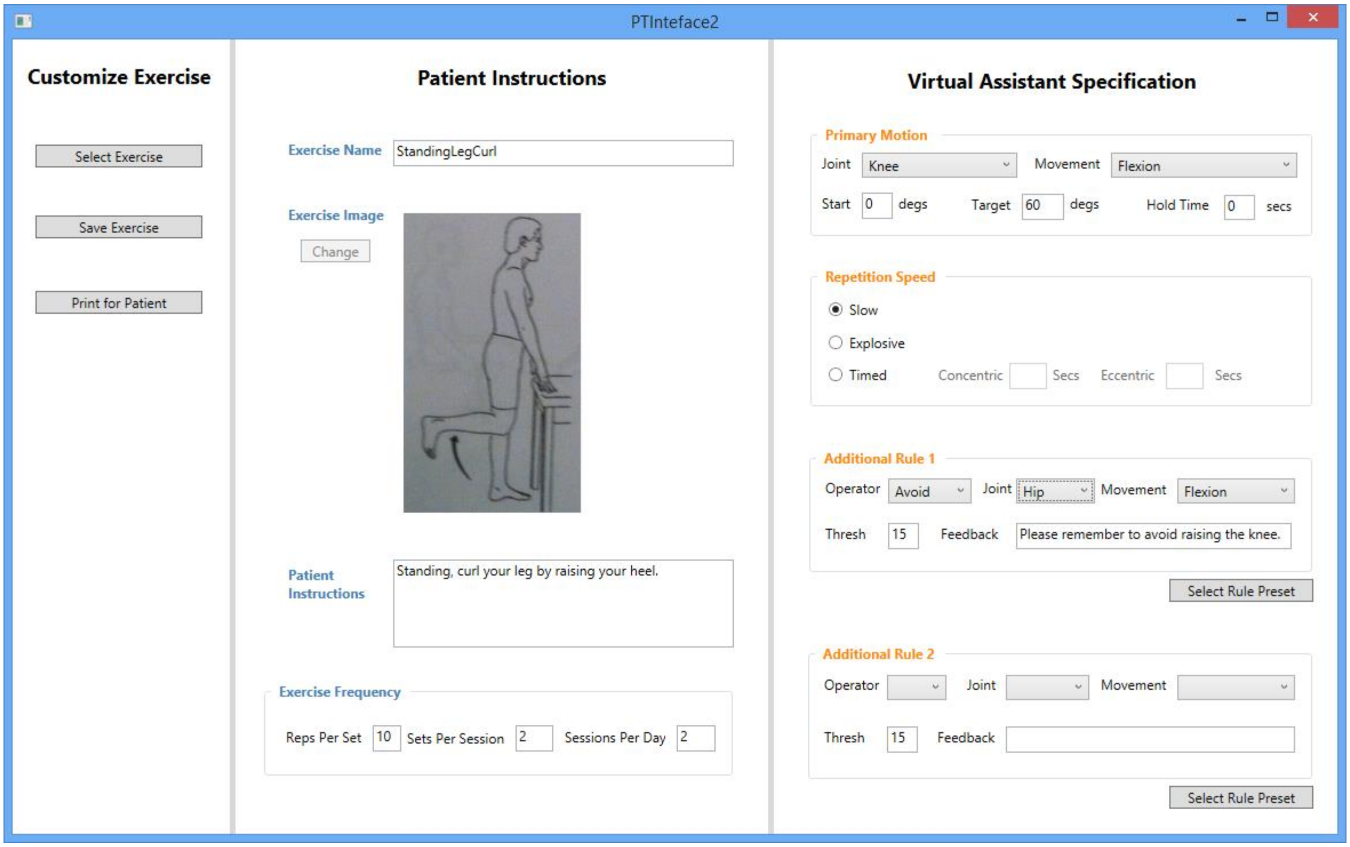


Figure 6.3. Third and final interface for Virtual Assistant Authoring Tool. Evaluated with PTs 8 and 9.

6.2. Results

6.2.1. PTs' Virtual Assistant Specifications

This section contains the PT specifications that can be compared with the correct specifications from Table 6.1. Overall, the initial interface was very difficult to use. PTs had more success in creating the correct virtual assistants with later iterations of the interface. Table 6.2-6.4 details the PT specification results with the three interfaces and summarizes the outcomes.

Table 6.2. Virtual Assistant specifications using the initial interface (Figure 6.1). Key: LLR = Lying Leg Raise. SLLR = Side-lying Leg Raise. IHR = Internal Hip Rotation.

PT #	Exercise	Actual PT Specification	Outcome Summary
1	LLR	Primary Motion: Hip abduction. Additional rule: avoid Hip flexion. Patient feedback: "do not let leg go in front of body"	Failure – Incorrect specification
	SLLR	Unable to finish due to confusion over interface.	Failure – Aborted due to confusion
	IHR	Unable to finish due to running out of time	Failure – User lost too much time due to discussion and confusion to complete task.
2	LLR	Primary Motion: Hip flexion. Additional rule: avoid knee flexion. Patient feedback: "Keep your knee locked straight"	Success – Virtual Assistant specifications are correct.
	SLLR	Primary Motion: Hip abduction. Additional rule: avoid knee flexion. Patient feedback: "keep your knee straight"	Partial failure – the mistake recognition was incorrectly specified.
	IHR	Primary Motion: Hip internal rotation. Additional rule: None. Patient feedback: None.	Partial failure – PT didn't specify the mistake recognition due to confusion.
3	LLR	Primary Motion: Hip flexion Additional rule: none. Patient feedback: None	Partial failure – PT didn't specify the mistake recognition due to confusion.
	SLLR	Unable to finish – lost too much time due to discussion and confusion in completing task.	Failure
	IHR	Unable to finish – lost too much time due to discussion and confusion in completing task.	Failure

Table 6.3. Virtual Assistant specifications using interface #2 (Figure 6.2). Key: LLR = Lying Leg Raise. SLLR = Side-lying Leg Raise. IHR = Internal Hip Rotation.

PT #	Exercise	Actual PT Specification	Outcome Summary
4	LLR	Primary motion: Hip flexion Additional rule: Avoid knee flexion. Patient feedback: "Tighten quads to maintain knee extension"	Success
	SLLR	Primary motion: Hip Abduction Additional rule: Avoid hip flexion. Patient feedback: "Do not bring leg forward"	Success
	IHR	Primary motion: Hip Internal Rotation Additional rule: Avoid Hip Flexion. Patient feedback: "Keep thigh flat in seat; do not raise or lower thigh."	Success
5	LLR	Primary motion: Hip flexion Additional rule: Avoid knee flexion. Patient feedback: "Keep knee straight"	Success
	SLLR	Primary motion: Hip Abduction Additional rule: Avoid hip flexion. Patient feedback: "Keep leg back (in line with body)"	Success
	IHR	Primary motion: Hip Internal Rotation Additional rule: Avoid Hip Flexion. Patient feedback: "leave thigh stationary: don't slide"	Partial failure – additional rule does not match the patient feedback.
6	LLR	Primary motion: Hip flexion Additional rule: Avoid knee flexion. Patient feedback: "Keep knee straight when lifting leg"	Success
	SLLR	Primary motion: Hip abduction Additional rule: Avoid hip flexion. Patient feedback: "Keep body straight; do not bend at your hip"	Success
	IHR	Primary motion: Hip internal rotation Additional rule: Avoid hip abduction. Patient feedback: "Keep thigh straight ahead; only move lower leg"	Success
7	LLR	Primary motion: Hip flexion Additional rule: Include knee extension. Patient feedback: "Please remember to keep your knee straight"	Partial failure - Additional rule was unexpected. Also PT expressed confusion over virtual assistant settings.

	SLLR	Primary motion: Hip abduction Additional rule: Avoid hip flexion. Patient feedback: “Remember to avoid bringing your hip forward”	Success
	IHR	Primary motion: Hip internal rotation Additional rule: Avoid hip abduction. Patient feedback: “Please remember to avoid bringing your hip outwards”	Success

Table 6.4. Virtual Assistant specifications using interface #3 (Figure 6.3). Key: LLR = Lying Leg Raise. SLLR = Side-lying Leg Raise. IHR = Internal Hip Rotation.

PT #	**Exercise**	**Actual PT Specification**	**Outcome Summary**
8	LLR	Primary motion: Hip flexion Additional rule: Avoid knee flexion. Patient feedback: “Keep knee straight”	Success
	SLLR	Primary motion: Hip abduction Additional rule: Avoid hip flexion. Patient feedback: “Raise leg straight up towards ceiling, not forward”	Success
	IHR	Primary motion: Hip internal rotation Additional rule: Avoid hip abduction. Patient feedback: “Do not slide leg out, just rotate lower leg”	Success
9	LLR	Primary motion: Hip flexion Additional rule: Avoid knee flexion. Patient feedback: “Remember not to bend your knee”	Success
	SLLR	Primary motion: Hip abduction Additional rule: Avoid hip flexion. Patient feedback: “Keep your leg in line with your body”	Success
	IHR	Primary motion: Hip internal rotation Additional rule: Avoid hip abduction. Patient feedback: “Remember to turn your hip in, don’t slide your leg”	Success

6.2.2. PT Interview Results

The following sections describe the major findings from PT comments during the tool evaluation tasks and in post-task interviews. Each finding is accompanied by how it informed interface modifications. The findings are categorized in to three sections: 1. Fitting into PT workflow, 2. Designing the exercise specification interface, and 3. Design considerations regarding the patient. Each section contains a table that summarizes the findings followed by a more in-depth discussion of each point.

6.2.2.1. Fitting into PT workflow

The following table summarizes findings related to PTs' workflow and the efficiency of the tool.

Table 6.5. Findings regarding fitting the Virtual Assistant Authoring Tool into PT workflow

Authoring Tool Interface Finding	**Resulting Interface Improvements**
PTs are very constrained in time for prescribing exercises. They can only spend about one minute per exercise prescription. Thus, they prefer exercise customization over exercise creation.[1] (PTs 2 through 9).	Common exercises were preloaded to allow PTs to select them from a list.
PTs need presets for common options to speed up prescription process.[2] (PT 1, 5, 6)	Common presets for the exercises were stored, such as number of reps, sets, and common rules. PTs can change them as desired.
PTs need a backup option to create new exercises about 2-10% of time. During this process, they need the ability to upload a custom picture and enter custom instructions and rules.[3] (PT 3, 4, 5, 7)	Added capability for PTs to upload pictures associated with exercises and customize patient instructions.
PTs need to print the prescription so that patients can take home physical copies.[4] (PTs 3, 5, 9)	Added printing option to print patient-friendly format.
PTs need exercises to be organized and searchable by many criteria. There should also be a method to group exercises and save them as sets for each patient.[5] (PT 3, 4, 6)	This feature was not added for this evaluation since there were only 4 exercises. The functionalities for grouping exercises and making them searchable by keyword will be part of future work.

[1] Currently, PTs use an exercise catalog software to select exercises to print out for patients. PTs stated that they can only spend about 1 minute per exercise prescription. They typically

prescribe 5 exercises per visit, and ideally would like to keep it under 5 minutes total. 10 minutes would be acceptable if it's the patient's first visit. Thus, they stated that they do not have time to create new exercises often. In fact, in practice, they only create new exercises about 5% of the time, using catalogued exercises the rest of the time.

[2] Along with common exercises to select from, PTs also stated a need for presets regarding the configurations of these exercises. Common presets include the speed of the exercise, the number of repetitions, sets, and sessions per day, and the rules regarding these exercises.

[3] When PTs create new exercises, they currently must find an existing similar exercise in a catalog (e.g. VHI or Perfect Fit Pro) and modify the drawing and/or text. They stated a need for being able to take a picture and upload it to the system to create a new exercise. In some clinics, there are liaisons from companies such as Perfect Fit Pro that work there to gather new exercises needed by PTs and submit them to the company for creation. But PTs stated that this process takes 6+ months before the exercises are available in the database.

[4] Since PTs already use existing catalog software to select and print exercise sheets for their patients, they do not have time to use a new software system in addition. Thus, the virtual assistant authoring tool must also allow PTs to perform functions they already do now, including printing the exercise illustrations and custom specifications in a patient-friendly manner.

[5] PTs expressed a need for better organization and search of exercises. Because there are potentially thousands of exercises for the human body, they needed them to be searchable by keyword, joint, injury type, and so forth. In addition, they need the option for grouping the exercises. For example, PTs who see patients that are recovering from total knee replacement surgeries stated that having exercises grouped by phases would be helpful, e.g.:

a. Phase 1: Range of motion, stretching, etc
b. Phase 2: Weight bearing, functional exercises.

And the exercise prescriptions for each patient should be saved as a group itself so that they can be easily modified.

6.2.2.2. Designing the Exercise Specification Interface

The following table summarizes findings related to the design of the interface for exercise and Virtual Assistant specifications.

Table 6.6. Exercise specification interface results

Authoring Tool Interface Finding	**Resulting Interface Improvements**
PTs need additional options for monitoring movement speed.[1] (PT 1, 3)	Added the various speed options, including ability to specific how many seconds for concentric and eccentric phases.
The starting angle is very important to monitor and should be a preset.[2] (PT 1, 2, 4 5)	Added "starting at 0" as a preset option, with the value being customizable.
Interface should make it clear to PTs which specifications are for patient and which are for the virtual assistant.[3] (PT 1, 2, 3, 6, 7)	Separated the interface components for patient-instructions and virtual assistant specifications.
Input error checking is important.[4] (PT 1, 2, 3, 7)	Added rule-checking mechanism, which prompts the user when detecting a conflict between two rules or lack of rule input.
Language translation from vernacular to virtual assistant specification can be ambiguous.[5] (PT 5, 7)	Embedded tool-tips and explanation links in rule specification to guide PTs.

[1] PTs stated a need for more options for monitoring and guiding movement speed, including slow, explosive, and specific timings for eccentric and concentric phases. The concentric phase is the phase where the muscle is contracted against resistance. For example, for the standing leg curl, the concentric phase is when the heel is being raised (the hamstring muscle is contracted). The eccentric phase is the phase where the muscle is being elongated. For the standing leg curl, it is the phase when the heel is being lowered (the hamstring muscle is being elongated). An example of phase-specific timings is asking the patient to count to 4 while raising the heel, and count to 4 while lowering it back down. The virtual assistant could count with the patient during this time to help them do it correctly.

[2] PTs stressed the importance of doing complete reps, meaning that after each rep the patient returns completely to the starting position. They said that this should be a preset for all exercises, but that it should be customizable in case they prescribe partial reps. However, they said that they would almost never prescribe partial reps.

[3] PTs are used to typing in instructions for patients with their current software; they're not used to specifying instructions for a virtual assistant. Thus, some PTs had trouble specifying the exercises, only altering the patient vernacular instructions and leaving the virtual assistant part blank. This shows that there is a need for separating the patient instruction part from the virtual assistant specification part so that PTs can clearly know what their specifications are for. This also shows a need for error checking

[4] The study showed that there is need for two main types of error checking. The first is to make sure that PTs have specified the necessary virtual assistant parameters. The second part is to make sure that the rules specified do not conflict. The virtual assistant authoring tool was modified to perform these types of error checking and alert the PTs accordingly.

[5] An example is the rule for avoiding bending the knee during leg raise exercise. Most PTs correctly specified "avoid knee flexion", but P7 said "include knee extension". This may also be due to the fact that "include" is the default visible option in the dropdown. To remedy this, the default visible option has been changed to a blank. For avoiding raising the knee during leg curl exercise, everyone correctly specified "avoid hip flexion". There was no ambiguity there.

6.1.2.3. Designing for the Patient

PTs also had comments about on design considerations that they would like to see for making the system more suitable for patients, as shown in the following table.

Table 6.7. Findings related to design considerations for the patient

Authoring Tool Interface Finding	**Resulting System Improvements**
Sensor-wearing should be minimized to reduce burden on patients.[1] (PT 3, 5, 7)	Forthcoming requirements for adding a trunk sensor to detect body position was eliminated.
There needs to be intelligence for managing delivery of multiple patient interventions.[2] (PT 6, 9)	System was modified to deliver only one feedback at a time.
Patient feedback should not nag the patient and should allow the patient to easily turn it off.[3] (PT 3, 9)	System was modified to silence its feedback after a certain number of repetitions.
Patients should be allowed to submit their own feedback.[4] (PT 3, 9)	A patient submission feature was added to the virtual assistant.
There are various considerations specific to geriatric population.[5] (PTs 1 through 9)	Modifications were made to sensors to make them easier to wear correctly.

[1] PTs stated that most patients would not cheat as far as lying down or sitting to do standing exercises. They felt that having patients wear trunk sensors in these situations to detect this form of cheating would encumber the patients unnecessarily. Trunk sensors should only be used if the exercise specifically involved trunk monitoring.

[2] PTs stated that feedback for multiple mistakes could overwhelm and confuse patient if delivered simultaneously, e.g. “Please slow down, remember to not raise the knee, remember to start with your leg straight”. Possible solutions are: ask patient to “pause for a second” or deliver only the most important feedback at any given time.

[3] Some patients may be in too much pain to do the exercises that day. In that case, the reminder should not bug the patient repeatedly and should be easy to turn off. Some patients may be able to exercise, but not able to do them correctly yet. A bit of cheating may be required. In this case, the feedback should not nag them with every repetition, causing discouragement. It should be able to detect inability to adhere to proper form and go silent quickly. PTs will be able to see the data and work with the patients on a gentler prescription.

[4] PT 4 stated that if patients are in too much pain that day (e.g. having chemo that day) and need to skip the exercises, they should be able to record that information. PTs can then see this data in the red-flag interface and can consider alternative treatments (e.g. this patient has skipped 75% of his/her exercises this week because of inflammation; maybe they should discuss a cortisone shot or another anti-inflammatory). This could also be a pop-up prompt if they stop short of their prescribed number of reps (e.g. if prescribed 10 reps, and they do 7 and stop, the popup could ask why).

With regard to the types of input, PT 4 thought freeform would be better than a list of responses to choose from. “I think letting patients subjectively type something will tell us a lot more.” PT 9 said the freeform input should have a short maximum, similar to Twitter’s 140-character limit, to speed up reading for PTs. For elderly patients who would not want to type on a small device, this could also be audio submission, recorded with speech-to-text transcription for PTs to see on their dashboard. This feature could also allow them to input and track their symptoms (pain, dizziness, stiffness, inflammation, etc) over time as another metric of progress.

[5] Every PT stated that they thought the verbal feedback is a helpful feature, especially since reading on a small screen can be difficult for some elderly patients. They liked the idea of counting along with the patient and speaking guidance when they make mistakes.

PT 2 thought that a dedicated device would probably be better than smart phone from a usability perspective. Smartphones may have features, extra apps, lock screens, and so forth that could be confusing to some elderly patients.

PTs gave advice on helping to ensure sensors are placed correctly. When asked about a sleeve vs. a strap, PT 2 said that a sleeve would be too cumbersome and that a color-coded strap that corresponds to an easy-to-read diagram would be helpful. PT 9 said that a middle-solution, a cuff, could be best. She referred to an existing tool that used a cuff housed with an accelerometer to detect foot-drop and said that the cuff is very difficult to wear incorrectly.

Conclusion

The study showed that the authoring tool can be feasible for PTs to use to customize a virtual rehabilitation assistant. After iterative interface improvements, PTs were able to specify the exercises correctly through the authoring tool. PTs also gave many important guidelines for designing the authoring tool to be suitable for in-clinic use, including strict time constraints and the need for new options and pre-sets regarding movement speed, exercise parameters, and delivery of patient feedback.

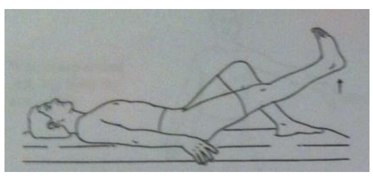
While the evaluation showed that the authoring tool can be feasible for use by PTs, the VRAs created in this rule-based architecture should also be accurate enough to recognize correct and incorrect exercise forms. The follow chapter describes an evaluation of the accuracy of VRAs in exercise mistake recognition.

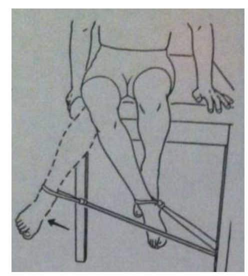
7. Evaluation of Virtual Rehabilitation Assistant Recognition Accuracy

The goal of this study was to test the accuracy of the virtual assistant's ability to recognize correct and incorrect exercise repetitions. I recruited five Doctor of Physical Therapy (DPT) students from the University of Pittsburgh to perform four exercises while being monitored by the virtual assistant. The students had clinical experience in prescribing and demonstrating these exercises to patients. I instructed the students to perform the exercises correctly and incorrectly, and compared these categories to the virtual assistant's own classifications of correctness.

7.1. Method

The four exercises studied were the same exercises evaluated by PTs in the previous chapter.



A. Leg Curl B. Lying Leg Raise C. Sidelying Leg Raise D. Internal Hip Rotation

Each participant performed 20 repetitions of each exercise, 10 correctly and 10 incorrectly. Latin Square experimental design was used to counterbalance the order in which each participant performed the exercises, shown in Table 7.1. The correct and incorrect repetitions were interleaved five at a time. For example, Participant 1 did exercise A (Leg Curl) first, and did 5 correct repetitions followed by 5 incorrect repetitions. This process was then repeated for a total of 20 repetitions for that exercise.

Table 7.1 – Latin Square for exercise sequences for participants

Participant	1st Exercise	2nd Exercise	3rd Exercise	4th Exercise	Correct/Incorrect
1	A	B	C	D	Correct first
2	B	A	D	C	Correct first
3	C	D	A	B	Incorrect first
4	D	C	B	A	Incorrect first
5	A	B	C	D	Correct first

7.2. Results

In general, the virtual assistant, using the rule-based architecture described in Chapter 5, was able to recognize correct and incorrect exercise repetitions with good but not perfect accuracy, between 80 and 100% (Table 7.2). Most of the errors in mistake recognition were false positives, i.e., the system classified a correct exercise movement as a mistake. This type of error is more egregious than false negatives, where the system mistakes an incorrect repetition as correct, because the patient may feel unfairly blamed. This could be partly ameliorated by increasing the mistake tolerance or being gentler in patient feedback.

Table 7.2 – Results of accuracy evaluation of virtual assistant's ability to detect correct and incorrect exercise forms.

Participant	Standing Leg Curl	Lying Leg Raise	Side-lying Leg Raise	Internal Hip Rotation
1	95%	100%	*	90% **
2	100%	70%	75%	90%
3	80%	95%	*	100%
4	90%	95%	80%	90%
5	***	100%	95%	70%

In four of the exercise sets, indicated with asterisks in Table 7.2, anomalies occurred. The anomalies illuminated three important issues regarding exercise form detection using wearable IMU sensors.

<u>* Subtle sensor malfunctions</u>

For participants 1 and 3, during the side-lying leg raise exercise, the virtual assistant recorded all repetitions as being incorrect. Detailed analysis of recorded sensor readings showed that the gyroscope, when the sensor was oriented on its side as it was during this exercise, had begun to drift nonstop throughout this exercise, registering a subtle but continuous false motion. This gyroscope drift was also verified in a 3D visualization application (3-Space Suite by YEI Corp) and appeared to occur at random.

Using a diagnostic tool provided YEI Corp, I was able to reset the gyroscope to eliminate this erroneous behavior. However, the important issue raised seems to be "what happens when a sensor subtly malfunctions and records false exercise performances?" Such malfunctions can happen under specific circumstances, such as random times when the sensor is placed on its side.

One approach to combatting this misreporting of patient error is to identify the types of sensor error that can occur and detect them using intelligence on the quality-checking side of the system. For example, the misbehavior of a constant gyroscope drift can be registered as a known error type, its occurrence automatically detected by checking for monotonic increases or decreases in readings, and the PTs can be alerted to replace or reset the sensor. Another approach can be to identify improbable or impossible movements by the human body as a means of detecting sensor errors. For example, the constant gyroscope drift in this case suggested that the participant's leg was moving forward nonstop for the entire set. This is a highly improbably movement during this exercise, and a sensor defect could be deduced by the system.

** Mistakes going undetected when occurring outside of recognized repetitions

The next issue is related to how the mistake recognition is implemented in this system. Sequentially, the system first detects a repetition, after which it checks the rules and other movement data to see if any rules were violated. However, if the repetition itself was never detected, the mistake would never be recognized.

This anomaly happened during the Internal Hip Rotation exercise. When participants did them incorrectly, i.e., slid their leg across, they didn't rotate their hips at all so system did not recognize any repetitions. Because of that omission, the system also didn't check for mistakes (sliding the leg across). The system remained silent, waiting for a repetition to occur.

This issue was remedied by having the system check for mistakes independent of repetitions, so that any time patients slid their leg across, regardless of whether they turned their hip, the system immediately flagged the mistake. After this change, the system recognized the correct and incorrect exercise forms with high accuracy.

*** Even trained persons can exceed 20 degree error threshold for certain exercises

For the Standing Leg Curl exercise of Participant 5, the system reported that almost all of her repetitions were erroneous. Detailed angle analysis showed that she actually raised her knee slightly above 20 degrees, the threshold for qualifying a repetition as a mistake. Simulating the exercise myself, I saw that 20 degrees is not very noticeable.

Because only one participant exhibited this behavior, it could be an outlier, but I believe that more analysis should be done to see what error thresholds are suitable for each exercise as they could differ significantly. During the interviews with PTs, most said that as long as patients did not make significant errors (greater than 30 degrees for example), it would be satisfactory. But it seems that the threshold beyond which the mistake would be considered significant can depend strongly on the exercise.

8. Discussion, Conclusion and Future Work

8.1. Summary

In this thesis, I describe an exploration of a technology that does not exist today: a Virtual Rehabilitation Assistant to support physical therapy. By leveraging wearable sensors, a virtual assistant can monitor home exercises, give real-time instructions and feedback to patients, and give PTs detailed, quantitative data on patients' performances, helping PTs to make better-informed decisions on treatment adjustments.

I carried out this thesis in two stages, first, investigating the feasibility of deploying a Virtual Rehabilitation Assistant into patient homes and having PTs use the gathered data to make treatment decisions, and then, exploring the creation and feasibility of an authoring tool with which PTs could customize a virtual assistant according to their exercise prescription needs.

8.1.1. Investigating the feasibility of a Virtual Rehabilitation Assistant in homes

To investigate how a Virtual Rehabilitation Assistant could be used in patient homes and how PTs might use the resulting data to make treatment adjustments, I created a technology probe called SenseCap. SenseCap recorded balance exercise metrics, including time of exercise, duration, rotation velocity, rotation frequency, range of motion, and symptom levels. I deployed SenseCap into 10 patients' homes for seven days. Patients wore SenseCap when they performed prescribed head rotation exercises and took it off when they finished. Patients found SenseCap easy to use and reported added motivation due to increased accountability. PTs found that this information could be helpful for adjusting their prescriptions, communicating with patients about exercise mistakes, and documenting patient progress.

To my knowledge, this is the first exploration of a Virtual Rehabilitation Assistant outside of a controlled lab environment deployed into patient homes. The results showed that a Virtual Rehabilitation Assistant could be feasible in the real world for outpatient physical therapy treatments. This ecological deployment also highlighted issues and design implications that would be unseen in a controlled laboratory setting, including unexpected exercise movements, unexpected positioning of sensor, and unexpected compliance behavior (significant above-compliance) which resulted in a PT intervention.

8.1.2. Exploring the creation and feasibility of a virtual assistant authoring tool

To lower the adoption barrier for PTs, I explored a method for them to be able to create and customize virtual assistants without requiring engineering expertise. I designed and implemented a prototype where PTs can use their familiar anatomical language to specify the desired exercise motions for which the virtual assistant should be able to recognize, record, and provide feedback on. I evaluated this authoring tool with nine PTs to iteratively improve upon the interface and gather feedback regarding usability design implications. The results of the evaluation showed that the authoring tool can be feasible for use by PTs and that many factors need to be considered in designing such a VRA system. These factors include designing the system to fit into the PTs' workflow and their strict time constraints as well as giving PTs the necessary options to monitor exercise parameters and deliver feedback appropriately.

Informing the Design of Future Virtual Rehabilitation Assistant Authoring Tools

Findings from this study can be applied to future virtual rehabilitation assistant authoring tools such as those for occupational therapy. Firstly, the evidence showed that the initially conceived model in which the physical therapists create exercises in their entirety for their patients is flawed. The model that more appropriately fits PTs' workflow is one where one dedicated PT creates pre-populated exercises and the other PTs select and customize them. The study found that PTs rarely need to create new exercises, but they often adjust existing ones along several parameters depending on patient needs. This model is likely to be applicable to occupational therapists as well since they may have similar time constraints and a set of frequently prescribed exercises. The same model may also be applicable to fitness trainers and other professionals who prescribe exercises for clients.

Secondly, the virtual assistant runtime environment architecture can also be used as a template for future authoring tool designers. The modularization of motion analysis intelligence, in this case the creation of motion widgets, gives flexibility to the system to enable it to recognize many combinations of movements as specified by the clinician or other exercise domain expert. Modularization is a fundamental concept in software engineering used to encapsulate a set of related functionalities to prevent them from being tightly bound to other logic. The modularized software objects can then be recombined and extended in a versatile manner allowing the resulting software to achieve new levels of flexibility and functionality. In this work, I have applied this concept to motion analysis intelligence, which is traditionally hard-coded or generated via statistical models based on machine-learning training. Those techniques create intelligence that is hard to alter and customize without either changing the code, or retraining the machine-learning model to detect new variations. By modularizing the basic movement analyzers, they can be recombined to create intelligence that is more flexible and easier to customize. This flexibility allows the virtual assistant intelligence to be able to adapt to the specifications of the physical therapists. Also, the interaction of the sensor data, motion widgets and the rule engine could serve as a schematic for future implementations of other exercise movement authoring tools.

To my knowledge, this is the first time a virtual assistant authoring tool has been created. In the current state of art, the intelligence and exercise rule specifications within virtual assistants are created, customized and deployed by engineers and programmers. By allowing PTs to make their own specifications when they do not have access to engineering resources, the authoring tool could increase the usability of virtual rehabilitation assistant technology and help lower its barrier of adoption.

8.2. Future Work

Several challenges remain for the adoption of virtual rehabilitation assistant technology by real-world physical therapy clinics.

Database of Prepopulated Exercises

Since findings showed that PTs strongly prefer selecting and customizing prepopulated exercise specifications rather than creating them in their entirety, the first step would be expanding the database of these default specifications. This could be done with dedicated PTs, whose domain expertise, combined with the authoring tool, could allow them to rapidly create specifications and common presets. The default exercises themselves could be derived from existing exercise catalogs, including the VHI catalog [VHI, '12], which the PTs currently use to create printouts for patients to take home. The populated database of exercise specifications could be stored in the cloud for PTs to access. As PTs customize and create variations of these default exercises, they could also have the option of uploading them to the cloud to share with others.

Other Exercises

A second challenge is expanding the authoring tool's capability for specifying more exercises, including complex exercises and exercises for different body regions. Research needs to be conducted to explore motion analyzers for other regions of the body. While elbow and shoulder are analogous to knee and hip in their movements, spine, wrists and ankles can vary in movement capabilities. For example, one type of spine movement that PTs are interested in monitoring is *lordosis* or rounding of the spine. There are exercises, such as squats, where PTs commonly ask their patients to avoid lordosis.

In addition to analyzing more body regions, the authoring tool should also be expanded beyond isolation exercises to allow PTs to customize more complex, functional exercises, such as jumping jacks, leaping from side to side, lifting boxes over shoulders, and so forth. PTs expressed that these complex exercises would be difficult to prescribe through the tool in its current form. How might the motion analyzers have to change to encapsulate motions not just for single joints, but also for multiple joints working in complex coordination? One possibility is to expand the set of motion widgets beyond just those based on joints; new ones could be added that are based on common compound-joint motions, such as pushing, pulling and jumping. These motions typically involve at least two joints - for example, pushing usually involves the elbow and shoulder joints working simultaneously, and jumping requires the knee and hip joints working in tandem. So in the example of authoring of a jumping jacks exercise, the primary motion may be “jumping” and the additional rule may be “include shoulder abduction” to indicate that the jumps should be accompanied by side-to-side swaying of the arms. Overall, more research is need to explore how the specification interface and motion analysis implementation might have to change to allow PTs to specify compound exercises in an intuitive manner.

Evaluating Real-time Coaching Feedback

Another challenge involves evaluating and optimizing the patient interface, including the coaching mechanism, which can help patients perform these exercises and their variations correctly. The coaching mechanism could provide reminders when patients forget to do exercises, count repetitions and elapsed time aloud for the patients, offer encouragement when proper exercising and progress are detected, and offer corrections when mistakes are detected. Though these features are beneficial, there are also potential drawbacks: reminders could irritate patients and mistake detections could have false alarms, blaming patients for errors they did not commit. Further research is needed to examine ways of minimizing the drawbacks while maximizing the benefits.

Conducting Clinical Trial to Show Efficacy

Finally, because the adoption of the technology by stakeholders in the medical sector, including hospitals, clinics and insurance companies, requires proof that the technology improves patient progress, which ultimately reduces medical costs, a clinical trial should be conducted to evaluate the technology’s efficacy in this regard. In this trial, there could be a control group and two experimental groups, A and B. The control group could consist of physical therapy patients that receive treatments without virtual assistant technology. The experimental group A could receive treatments with the monitoring portion of virtual assistants alone (no coaching mechanisms) and experimental group B could receive treatments with both monitoring and coaching mechanisms of virtual assistants. Patients’ progress can then be compared over several months to and the effects of the virtual rehabilitation assistants, including the monitoring and coaching functionalities, can be determined. If results were positive, this trial could help push the technology through existing inertia and catalyze its adoption in the real world.

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Appendices

Appendix A – Sensor Validation Protocol

1. Have user read consent form
2. Review consent form with user and get signature
3. Sign the consent documentation form
4. Get demographics info from user (age, gender, height, weight)
5. Get user's initial dizziness rating on a scale of 0 – 10.
6. Demonstrate the helmet and metronome to user
7. Demonstrate the motions in accordance with the metronome
8. Put the iPod into the helmet at the position indicated on the data sheet
9. Give the user a clean, disposable hair-cap
10. Ask user to sit down in chair and put on helmet
11. Adjust helmet to make sure it's snug
12. Start playing the metronome at the speed of the current trial to give him/her a sense of the rhythm.
13. At the count of three, start the Polhemus recording device, have the helper start the iPod recording, and have user start the head movments
14. The Polhemus will automatically beep and stop after 30 seconds. At this time, have the helper stop the iPod and have the user stop the movements.
15. Ask user to rate their dizziness on a scale of 0 – 10.
16. Have the helper start a new recording session on iPod.
17. Repeat steps 9 through 12 until it's time to change iPod position.
18. Change iPod position and repeat steps 9 to 13.
19. After repeating with the 3 positions, ask user to remove helmet and discard hair-cap
20. Pay user and have him/her sign the payment form.

Appendix B – Patient In-Home Study Questionnaire

Background Information of Patient (at deployment of SenseCap)

Subject ID _________________________ **Date____________________________**

Gender: ☐ Male ☐ Female

Age: _____

Patient's Feedback (at return of SenseCap)

Subject ID _________________________ **Date____________________________**

Thank you so much for filling out this questionnaire. We value your feedback and it will help us improve SenseCap.

1. How easy was the hat to put on?

☐ very easy ☐ somewhat easy ☐ neutral ☐ somewhat difficult ☐ very difficult

2. How comfortable was the hat to wear?

☐ very comfortable ☐ comfortable ☐ neutral ☐ uncomfortable ☐ very uncomfortable

3. Did the hat interfere with your exercises?

☐ did not interfere at all ☐ interfered a little ☐ interfered a lot

4. How many times did the hat fall off during exercise?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ more than 5

5. Please give your overall impression of SenseCap

____

____

____

6. Please give any suggestions you have to improve SenseCap

Thank you very much!