

A Technology Probe of Wearable In-Home Computer-Assisted Physical Therapy

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ABSTRACT

Physical therapists could make better treatment decisions if they had accurate patient home exercise data but today this information is only available from patient self-report. A more accurate source of data could be gained from wearable computing designed for physical therapy exercise support. Existing systems have been tested in the lab but we have little information about issues they may face in home settings. We designed a technology probe, SenseCap, and deployed it for seven days in ten physical therapy patients' homes. SenseCap is a wearable physical therapy support system that gathers patient exercise compliance and performance data and summarizes the data in charts on an iPad Dashboard for physical therapists to view when patients return to the clinic. In this paper, we present the results of our deployment, show in-home patient exercise data gathered by the probe, and make design recommendations based on patient and physical therapist responses.

Author Keywords

Technology probe, physical therapy, rehabilitation, quantifying, exercise, ubiquitous computing, mobile, wearable, iPod

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Physical therapy is a key component 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 [1,12] and more than 20 million have knee osteoarthritis, suffer joint pain,

weakening of quadriceps muscles, and restrictions in mobility [13].

Mobile technologies are promising for supporting home physical therapy exercises. Mobile sensors can be used to provide real-time analysis of physical movement and record exercise metrics for patients and physical therapists (PTs) to review. These metrics can allow PTs to make more informed decisions regarding treatment adjustments.

Researchers have explored the use of wearable sensors for supporting physical therapy, but these studies were done in controlled laboratory settings where researchers can oversee patient exercises and technicians can set up and monitor the technology. We lack information on how wearable physical therapy support systems would work in patients' homes where therapists are not present, context is uncontrolled and patients have no professional support. In this work, we bridge this gap by deploying a technology probe to examine how patients and PTs would use such a system in a real context.

Our technology probe, SenseCap, consists of an iPod Touch 4G fitted into a baseball cap. The physical therapy used in this probe study is a head-rotation exercise commonly prescribed to balance rehabilitation patients. 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.

The contributions of this work are the lessons learned and the design recommendations derived from the in-home deployment of SenseCap to physical therapy patients. The findings and design guidelines focus on how to capture and communicate important data, as well as PT and patient needs that are important to consider.

BACKGROUND

Physical therapy treatment programs typically last several months and involve bi-weekly (or more) clinical visits with physical therapists (PTs) [16]. At the start of the treatment program, PTs diagnose conditions and prescribe home exercise regimes. In follow-up visits, PTs assess patients' progress and make decisions on how to adjust their exercise prescription, deciding which exercises to add or remove and how to adjust exercise frequency and difficulty.

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Lack of Home Exercise Information

Because the exercises are performed at home, PTs cannot supervise patients and do not have 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. For example, 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 [14], 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.

Technological Support for Physical Therapy

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 the Kinect and Wii in conjunction with an output device such as a television. However, research has shown that infrastructure-based technologies may not be suitable for many patients. Axelrod & Fitzpatrick [2] 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 [3] showed that many patients do not like technology tethered to the living room.

Wearable technology may address the above preferences. Along with their potential to accurately measure body joint movements, wearable devices are portable and self-contained, making them potentially easier to set up and configure. They may be able to track movements unobtrusively while patients engage in their activities of interest. With the increasing ubiquity of mobile sensors (e.g. accelerometers and gyroscopes), many researchers have explored their use in-lab for supporting physical therapy treatment [5, 10, 11, 17, 18, 19]. These wearable systems range from simple (single sensor) to complex (multiple sensors, body area networks, and so forth).

Brutovsky and Novak [5] explored placing a tri-axial accelerometer sensor node on knee rehabilitation patients' legs during leg raise exercises. Visual and audio cues were delivered to the patient through a hand-held PDA to guide the patients. The system collected exercise metrics and generated compliance reports. Melzi and colleagues [10] proposed a wireless body-area network of accelerometers to capture exercise movements and quantify performances. The researchers used an ensemble of 2-axis accelerometers on various parts of users' arms during bicep curl exercises. As typical of physical therapy support systems, the number

of repetitions, speed of performance and fluidity of movement were measured. Taylor *et al.* [17, 18] also explored using multiple body-worn accelerometers to measure the quality of knee rehabilitation exercises. They used machine learning to train models to distinguish between correct performances and errors. The performance data are then presented on a computer screen.

Because these systems have undergone tests in laboratory settings only, we lack information on actual in-home use by patients. What complications arise when patients use such systems in real homes? What do home exercise compliance data really look like (cf. [14])? Chandra and colleagues explored the needs of physiotherapy patients in the home, but the studies were done with storyboarding [6]. Deploying real systems into real patient homes can raise many issues not illuminated in a lab or hypothetical setting. In this paper, we present a technology probe deployed into ten patient homes to help answer these types of questions and provide design recommendations.

Technology Probe for In-Home Physical Therapy

As Hutchinson and colleagues argue [9], “a [technology] probe is an instrument that is deployed to find out about the unknown—to hopefully return with useful or interesting data.” The technology probe's goal is to explore real-world usage in order to inform new designs.

Probes are typically simple and contain one main function, unlike prototypes, which may contain many layers of functionalities and address a range of needs [9]. The reason for limiting functionality is to aid ease of development and deployment. The goal of the probe is not to see how comprehensive in functionality the system can be, but to see how real stakeholders use the system in a real context in order to generate rich and informed design ideas.

In this vein, SenseCap contains the core functionality of gathering the patient exercise compliance and performance data for balance rehabilitation. We could have added many more functionalities such as a range of mistake detection and vocal feedback but we wanted to probe how patients currently perform the exercises at home before further complicating the system.

Balance Rehabilitation as a Test Domain

We chose balance rehabilitation as a probe domain because balance disorders have a high prevalence in the U.S., affecting approximately 69 million Americans [1].

Gaze Stabilization Exercise

Commonly prescribed to balance rehabilitation patients is a head-turn exercise, also called the Gaze Stabilization Exercise [4]. Patients fix their eyes on a target, such as 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 [20].



Figure 1. The SenseCap

SENSECAP

Patients wear SenseCap when they perform the head-turn exercise and take it off when they finish. SenseCap was co-created with our research collaborators at the Center for Balance Disorders at University of Pittsburgh Medical Center.

SenseCap Architecture

SenseCap has three components: an iPod Touch 4G, a cap with a sewn-in sleeve to hold the iPod (Figure 1), 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).

SenseCap Metrics

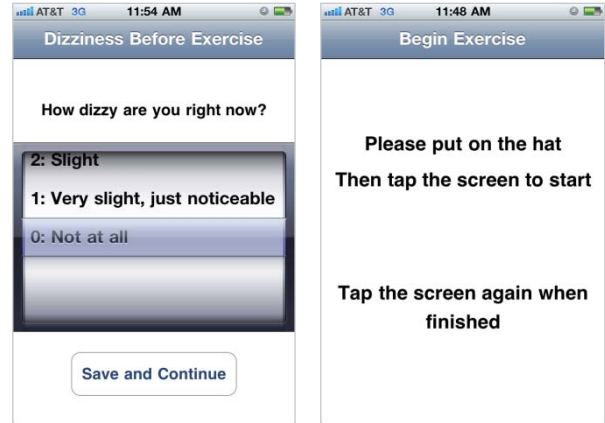
SenseCap gathers the following quantitative patient exercise data, used for metrics useful to PTs.

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.

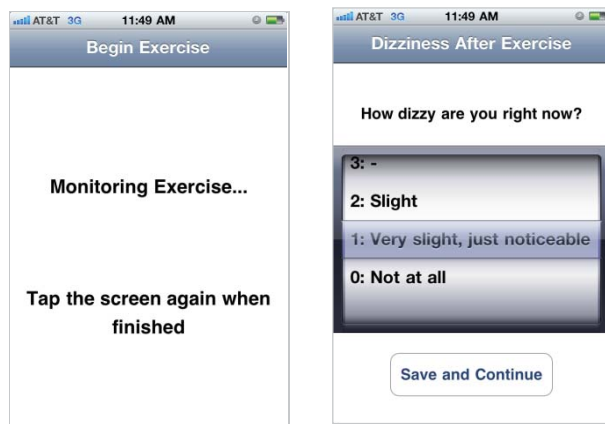
Exercise duration – For this exercise, PTs use duration rather than number of repetitions because the latter can become high and cumbersome to count (100+). A simple difference between start and end time of sessions is used to record the duration. The durations were rounded to the nearest 10 seconds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

Average head-turn velocity – The iPod provides the rotation velocity about its own X, Y and Z axes. We 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 – We segmented the data to calculate the number of repetitions, which was then divided by the exercise duration to create turns per second.



Figures 2.1 and 2.2 – SenseCap iPod user interfaces



Figures 2.3 and 2.4 – SenseCap iPod user interfaces

Average head-turn range of motion – We 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.

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.

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



Figure 3. The iPad Dashboard

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, we 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.

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 3.

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, we felt it necessary to validate this functionality of SenseCap.

Before conducting the in-home study with patients, we 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).

We asked each participant 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). We controlled the frequency of head turns 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. We concluded that SenseCap measurements were valid.

TECHNOLOGY PROBE DEPLOYMENT

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

Method

All patients were given the head-turn exercise prescription by their PTs. We did not intervene in the prescription process. They were briefly instructed in SenseCap use by either the first author or the PT second author 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.

Next we present and discuss patient home-exercise compliance and performance data captured by SenseCap.

Compliance Results

Columns 6 through 12 of Table 1 show the actual exercise frequency of patients. Red cells with normal font are days where the patient was under-compliant, *i.e.* exercised less than prescribed. Green cells with italic font are days where the patient exercised the same amount as prescribed. Blue cells with bold font are days where the patient was above-compliant, *i.e.* exercised more than prescribed. For example, patient 1 was prescribed 3 sets of exercises, 30

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			
2	F	65	2x30s	Yaw	1x30	1x30	3x30	<i>2x30</i>	1x30	1x30	3x30	
				Pitch	1x30	1x30	3x30	<i>2x30</i>	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	<i>3x30</i>	6x30	<i>3x30</i>	<i>3x30</i>	5x30	6x30	<i>3x30</i>	
				Pitch	1x30	5x30	4x30	<i>3x30</i>	0	6x30	<i>3x30</i>	
7	F	47	4x60s	Yaw	5x60	<i>4x60</i>	4x90	4x90	4x120	Returned early		
				Pitch	<i>4x60</i>	<i>4x60</i>	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	<i>3x30</i>	<i>3x30</i>	1x30	2x30	2x30	1x30	
				Pitch	0	<i>3x30</i>	<i>3x30</i>	1x30	2x30	2x30	1x30	
10	M	36	5x60s	Yaw	4x60	6x60	10x60	<i>5x60</i>	<i>5x60</i>	iPod error **		
				Pitch	3x60	7x60	10x60	<i>5x60</i>	<i>7x60</i>			

* Patient stopped using the device for fear of acquiring brain cancer from iPod device.

** iPod contained a software bug which caused a crash when saving data; data from these sessions were lost.

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 surveyed 300 PTs of various domains about their patients’ compliance rates; these rates were measured by patient retrospective self-report [14]. 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.

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.

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 [15]. 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.

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.

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

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.

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

Method

We visualized the following exercise data components on an iPad PT Dashboard: Patient compliance, performance metrics, and symptom levels. The visualizations were created with our PT co-author.

We presented these data and their visualizations 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. We created this hypothetical patient data 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. We named the hypothetical patient Sally.

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, we used a stacked bar chart as shown in Figure 4.

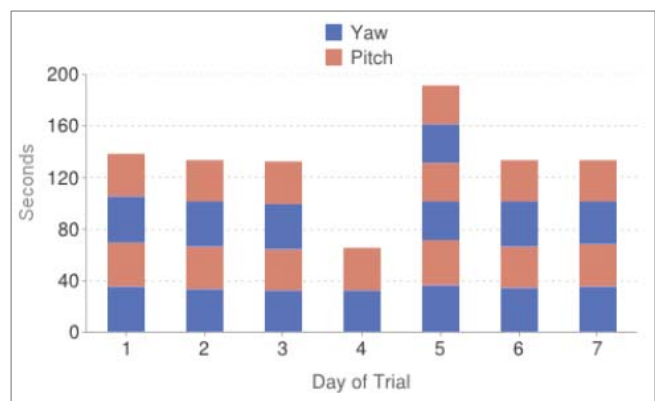


Figure 4. Patient Sally exercise compliance chart. Each block represents one exercise performed.

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.

Communicating Exercise Performance Metrics

We presented data regarding head-turn velocity (degrees/sec), turns-per-second, and range of motion (degrees) to PTs. Figure 5 shows an example metric chart (range of motion).

Unlike the duration chart, we did not mix the two exercises into one since the blue and red dots may overlap and become indistinguishable. Thus, we 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.

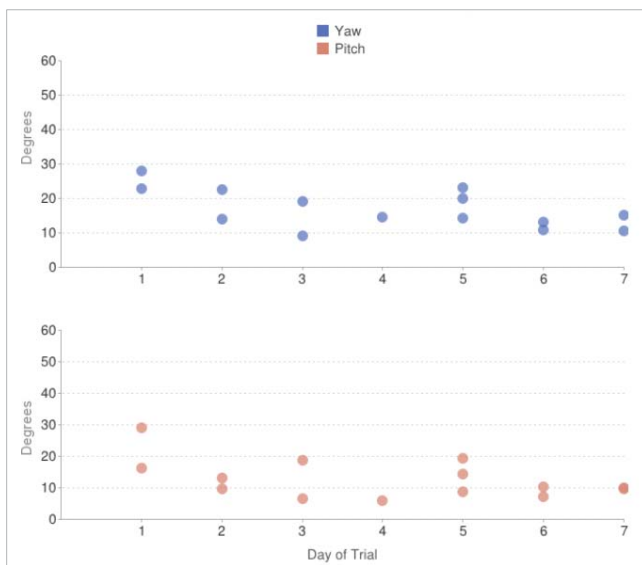


Figure 5. Patient range of motion chart. Each dot represents one exercise performed. Dots may overlap.

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. We used a pair-point graph with connected lines, as shown in Figure 6. 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).

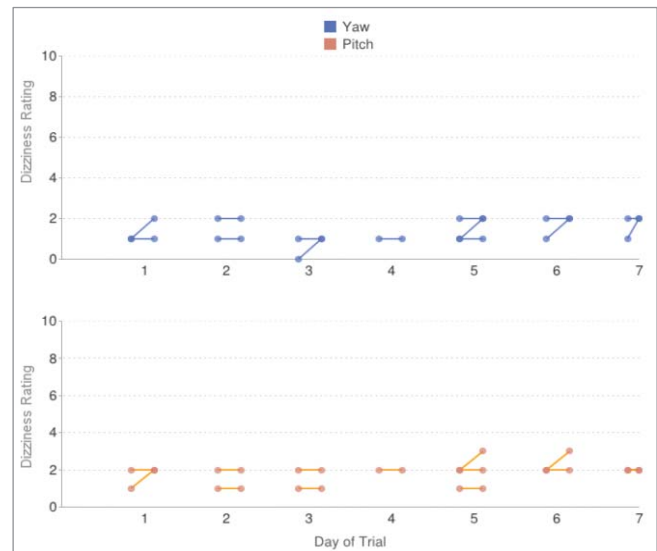


Figure 6. Pre and post-exercise dizziness levels. Each pair of dots, connected by a line, represents the pre- and post- dizziness of an exercise performed. Dots may overlap.

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, we 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...”

DESIGN RECOMMENDATIONS

In this section, we synthesize our findings, present additional lessons learned, and provide 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.

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.

We thus recommend 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 4. 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.

We recommend 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, we 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-exercise 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.

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, we 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, we allowed patients to tap the screen anywhere to begin monitoring exercise and tap anywhere when finished. However, we 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, we 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.

We recommend 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 we discovered was a variation in how patients wore their caps. We 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.

We 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, we 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 we re-ran the patient data using the new algorithm, the false errors disappeared.

We recommend 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.

CONCLUSION AND FUTURE WORK

In this paper, we presented a technology probe for wearable physical therapy support systems. We deployed SenseCap 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.

Based on the probe, we presented lessons learned and design insights from both patient and PT perspectives for creating wearable systems for supporting physical therapy. The lessons and design insights focused on data that are important to capture and communicate and patients' special needs and preferences to consider.

For a future system, we plan to explore more interactivity features including real-time error recognition and guidance. We plan to implement several error-recognizers and types

of corrective feedback (auditory and tactile) to the SenseCap probe to explore how patients respond to real-time coaching at home.

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