Ploderer, Bernd, Fong, Justin, Withana, Anusha, Klaic, Marlena, Nair, Siddharth, Crocher, Vincent, Vetere, Frank, & Nanayakkara, Suranga
(2016)
ArmSleeve: A patient monitoring system to support occupational therapists in stroke rehabilitation.
In Foth, M (Ed.) *Proceedings of the 2016 ACM Conference on Designing Interactive Systems.*
Association for Computing Machinery, United States of America, pp. 700-711.

https://doi.org/10.1145/2901790.2901799

ArmSleeve: a Patient Monitoring System to Support Occupational Therapists in Stroke Rehabilitation

Bernd Ploderer[1,2], Justin Fong[1], Anusha Withana[1,3], Marlena Klaic[1,4], Siddharth Nair[1], Vincent Crocher[1], Frank Vetere[1], Suranga Nanayakkara[1,3]

[1]Microsoft Research Centre for SocialNUI, University of Melbourne, Australia
[2]Queensland University of Technology, Brisbane, Australia
[3]Augmented Human Lab, Singapore University of Technology and Design, Singapore
[4]The Royal Melbourne Hospital, Australia
{ploderer, vincent.crocher, f.vetere}@unimelb.edu.au, {justinf, siddharthn}@student.unimelb.edu.au, {anusha, suranga}@ahlab.org, marlena.klaic@mh.org.au

ABSTRACT
This paper describes the design of "ArmSleeve", a patient monitoring system to support occupational therapists in their upper limb rehabilitation work with stroke patients. Occupational therapists can provide rehabilitation in clinics, but they have limited insights into how much their patients use their affected arm and hand in daily life, which is critical for effective recovery to occur. Our work addresses this problem through three interrelated studies: (1) interviews with therapists to examine their current rehabilitation practices; (2) the design of the "ArmSleeve Sensor" to monitor a patient's upper limb movement; and (3) the design and evaluation of the "ArmSleeve Dashboard" to visualize this information for therapists. The findings show the importance of collecting objective data to assess exercise and activities outside therapy, but also a lack of contextual information to interpret this data. We discuss considerations for how to address this issue through patient engagement as well as considerations for designing wearable sensor technology that is usable in everyday life.

Author Keywords
Wearable technology; dashboard; information visualization; stroke rehabilitation; occupational therapy

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

INTRODUCTION

Stroke is the leading cause of disability in high-income countries, with one of the most common resulting disabilities being paralysis of an upper limb [25]. People

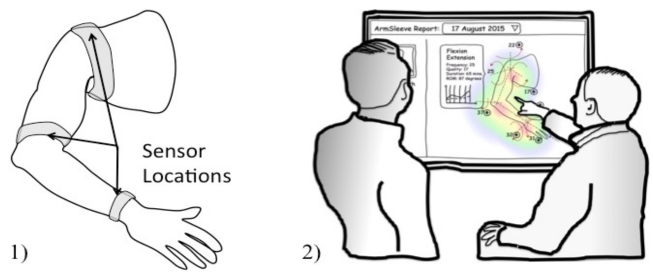

Figure 1: The ArmSleeve system was designed to support occupational therapists through objective upper limb data captured in the daily life of their patients. The system consists of the (1) ArmSleeve sensor prototype and (2) a dashboard.

living with stroke often have difficulty producing voluntary movement and experience difficulty in coordinating fingers, hands and arms. They can also experience deficits in sensation and proprioception, as well as muscle shortening and weakness, which further complicate upper limb movement. It is estimated that 65% of those who live with stroke also live with a resulting disability that affects their ability to independently carry out activities of daily living (ADL) such as eating, dressing and washing [13].

Occupational therapists (OTs) can support stroke patients in re-developing motor skills and in learning to perform activities of daily living. During therapy sessions OTs employ a variety of techniques to support rehabilitation, such as functional electrical stimulation, constraint induced motor training, facilitation, and virtual reality applications [5, 27]. Furthermore, OTs provide patients with exercises to engage the affected arm in everyday activities that are context specific, such as reach and grasp tasks in the kitchen and bathroom [31]. This combination of therapy, exercise and context specific retraining is critical for neuroplasticity [30]. However, adherence to rehabilitation programs is often low due to the effort required to use a paretic upper limb, lack of motivation, musculoskeletal issues, and fatigue [16]. Additionally, OTs lack objective data about the degree to which exercises have been performed, or about how much patients have engaged their affected upper limb at home. While retrospective recall and

DIS 2016, June 04 - 08, 2016, Brisbane, QLD, Australia

ACM 978-1-4503-4031-1/16/06 $15.00
DOI: http://dx.doi.org/10.1145/2901790.2901799

exercise diaries can gather subjective data, the quality of this data is limited and relies on patients that are motivated and have adequate cognition [33].

The aim of our research is to support occupational therapists (and stroke patients) by providing a collection of objective data about patient upper limb movement in daily life. In this paper we firstly report on an analysis of OT's current practices and needs, such that they able to better understand a patient's upper limb movement in daily life. Based on these insights we then report on the design and evaluation of the *ArmSleeve* system. The system consists of the *ArmSleeve Sensor* to monitor upper limb movement, and the *ArmSleeve Dashboard* which provides therapists access to upper limb movement information (see Figure 1). Based on design workshops and interviews with OTs we show how the dashboard can enhance rehabilitation through ongoing assessment and improved patient engagement.

RELATED WORK

HCI Work on Upper Limb Rehabilitation After a Stroke

There is a growing body of HCI work on supporting rehabilitation after a stroke. The majority of this work focuses on patients, often through interactive games combined with emerging interaction techniques to encourage upper limb exercise. Boulanger et al. explored the multi-touch capabilities of the Microsoft Surface Table to design games that encourage patients to exercise finger and wrist extension movements [7]. The CONTRAST system also uses games on a tabletop display to encourage exercise but includes physical objects, like a cup, to exercise grasping and moving actions on a tabletop surface [15]. The PhysiCube system utilizes tangible objects (Sifteo Cubes) and game mechanisms to encourage patients to practice grasp and lift movements [34]. Khademi et al. used the Leap Motion hand tracking system and a modified version of the game of Fruit Ninja to help stroke patients practice their finger individuation [18]. Peiris et al. built SHRUG, an interactive shoulder rehabilitation exerciser, which allows patients to train the affected shoulder together with the unaffected shoulder by lifting a bar onto prongs [26]. All of these systems are designed for patient use in clinical settings to engage in rehabilitative exercises.

A second line of HCI work focuses on designing rehabilitative systems that patients can use in their own homes. This research aims to design for exercise activities that are meaningful to the patient and that fit into the routines of their daily lives. For example, Alankus et al. designed motion-based games and deployed them in the home of a woman who was 17 years post-stroke [2]. In another example, Balaam et al. used a participatory design approach to create artifacts for people living with the effects of a stroke [3]. In both cases, researchers faced challenges in balancing the need for activities that are meaningful and motivating, with the demands of rehabilitation work Furthermore, their work highlights the importance of understanding the social context in which an interactive system might be used, including the role of family and informal carers.

There is far less research on the needs of clinicians, especially the occupational therapists (OTs), who care for patients during rehabilitation. Moraiti et al. worked with OTs to explore the use of Do-It-Yourself (DIY) toolkits like Arduino and the Skweeze system, which can be embedded into everyday objects like cushions and socks [23]. By embedding these toolkits into everyday objects, the OTs learnt how to develop their own smart therapeutic aids, tailored for the specific interests and needs of their patients.

Monitoring Upper Limb Movements in Daily Life

HCI offers a wide range of work on monitoring health and wellbeing over extended periods of time in daily life under the umbrellas of personal informatics [20] and Quantified Self [9]. This work is often driven by body-worn sensors (e.g., Fitbit, Jawbone Up) to monitor lower limb movement, i.e., how much (typically healthy) people walk and exercise in daily life [28].

Beursgens et al. applied a personal informatics approach to design Us'em: a watch-like device worn on both arms to monitor upper limb movement of stroke patients in daily life [6]. Us'em only measures acceleration at the wrist. The system does not isolate upper limb movement from torso movements, nor does it precisely measure how a particular part of the upper limb moves. Nevertheless, by providing a comparison in activity levels between the affected and the unaffected upper limb it provides a useful starting point to understand how much the affected upper limb of a stroke patient is engaged in daily life.

Attempts to accurately monitor upper limb movement have been less successful. Accurate upper limb monitoring systems through body-worn systems is very complex, both conceptually and technologically. The upper limb can move at multiple degrees of freedom at the shoulder and elbow, and additional motion of wrist and fingers further increases the complexity. Hence, unlike walking where well-established models exist to describe and quantify steps [35], upper limb motions are difficult to quantify. Likewise, while pedometers can monitor steps walked with one sensor unit, accurate upper limb monitoring systems require multiple sensors to distinguish between shoulder and elbow movements, and to exclude movements coming from the torso. Despite these difficulties, studies in clinical settings over short timespans have shown that body-worn sensors can capture upper limb motion of healthy participants and stroke patients with some success [11, 19, 32].

In summary, there are various strong efforts to engage patients living with the effects of a stroke in upper limb exercise and to monitor their movement. While this focus on the patient is important, there has been little consideration for the needs of occupational therapists and on creating systems that allow them to benefit from the data collected by upper limb monitoring systems.

RESEARCH SETTING AND APPROACH

The aim of this research is to design a system that supports the practices of occupational therapists (OTs) in providing data about the upper limb movement of stroke patients in daily life. In particular, this research aims to (1) understand the current practices and needs of OTs, (2) design a body-worn sensor system (*ArmSleeve Sensor*) to monitor upper limb movement, and (3) design a web-based dashboard to visualize the movement data to support OTs (*ArmSleeve Dashboard*). The technology we designed is called "ArmSleeve", because the team envisioned a system consisting of multiple sensors along the arm to monitor movement, which could eventually be embedded in the sleeve of a shirt. The final system described here consisted of a wearable technology worn on the patient's arm.

Research Setting

This research was conducted in collaboration with a large tertiary hospital in [anonymized]. The hospital offers various rehabilitation programs for stroke patients, including upper limb programs and community therapy services. Rehabilitation of the upper limb is a core practice of therapists across both inpatient and outpatient settings. The primary goal of occupational therapy interventions are to enable people to participate in their activities of daily living ranging from personal and domestic tasks, through to community, employment, leisure and recreational activities.

Patients experiencing a stroke are initially managed within the acute stroke unit by a team of medical, nursing and allied health staff. Patients receive occupational therapy intervention a minimum of 3 times per week. Patients requiring further rehabilitation may be transferred to the sub-acute inpatient setting. The length of stay for a period of inpatient rehabilitation varies from a couple of weeks up to many months. These patients receive occupational therapy intervention on a daily basis. Chronic stroke patients who are residing within the community may attend community-based therapy where they attend for up to 3 sessions per week over a 6 – 10 week period.

The hospital recently established a 'hub' with upper limb workstations based on robotic and gaming technology. A dedicated movement laboratory has also been developed to assess and study patient progress. While these technologies provide support during rehabilitation sessions, the OTs were keen to explore how technology could monitor and support patients outside therapy sessions and more specifically in home and community settings.

Research Approach

We conducted this research through a series of research and design activities with 10 OTs at [anonymized hospital]. These activities involved the following:

- Study 1 - understand *OT practices and needs*,
- Study 2 - design and evaluate the *ArmSleeve Sensor* to track arm movement through wearable technology, and
- Study 3 - design and evaluate the *ArmSleeve dashboard*, to understand how the information generated by the sensors can be presented to enhance the work of therapists.

STUDY 1: PRACTICES AND NEEDS OF THERAPISTS

Research Aim and Study Design

The aim of study 1 was to examine the practices of OTs, specifically to understand their needs for monitoring patients in between therapy sessions. The first author conducted semi-structured interviews with 8 OTs working in upper limb rehabilitation. One OT was a student, all other OTs had at least 2 years of clinical experience. The interviews focused on current practices of OTs, i.e., how they assess and treat patients during upper limb therapy and how they currently elicit information about the patient's activities in between therapy session.

We prepared a video showing one of the authors performing activities of daily living (eating, cleaning, opening doors) in the manner of a stroke patient. This video was used as a probe in the interview to elicit how OTs analyze upper limb movements and what information they would desire if they could observe a patient in daily life outside the clinic. The interviews lasted 30 minutes and the recordings were transcribed verbatim for later analysis.

We analyzed the data qualitatively following a thematic approach [8] to examine how OTs currently assess upper limb movement and what information they desire about their patients. Immediately following each interview, the first author created mind-maps to capture themes emerging in the interview. Authors 1 and 2 listened to the audio recordings and read through all interview transcripts to familiarize themselves with the data. After generating initial codes on paper about what information OTs seek and desire, Saturate [1], was used to code all transcripts. Recurring codes and emerging themes were refined through discussion and affinity diagraming with the other authors, and are presented as findings below.

Meaningful Goals, Activities and Motions

The role of an Occupational Therapist (OT) is to improve their patient's ability to perform activities of daily living (ADL). Hence at the start of the rehabilitation process OTs establish which activities are important to the life of a patient and define goals that are meaningful to the patient and realistic to achieve for the timeframe of the rehabilitation. These goals often focus on fundamental activities like dressing and feeding, e.g., to *"open his hand up so he's able to grasp the drink bottle and with the two hands, bring the drink bottle to his mouth."* (OT5). Goals also include activities that may seem less essential for daily living, yet are important and therefore motivating to the patient, like being able to play a musical instrument again.

"I have a patient that has a little bit of shoulder movement, some flickers in his elbow but no movement in his wrist. His goal was to be able to play the ukulele and to strum it with

his hand. I guess it's around saying I don't want to ruin your hopes but picturing that more as a long term goal … we refined the goal together so the goal is now in the four weeks that he's able to independently position his arm on his ukulele as a pre-cursor to strumming it." (OT3)

An important skill of the OT is to break down meaningful activities (like playing the ukulele) into simple motions (like lifting the arm from the shoulder and flexing the elbow). OTs also compose whole activities based on these simple motions. Such OT skills are critical to establish goals that are realistic based on the capabilities of a patient. Identifying relevant motions related to activities is also critical to set exercises performed during rehabilitation and to correct motions performed in an unhealthy manner.

Exercise and Activities Outside Therapy

Rehabilitation progress is achieved through intensive exercise of the upper limb during a therapy session as well as outside therapy. The number of upper limb therapy sessions per week varied from one to five therapy sessions per week, depending on whether patients stayed at the clinic or at home. Regardless of how many therapy sessions they had, the therapists emphasized that the time spent exercising during therapy was not sufficient to make progress. Hence many patients received programs to exercise their upper limb outside therapy.

"I work in community-based rehab, so I see someone for an hour … It's such a small period of time in their weekly schedule … Our patients need to be doing a whole lot more therapy and that therapy needs to be task oriented, it needs to be meaningful, and it needs to be mass practice and repetition outside of the hours that we see them, which is why we develop home exercise programs for people. They really need to be doing an hour of repetitive upper limb therapy a day I would say to make progress." (OT3)

These exercise programs focused on repetitive sets of either specific motions or functional activities. Examples of motion-based exercises include *"practicing to do wrist extension, and also against gravity"* (OT1) and *"basic reach and basic shoulder and elbow movements – reaching out and looking at trying to reduce his compensatory movements"* (OT3). Alternatively, examples of functional exercises given by the OTs include: *"bringing his left hand up to his mouth to hold a spoon"* (OT6), or *"practicing to reach for a cup, and repetitions of that as many as they can, over an hour in the afternoons each day"* (OT1).

Additionally, OTs encouraged patients to use their upper limb in activities of daily living when opportunities arise. For example, *"wash dishes with [the patient's] affected arm"* (OT3) or *"shaking people's hands"* (OT5).

Objective Data to Assess Exercise and Activities

It is very difficult for an OT to discern whether a patient has adequately completed her exercise program and to know to what extent a patient is actually using her upper limb in other activities of daily living. OTs typically discuss the patient's activities and exercise programs at the start of a rehabilitation session and some patients keep diaries to keep track of their exercise. This discussion works well for patients who are motivated, and some therapists pointed out that they could infer whether patients adhered to their exercise program based on their progress (or lack thereof). Regardless of the progress, however, the therapists desired more detailed information on the activity levels of their patients: *"I see them on a Wednesday, after giving them exercises – I still don't get a real sense of what's happening for them over that 24 hour period, how much that arm is being moved and engaged [in activities]. I still feel like I'm really lost from that point of view. And to show that what we are doing from the therapy point of view is effective, we need this information."* (OT1)

The OTs hence desired objective data about the exercises and other activities of daily living (ADL) that their patients performed with the affected arm. Their key questions were: (1) *"Whether they're doing their home exercise program or not."* (OT3), and (2) *"How much they're using their arm in things [ADL] like showering, getting dressed. Is it hanging like a dead weight by their side, and then they're using their right arm to do everything, or are they actually trying to use that left hand a little bit?"* (OT6)

Achieving objective data about upper limb movement is also conceptually difficult. How do we quantify upper limb movements? Do we collect data for each joint by joint or the arm as a whole? And how do we describe objectively how much or how well a patient engages the upper limb in an activity like eating a meal? To understand these issues from an OT's perspective, we discussed with them the previously mentioned video of a person performing exercises and activities. We asked the OTs to think aloud what they observed in this video and how they would quantify their observations. Through these discussions we learnt that OTs desire the following data:

- **Number of movements**, ideally based on exercises activities, or alternatively as motions for each joint (shoulder, elbow, wrist, fingers): "*it would be really good to know that the arm is moving in the first place, that they are actually using that arm. If we get down to the nitty-gritty it would be really nice to know if the shoulder is moving or the elbow is moving, or what joints they are actually moving to assist them with doing that task.*" (OT1)
- **Time spent moving the arm**: *"Are they incorporating their arm [into ADL]? For how long?"* (OT1)*"; "it's good if they're using their arm to do their exercises for half an hour a day [during therapy], that is important, but the more important thing is that they're using the other twenty-three-and-a-half hours of the day."* (OT6)
- **Quality of movements** based on observations of unnatural motions and compensatory movements, like lifting the shoulder to reach forward: *"There's always that risk of them doing a home exercise program and*

they don't have a therapist there and they might not be physically able to or might not be aware that they need to do normal movements. So they might be practicing for the majority of their time abnormal movement patterns and they come back to therapy and we spend the whole therapy session correcting it again." (OT3)

- **Range of motion** (ROM) for each joint: *"I'd look at it like this as a whole - how do they go reaching for that muffin. But then I'd be thinking do they have good wrist active or passive range, of their fingers to grasp, what's their elbow range like."* (OT7)
- **Common postures** of the upper limb: *"how they position their arm when not observed."* (OT2)

STUDY 2: DESIGN AND EVALUATION OF THE ARMSLEEVE SENSOR

Research Aim and Study Design

In study 2 we explored how upper limb movements can be monitored through sensor technology. We sought to develop a sensor that can be worn comfortably throughout the day by stroke patients and captures the data desired by OTs, as identified in study 1.

Study 2 led to the development the *ArmSleeve Sensors*, a wearable technology prototype that monitors movements of the shoulder, elbow and wrist. The ArmSleeve sensors were developed and evaluated through a series of design-led investigations with the following aims:

1. explore *how* the movement of the upper limb can be monitored based on the needs identified in study 1,
2. evaluate the *accuracy* of the data collected

Design of the ArmSleeve Sensor

To explore how movement of the upper limb can be monitored, we analyzed the arm movements that OTs found critical to their practice (based on study 1) and we went through several iterations of prototyping with various sensor technologies to capture these movements. These iterations were based on informal tests and discussions of the prototypes on ourselves until we arrived at a mature prototype that we could evaluate in a laboratory setting.

Based on the findings from study 1 we aimed to capture information about the upper limb as a whole as well as information about each joint. The human upper limb consists of three main joints: shoulder, elbow and the wrist. These joints could result in a total of seven angular motions as shown in Figure 2-a, as θ_1 to θ_7. The final prototype captured the first five of these motions (see Figure 2-b). Rotations θ_6 and θ_7 were omitted due to the increased technical complexity and increased intrusiveness for the person wearing the sensors.

The motion data was captured through Inertial Measurement Units (IMUs) placed at the wrist, above the elbow and at the shoulder (Figure 2-c). IMUs are small and relatively low in power consumption. The selected IMUs consisted of a magnetometer, a gyroscope and an

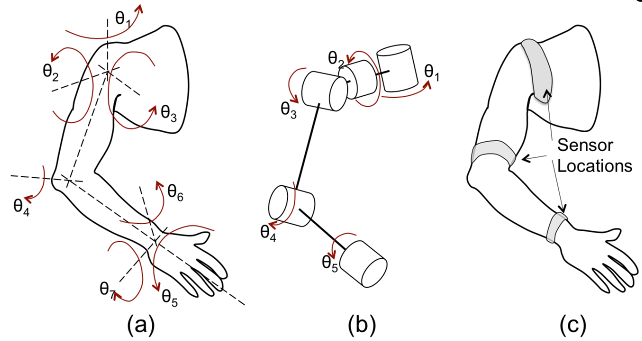

Figure 2: Analysis of sensor requirements. a) degrees of motion in arm joints, b) selected set of motions to be captured and c) chosen sensor locations.

accelerometer. The information from these three sensors was combined to produce a measurement of the orientation of the IMU relative to earth. Two IMUs can be used to calculate the orientation of the upper arm and the forearm relative to earth. A third IMU was used to sense the torso orientation, and to distinguish between movements of the torso and the arm. From these sensors, motions of the three degrees of freedom in the shoulder (adduction/adduction, flexion/extension, internal/external rotation), one in the elbow (flexion/extension) and one in the wrist (pronation/supination) can be calculated (Figure 2-b).

The ArmSleeve prototype consisted of three independent sensor units. Each sensor unit contained an IMU (Invensense MPU9250), a microprocessor (nrf51822 ARM M0+), a real time clock and a SD card as data storage, a rechargeable battery, LED and a power supply unit. The microprocessor acquires data from the IMU apply low level noise filtering and calibration, fuse the accelerometer, gyro and compass data together and save data in the data storage unit (SD card) along with a time stamp. The real time clock helps to keep the time constant between different sensor units, which allows us to combine the data recorded from separate units to re-create the complete motion of the arm. Bluetooth is used to synchronize the time between sensing units and to receive user inputs. Each sensing unit has two buttons to set the sensor into calibration mode and query the sensor status (such as battery level, and functional status). To analyze the recorded data, OTs need to remove the SD cards from each sensor unit and import the data on a computer into the ArmSleeve dashboard.

Accuracy of the ArmSleeve Sensor

We evaluated the accuracy of the ArmSleeve sensor in a laboratory setting. We captured data from a healthy participant performing a series of arm movement simultaneously through the ArmSleeve sensors and the Vicon® motion capture system, which is considered "gold standard" technology [36]. The ArmSleeve sensors were attached to a healthy participant using Velcro straps and medical tape at the shoulder, elbow and wrist as seen in Figure 2-c. Furthermore, reflective markers for the Vicon system were placed on the participant to measure upper body movement. The participant performed two sets of movements: (1) simple motions for each degree of freedom

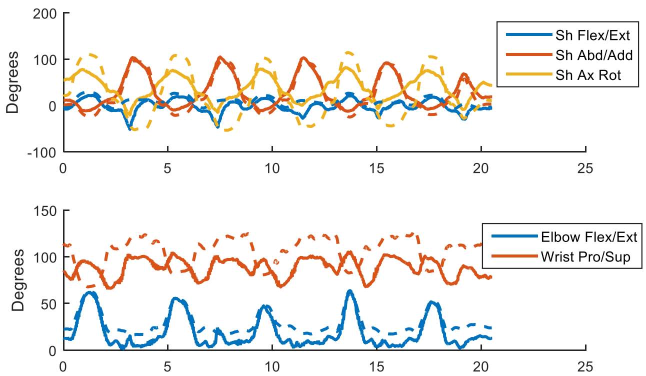

Figure 3: Comparison of motion data captured from ArmSleeve Sensors (solid lines) and Vicon® Motion Capture System (dashed lines). The graph shows shoulder (top), elbow and wrist motion (bottom) for 5 sets of swinging the right arm.

(e.g., shoulder abduction) and (2) activities of daily living (e.g., lift a can to the mouth, open a door). Motion data for each task and for each degree of freedom at the shoulder and elbow was exported from both systems for comparison.

The analysis showed that the ArmSleeve system collects data that is comparable to the data generated by the Vicon® system. Figure 3 shows motion data captured by both the ArmSleeve and the Vicon system for 5 sets of abduction motions, where the participant was swinging the right arm along the frontal plane and back. It can be observed that the ArmSleeve system was capable of producing similar data to that produced by the Vicon. Particularly, the measurements in flexion/extension of both the wrist (bottom graph) and shoulder (top), and abduction/adduction of the shoulder (top) are well represented. However, measurements of shoulder axial rotation, and wrist are less accurate. In other movements, both the simple movements and those involving activities of daily living, we observed some other differences in the measurements – particularly offsets in the reported angles. In these instances, the overall changes in the degrees of motion are consistent, however, the sensors report different starting angles.

Differences in the data generated by the ArmSleeve and Vicon systems are predominantly due to errors in the placement of the sensors on the arm. To address this issue sensors need to be properly aligned through careful application of the straps, and they need to be secured such that they do not move. Another limitation of the data relates to the accuracy of the Vicon. In some instances, the Vicon reported angles that are impossible for a human body to achieve. This has obvious implications on the comparison. Furthermore, the Vicon data is strongly filtered and hence produces smoother graphs, which makes it difficult to conduct a statistical comparison with the ArmSleeve data.

The ArmSleeve prototype shows that upper limb motions can be captured accurately in the lab, but further work is required to produce data on number of movements, time spent moving and indications of quality. Furthermore, significant work is required to develop sensors suitable for patient use in everyday life. In addition to more secure and precise straps, they must also be correctly packaged, so that they are easy to put on and take off, are easily charged, and data can be easily transferred by patients or therapists.

STUDY 3: DESIGN AND EVALUATION OF THE ARMSLEEVE DASHBOARD

Research Aim and Study Design

The aim of study 3 was to design and evaluate the ArmSleeve dashboard. The dashboard was designed for OTs to visualize a patient's arm motions as captured by the ArmSleeve sensors.

This dashboard was created through a series of design workshops. The first workshop was conducted within the research team, based on brainstorming and sketching ideas in response to the findings from study 1. A second workshop was conducted with two OTs, which also involved sketching ideas followed by a discussion of the sketches from the initial workshops. This workshop led to the ideas for the four main visualizations presented in the ArmSleeve dashboard (see Figure 4). The sketches were iterated into paper prototypes and mockups through ongoing discussion with the two OTs and the research team. The final prototype used for the evaluation was an interactive HTML prototype created with Axure RP.

We evaluated the dashboard with the same 8 OTs as in study 1 to assess how useful the information presented in the dashboard is for their rehabilitation practices. These OTs were not involved in the creation of the dashboard and hence provided a fresh perspective on the ideas encapsulated in the design. We asked the OTs to explore the different dashboard visualizations and to think aloud their first impressions and how they would incorporate this information into their work. We asked them questions about how useful they considered the visualizations presented on the dashboard for their own work and discussed options for revising the dashboard to enhance its usefulness. The evaluation lasted approximately 30 minutes and the recordings were transcribed verbatim for our analysis.

We analyzed the data through a thematic approach [8] like in study 1. Authors 1 and 4 immersed themselves into the data and coded the transcripts using the qualitative analysis tool Saturate. The themes presented in the findings show how useful different dashboard visualizations were to enhance the practices of OTs, as well as their limitations.

ArmSleeve Dashboard Design

The *ArmSleeve Dashboard* was designed in response to the findings of study 1, the constraints of the prototype of study 2, and ideas emerging in design workshops.

We sought to design a dashboard that OTs can use in a variety of ways: to get a quick overview before the therapy, to engage a patient in conversation with the data during therapy, and to conduct clinical research on the relationship between arm use in daily life and progress. The dashboard needed to present the data types discerned from study 1:

- Number of movements
- Time spent exercising or moving the arm
- Quality of movements, on a scale from 1 to 10
- Range of motion (ROM) for each degree of freedom
- Common postures of the arm

The detail of these data was based on discussions with the OTs in study 1 about data used in clinical practice, data available through the ArmSleeve sensor designed in study 2, metrics discussed in related work [10], and discussions with OTs to prioritize metrics during the design workshops.

For the purpose of our evaluation, the dashboard contained data for a fictitious patient, based on data collected in study 2 and mock data generated by the research team. Figure 4 shows how this data was visualized across four different dashboard pages:

a) An *overview* page to provide a snapshot of the patient
b) A *time line* to get an overview of the daily activity levels, allowing the tagging of exercise and other activities (like eating) based on discussion with patients
c) A *joint*-based visualization to explore range of motion (ROM) and number of movements for each degree of freedom
d) *Heat maps* to show common motions and arm positions

Assess Exercises and Activities Outside Therapy

The main strength of the ArmSleeve dashboard for the work of therapists was that it provided them with insights about the activities of their patients outside therapy. The preferred pages to assess exercises and other activities were generally the overview page and the timeline page.

The overview page provided a quick snapshot of the patient's activity levels through visualizations of the number of movements performed over a week, the average quality of these movements, and the time spent active for each day. A simple timeline showing movements performed over a week provided therapists with a quick glance of days when their patients performed well and when their patients did not reach their target levels: *"a lot of patients will try really hard today and then tomorrow they really suffer and then the next day they will probably do somewhere in between and then two days later they will be like 'oh I haven't done my exercises very much', and educating a patient around that when you've got hard data spike is really valuable."* (OT8) Some therapists preferred the time spent active as an indicator for the amount of exercise and the activities of daily living performed outside therapy: *"it's good if they're using their arm to do their exercises for half an hour a day, that is important, but the more important thing is that they're using the other twenty-three-and-a-half hours of the day that they can."* (OT6).

The timeline page was useful to analyze in detail which activities patients performed, and to some extent, how well

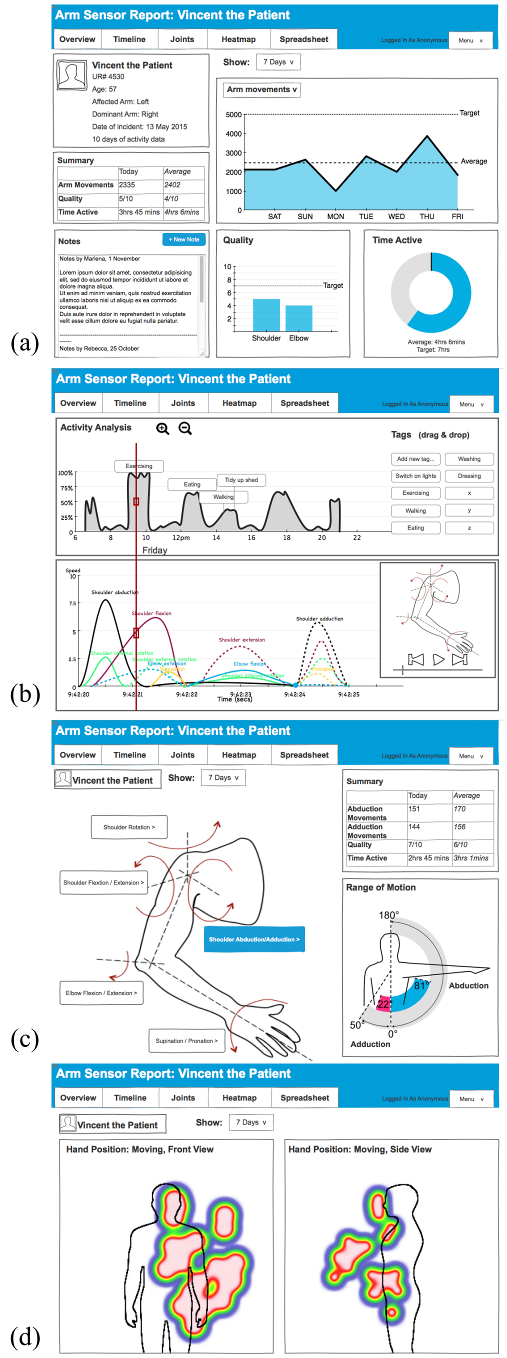

Figure 4: The ArmSleeve dashboard provides (a) a patient overview page, (b) a timeline with the ability to tag data points, (c) visualizations for range of motion for each joint, and (d) heat maps to show common arm positions.

they performed them. The detail in the timeline provided an indication whether patients performed their exercise programs at all: *"if you're worried that he's not doing his exercises, or he's not incorporating his hand when he's eating, well this would somewhat tell you whether there's a flat line or whether there are moments of activity."* (OT5). Some patients keep exercise or activity diaries, which OTs can use to make sense of the timeline data and to tag spikes in the data with activities like eating or exercising: *"we could get them to keep a diary or something like that and when they come then sit down with their diary."* (OT3)

The joints section provided a more detailed analysis of the progress made by a patient through the range of motion (ROM) for each degree of freedom at the shoulder, elbow and wrist. Improvements in the ROM are not always visible in therapy sessions, and therapists typically do not have the time to assess it in each therapy session. Seeing progress in ROM however is useful to see how patients progress over the course of a therapy and also to detect discrepancies between how patients perform in therapy and how they perform at home: *"the maximum is very useful to know because this client, when we test him, he can actually achieve a 130° of shoulder flexion and yet he's only getting 84° when he's using it outside of therapy."* (OT6).

Heat maps were useful to assess the activity levels of particular patients, i.e., patients with very low levels of mobility, and patients with hemispatial neglect, who have difficulty to attend to one side of space. Heat maps showed if these patients predominantly had their affected arm in a resting position, or if they were moving it regularly: *"'Cause you want to know when they're sitting particularly the ones that have neglect, do they just leave it dangling down here or are they positioning it in an appropriate way? I like that. It's good."* (OT4) The heat maps also showed whether the hand of the patient crosses the midline of their body. This indicates attendance to the neglected side in neglect patients, and it shows an increased range of activities of daily living that a patient can perform: *"if you can cross midline and do stuff you are getting better plasticity showing but you're also functionally significantly more independent than if you can only work here."* (OT8)

Engage Patients and Other Clinicians

A key strength of ArmSleeve is that OTs can use it to engage with patients and other clinicians. Firstly, OTs can use the data presented on the dashboard for discussion with patients to get a better understanding of their exercise levels, activities of daily living, and more broadly, how they cope in daily life. Particularly the timeline data and the tagging feature invited opportunities for OTs to engage their patients to learn more about exercise and other activities: *"I'd sit down with the patient and ask what they were doing between 8am and 10am on Friday and they say they went to the gym so I put in exercise."* (OT3). Therapists can use the data to inquire about how well patients cope with the exercise programs that they have been given: *"are they coping with what I've given them? If they're not doing their exercises, why?"* (OT7) Therapists may also use trends in the timeline data to ask more broadly about how the wellbeing of their patients: *"we can actually show them the days that they are doing better, and actually talk about, let's say 'Monday wasn't so good', maybe they had a lot of scans and investigations. Or maybe they had a really bad day and didn't want to do their rehab."* (OT1).

The dashboard also provides opportunities for OTs to engage, educate and empower patients in the rehabilitation process. Patients can use the data to learn more about how the arm works, what their capabilities are, and how they are progressing: *"I use that in two senses - to provide patients with motivation and say they've improved a little more this week and the flip side is if they're not improving I provide realistic feedback so in three weeks time when I discharge them from the service and they're 'my arm hasn't improved' it's not a shock to them."* (OT3). Some therapists emphasized that the dashboard provides a useful, additional voice to the therapy that motivates patients: *"I think it's quite motivating for patients. It's not just me speaking to them."* (OT7) Some therapists liked the heat map to discuss with their patients which areas they need to target when moving their arm: *"if it was all just red by his body [on the heat map] I could talk to him about how it's really important to let that arm sit down and extend the elbow to involve it one day in swinging while he's walking."* (OT2). Finally, it provides an opportunity for patients and therapists to collaboratively inquire the data and to adjust the goals of the therapy accordingly: *"It would be nice to be able to show patients visually how they are doing, and be able to say 'this is where we want you to be. This is your target for the next 2 weeks'. And then you could be pushing that target out as they improve."* (OT1)

Finally, therapists can also use this data to advocate for their patients in communication with other clinicians. The dashboard data is helpful in communicating the progress of a patient to other team members: *"other therapists, your physio colleagues, or your doctors, they can actually see that the patient's arm movement is improving."* (OT5) Objective data on the progress of a patient can help therapists to advocate for their patients to receive adequate resources required for rehabilitation: *"often what we are doing is advocate for rehab. And not every patient gets the rehab. If we can show to the team that they made all these improvements in terms of arm function, our case would be so much stronger."*(OT1).

Lack of Contextual Information

A major limitation of the ArmSleeve system is the lack of contextual information presented across the different dashboard pages. First and foremost this was evident in discussions about what a movement presented on the timeline page may mean. For instance, based on the dashboard alone therapists cannot know if a movement constitutes an exercise activity, if the patient is engaging in an activity of daily living like eating, if the arm is swinging while walking, or if the arm is moved by a caretaker who helps the patient get dressed: *"I find it really hard because you don't know what they're doing when they're doing this movement. Like I could be walking, going like this and that's going to be counting the movement of every joint whereas it's not specifically functional."* (OT4) The timeline presents some contextual information through the time of the day when movements are performed, which can indicate that a patient is eating or washing. However, the precise nature of the activity needs to be confirmed in conversation with a patient.

Secondly, the lack of contextual information was reflected in discussions of the quality ratings. The quality rating was displayed on the overview page as an average value between 1 and 10 for all the movements performed over the course of a day, thus allowing the OTs to see trends in the data over several days and weeks. The OTs desired information about the quality of movements outside therapy, but they felt that in order to truly judge the quality of a movement, they would have to see their patient: *"quality is something you really need to see."* (OT4) This is because the quality of a movement is dependent on its purpose in a particular context. For example, shoulder abduction is often used as an indicator for low quality, because many stroke patients exhibit excessive abduction while reaching forward. However, in certain contexts abduction can be a normal, high quality movement, which cannot be distinguished by the ArmSleeve system: *"I have some questions about measuring quality. This doesn't have any way to determine the movements are of quality and whether they're normal or not, it's just detecting [motion] - for some tasks a quality movement would be to abduct your arm, like to you bring your hand up to do your hair, and for reaching, to abduct your arm isn't a normal movement. So if you're able to measure abduction but then you're not able to know what the task is, how do you determine whether that's a quality movement for that task?"* (OT3)

DISCUSSION

HCI offers a growing body of work technology designed to support patients after a stroke, i.e., in exercising [2, 3, 15, 26] and monitoring [6, 11, 19, 32]. While this focus on the patient is important, the main contribution of this research is a system designed to support the work of occupational therapists. This research describes the design of the ArmSleeve system, a patient monitoring system to support therapists in their rehabilitation work with stroke patients. Through a design-led investigation with occupational therapists this research offers an understanding of their practices and a set of data that therapists desire about their patients' activities outside therapy.

A second contribution is offered through the design of a wearable technology, the ArmSleeve sensor, which monitors upper limb movement in daily life. Unlike other prototypes that present the intensity of movement through unprocessed accelerometer data [6], the ArmSleeve sensor can measure angular motion in three degrees of freedom at the shoulder, as well as elbow extension and wrist supination and pronation.

Finally, this research contributes a dashboard to visualize upper limb movement for therapists. While recent work has provided visualizations for single arm movements to support exercise [29], our work offers insights into visualizing arm movements collected over several weeks in both aggregated and detailed formats. Finally, we have shown how this information can provide therapists with insights into how much their patients engage their arm in activities of daily living and exercise.

Design Implications for Interpreting Sensor Data

We began this research aiming to help therapists understand *how much patients use their upper limbs in daily life outside therapy*. The therapists found useful objective data on ArmSleeve on *how much patients use their upper limb*. However, the therapists found it difficult to understand how this data relates to the patient's *daily life outside therapy*.

Studies of medical work show that health data is often not self-evident and additional work is required to make sense of the data and to apply it in practice. For example, related work on clinicians interpreting sensor data from Parkinson's patients [22] and multiple sclerosis patients 23] highlight similar challenges in interpreting sensor data in the absence of the patient. The work on multiple sclerosis patients [24] resolved this issue by presenting physiotherapists with video recordings of assessment tasks performed by their patients in clinical settings alongside with sensor data. This approach is not a practical solution for the ArmSleeve system, as it seeks to collect data over several weeks. Furthermore, occupational therapists are not only interested in clinical assessment tasks, but fundamentally in how patients participate in activities of daily living like eating, washing and dressing in the context of their home or in the community.

It is well understood in HCI that contextual information is crucial for users to make sense of data, yet that it is difficult to gather through technology [12]. While sensors can provide information about the time and place of upper limb movement, understanding the intention, purpose, quality as well as the outcome of a movement typically relies on human intelligence. In recent years we have seen significant improvements in computational efforts to understand human action in other domains, e.g., in the interpretation of language for personal assistants like Siri and Cortana. Similar directions are pursued in the interpretation of human movements. For example, machine learning has been applied to interpret upper limb motions of stroke patients to detect activities like drinking and brushing hair. The Internet of Things can provide clues about the activities of people through instrumented objects that people use in their activities of daily living, e.g., to recognize whether a person is lifting a cup or opening a door [4].

In future work we seek a more human-oriented approach in our design by engaging patients in the interpretation of sensor data. We see merit in the technological approaches discussed above to provide contextual clues. However, we believe that these improvements will be partial, and understanding the meaning of upper limb motion and its quality will continue to rely on human intelligence. The therapists in this study regarded the data presented on the dashboard as an opportunity to engage patients in a dialogue to learn more about their daily lives. Activity diaries kept by patients can enrich this dialogue and help to make sense of the data presented on the dashboard.

Engagement between therapists and patients is not merely a means to interpret sensor data, but it can be an end in itself. The therapists found that the dashboard provides an opportunity for mutual understanding and empathy. Therapists can use the dashboard data to probe patients to learn more about their everyday lives and the challenges they may face. Conversely, the dashboard provides patients with an opportunity to learn about their treatment and their progress, and it can help them to stay motivated.

It is important to note that such a participatory approach in the interpretation of sensor data is not without its challenges. Patients can offer expertise through their lived experience with the effects of stroke, but clinicians can overshadow such dialogue due to established hierarchies, clinical expertise and experience in interpreting sensor data [22]. It is also important to keep in mind that taking on responsibility for self-monitoring and interpreting data can be a burden [21], and not every patient may be able to or desire such involvement. Hence in future work we seek to work with patients who wish to be more actively engaged in their therapy. Through the design of ArmSleeve we hope to give these patients an opportunity to better understand their progress and to become empowered in their collaboration with therapists to achieve their desired therapy outcome.

Design Implications for Sensors Worn in Daily Life

We also began this research with the ambition of designing sensor technology that stroke patients can wear in everyday life. While we have presented a working prototype, considerable work is required to develop the sensors further into a system that these patients can use in daily life.

A major design issue is the "wearability" [14] of the sensor technology to ensure it is usable and provides comfort. A key question that we need to address is the placement of the sensor on the body, i.e., to ensure accurate data and comfort when worn over extended periods of time. Minimizing the size and weight of the device is also critical to increase comfort. Further critical issues are the containment of the sensor and how it is attached to the body. This is to ensure it fits the shape of the different parts of the upper limb, both when a patient is static as well as when she is moving. This is also important because patients or their caretakers need to find it easy to don and take off the sensor for charging the device, or for sleeping and washing. These issues are particularly important as our intention is for these devices to be worn over several days or weeks by people with impairments to their mobility and sensation.

A second design issue is the modularity of the sensor technology. The current system consists of three sensor modules, which can monitor shoulder movement in three degrees of freedom, as well as elbow extension and wrist rotation. While this setup is useful for patients working on improving upper arm movement, studies 1 and 3 also highlighted that there is considerable variability between patients. For example, a patient with hemispatial neglect may only require a single sensor module at the wrist to detect if the arm is moved at all and if it crosses the midline. Other patients, however, may benefit from sensors that capture wrist extension and finger movement, as these motions are critical to perform activities of daily living [27]. Hence in future work we seek to extend the range of motions that we can monitor with ArmSleeve. At the same time, we seek to explore how we can create modules of sensor units that collect data about a particular joint and motion of interest, and thereby minimize the amount of technology that needs to be worn.

We now seek to engage with patients in exploring these design issues to develop an understanding of their perspective on ArmSleeve and elaborate its design. It is well known that medical devices are often rejected due to the stigma attached to it [17]. While the therapists in this study were confident that many patients would find such a system useful, we aim to work with patients directly in future iterations, to learn about possible benefits and any concerns they may have about accountability and privacy.

CONCLUSION

We have worked with occupational therapists to build and evaluate the ArmSleeve system, which monitors the upper limb movements of stroke patients outside therapy. This design-led investigation has shown that in order for therapy to be effective, patients need to engage their arm in exercise and other activities consistently throughout their daily life. The ArmSleeve sensor prototype collects such patient data through a wearable technology worn on the arm. The ArmSleeve dashboard offers visualizations of the number, quality and range of arm movements over several weeks.

The evaluation of the ArmSleeve system demonstrated that therapists benefit from this system through insights into how much their patients use their upper limb outside therapy. However, it also highlighted a discrepancy between the motion data presented by the system, and the insights into activities of daily living that therapists desired. Based on ArmSleeve data alone, therapists were unsure whether movement related to exercise, activities of daily living, or simply a patient swinging the arm while walking.

In future work we seek to address this issue through engaging both patients and therapists into a dialogue to collaboratively interpret the data. While the work to date has focused on the therapist, we now also seek to work with patients to refine the dashboard and the sensors into a system that can be tailored to the needs of a patient and used seamlessly in daily living. Our vision is a system that fosters dialogue between a patient and their therapist, and which enhances mutual understanding and empathy.

REFERENCES

1. Saturate. http://www.saturateapp.com/.

2. Gazihan Alankus, Rachel Proffitt, Caitlin Kelleher and Jack Engsberg. Stroke Therapy through Motion-Based Games: A Case Study. *ACM Trans. Access. Comput.* 4, 1 (2011), 1-35. http://dx.doi.org/10.1145/2039339.2039342
3. Madeline Balaam, Stefan Rennick Egglestone, Geraldine Fitzpatrick, Tom Rodden, Ann-Marie Hughes, Anna Wilkinson, Thomas Nind, Lesley Axelrod, Eric Harris, Ian Ricketts, Susan Mawson and Jane Burridge. 2011. Motivating Mobility: Designing for Lived Motivation in Stroke Rehabilitation. In *Proceedings of Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1979397, 3073-3082. http://dx.doi.org/10.1145/1978942.1979397
4. J. Barman, G. Uswatte, N. Sarkar, T. Ghaffari and B. Sokal. Sensor-Enabled Rfid System for Monitoring Arm Activity in Daily Life. *Conf Proc IEEE Eng Med Biol Soc* 2011 (2011), 5219-5223. http://dx.doi.org/10.1109/iembs.2011.6091291
5. Angelo Basteris, Sharon M. Nijenhuis, Arno H. A. Stienen, Jaap H. Buurke, Gerdienke B. Prange and Farshid Amirabdollahian. Training Modalities in Robot-Mediated Upper Limb Rehabilitation in Stroke: A Framework for Classification Based on a Systematic Review. *Journal of Neuroengineering and Rehabilitation* 11 (2014). http://dx.doi.org/10.1186/1743-0003-11-111
6. Luuk Beursgens, Freek Boesten, Annick Timmermans, Henk Seelen and Panos Markopoulos. 2011. Us'em: Motivating Stroke Survivors to Use Their Impaired Arm and Hand in Daily Life. In *Proceedings of CHI '11 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1979761, 1279-1284. http://dx.doi.org/10.1145/1979742.1979761
7. Cati Boulanger, Adam Boulanger, Lilian de Greef, Andy Kearney, Kiley Sobel, Russell Transue, Z Sweedyk, Paul H. Dietz and Steven Bathiche. 2013. Stroke Rehabilitation with a Sensing Surface. In *Proceedings of Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2466160, 1243-1246. http://dx.doi.org/10.1145/2470654.2466160
8. V. Braun and V. Clarke. Using Thematic Analysis in Psychology. *Qualitative research in psychology* 3, 2 (2006), 77-101.
9. Eun Kyoung Choe, Nicole B Lee, Bongshin Lee, Wanda Pratt and Julie A Kientz. 2014. Understanding Quantified-Selfers' Practices in Collecting and Exploring Personal Data. In *Proceedings of Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1143-1152. http://dx.doi.org/10.1145/2556288.2557372
10. Ana de los Reyes-Guzmán, Iris Dimbwadyo-Terrer, Fernando Trincado-Alonso, Félix Monasterio-Huelin, Diego Torricelli and Angel Gil-Agudo. Quantitative Assessment Based on Kinematic Measures of Functional Impairments During Upper Extremity Movements: A Review. *Clinical Biomechanics* 29, 7 (2014), 719-727. http://dx.doi.org/http://dx.doi.org/10.1016/j.clinbiomech.2014.06.013
11. Z. Q. Ding, Z. Q. Luo, A. Causo, I. M. Chen, K. X. Yue, S. H. Yeo and K. V. Ling. Inertia Sensor-Based Guidance System for Upperlimb Posture Correction. *Med Eng Phys* 35, 2 (2013), 269-276. http://dx.doi.org/10.1016/j.medengphy.2011.09.002
12. Paul Dourish. What We Talk About When We Talk About Context. *Personal and Ubiquitous Computing* 8, 1 (2004), 19-30. http://dx.doi.org/10.1007/s00779-003-0253-8
13. Stroke Foundation. 2015. Facts and Figures About Stroke. https://strokefoundation.com.au/about-stroke/facts-and-figures-about-stroke.
14. F. Gemperle, C. Kasabach, J. Stivoric, M. Bauer and R. Martin. 1998. Design for Wearability. In *Proceedings of Proceedings of the 2nd IEEE International Symposium on Wearable Computers*. IEEE Computer Society, 857998, 116.
15. Ard Jacobs, Annick Timmermans, Marc Michielsen, Maaiken Vander Plaetse and Panos Markopoulos. 2013. Contrast: Gamification of Arm-Hand Training for Stroke Survivors. In *Proceedings of CHI '13 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2468430, 415-420. http://dx.doi.org/10.1145/2468356.2468430
16. Michael T. Jurkiewicz, Susan Marzolini and Paul Oh. Adherence to a Home-Based Exercise Program for Individuals after Stroke. *Topics in Stroke Rehabilitation* 18, 3 (2011), 277-284. http://dx.doi.org/doi:10.1310/tsr1803-277
17. Hyun Gu Kang, Diane F. Mahoney, Helen Hoenig, Victor A. Hirth, Paolo Bonato, Ihab Hajjar, Lewis A. Lipsitz, Medicine for the Center for Integration of and Aged Innovative Technology Working Group on Advanced Approaches to Physiologic Monitoring for the. In Situ Monitoring of Health in Older Adults: Technologies and Issues. *Journal of the American Geriatrics Society* 58, 8 (2010), 1579-1586. http://dx.doi.org/10.1111/j.1532-5415.2010.02959.x
18. Maryam Khademi, Hossein Mousavi Hondori, Alison McKenzie, Lucy Dodakian, Cristina Videira Lopes and Steven C. Cramer. 2014. Free-Hand Interaction with Leap Motion Controller for Stroke Rehabilitation. In *Proceedings of Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 2581203, 1663-1668. http://dx.doi.org/10.1145/2559206.2581203
19. Jihyoung Kim, Sungwon Yang and Mario Gerla. 2011. Stroketrack: Wireless Inertial Motion Tracking of

Human Arms for Stroke Telerehabilitation. In *Proceedings of Proceedings of the First ACM Workshop on Mobile Systems, Applications, and Services for Healthcare*. ACM, 2064948, 1-6. http://dx.doi.org/10.1145/2064942.2064948

20. Ian Li, Anind Dey and Jodi Forlizzi. 2010. A Stage-Based Model of Personal Informatics Systems. In *Proceedings of Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 557-566. http://dx.doi.org/10.1145/1753326.1753409
21. Deborah Lupton. Quantifying the Body: Monitoring and Measuring Health in the Age of Mhealth Technologies. *Critical Public Health* 23, 4 (2013), 1-11.
22. Helena M. Mentis, Rita Shewbridge, Sharon Powell, Melissa Armstrong, Paul Fishman and Lisa Shulman. Co-Interpreting Movement with Sensors: Assessing Parkinson's Patients' Deep Brain Stimulation Programming. *Human–Computer Interaction* (2015), 1-34. http://dx.doi.org/10.1080/07370024.2015.1073592
23. Argyro Moraiti, Vero Vanden Abeele, Erwin Vanroye and Luc Geurts. 2015. Empowering Occupational Therapists with a Diy-Toolkit for Smart Soft Objects. In *Proceedings of Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2680598, 387-394. http://dx.doi.org/10.1145/2677199.2680598
24. Cecily Morrison, Marcus D'Souza, Kit Huckvale, Jonas F Dorn, Jessica Burggraaff, Christian Philipp Kamm, Saskia Marie Steinheimer, Peter Kontschieder, Antonio Criminisi and Bernard Uitdehaag. Usability and Acceptability of Assess Ms: Assessment of Motor Dysfunction in Multiple Sclerosis Using Depth-Sensing Computer Vision. *JMIR Human Factors* 2, 1 (2015), e11. http://dx.doi.org/10.2196/humanfactors.4129
25. Dariush Mozaffarian, Emelia J. Benjamin, Alan S. Go, Donna K. Arnett, Michael J. Blaha, Mary Cushman, Sarah de Ferranti, Jean-Pierre Després, Heather J. Fullerton, Virginia J. Howard, Mark D. Huffman, Suzanne E. Judd, Brett M. Kissela, Daniel T. Lackland, Judith H. Lichtman, Lynda D. Lisabeth, Simin Liu, Rachel H. Mackey, David B. Matchar, Darren K. McGuire, Emile R. Mohler, Claudia S. Moy, Paul Muntner, Michael E. Mussolino, Khurram Nasir, Robert W. Neumar, Graham Nichol, Latha Palaniappan, Dilip K. Pandey, Mathew J. Reeves, Carlos J. Rodriguez, Paul D. Sorlie, Joel Stein, Amytis Towfighi, Tanya N. Turan, Salim S. Virani, Joshua Z. Willey, Daniel Woo, Robert W. Yeh and Melanie B. Turner. Heart Disease and Stroke Statistics—2015 Update: A Report from the American Heart Association. *Circulation* (2014). http://dx.doi.org/10.1161/cir.0000000000000152
26. Roshan Lalintha Peiris, Nuwan Janaka, Deepthika De Silva and Suranga Nanayakkara. 2014. Shrug: Stroke Haptic Rehabilitation Using Gaming. In *Proceedings of Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: the Future of Design*. ACM, 2686669, 380-383. http://dx.doi.org/10.1145/2686612.2686669
27. Alex Pollock, Sybil E. Farmer, Marian C. Brady, Peter Langhorne, Gillian E. Mead, Jan Mehrholz and Frederike van Wijck. Interventions for Improving Upper Limb Function after Stroke. *Cochrane Database Syst Rev.*, 11 (2014), 171. http://dx.doi.org/10.1002/14651858.CD010820.pub2
28. John Rooksby, Mattias Rost, Alistair Morrison and Matthew C Chalmers. 2014. Personal Tracking as Lived Informatics. In *Proceedings of Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1163-1172 http://dx.doi.org/10.1145/2556288.2557039
29. Richard Tang, Anthony Tang, Xing-Dong Yang, Scott Bateman and Joaquim Jorge. 2015. Physio@ Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises. In *Proceedings of Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 4123-4132.
30. Edward Taub, Gitendra Uswatte and Victor W. Mark. The Functional Significance of Cortical Reorganization and the Parallel Development of Ci Therapy. *Frontiers in Human Neuroscience* 8 (2014), 396. http://dx.doi.org/10.3389/fnhum.2014.00396
31. Edward Taub, Gitendra Uswatte and Rama Pidikiti. Constraint-Induced Movement Therapy: A New Family of Techniques with Broad Application to Physical Rehabilitation-a Clinical Review. *Journal of rehabilitation research and development* 36, 3 (1999), 237-251.
32. M. A. Urbin, R. R. Bailey and C. E. Lang. Validity of Body-Worn Sensor Acceleration Metrics to Index Upper Extremity Function in Hemiparetic Stroke. *J Neurol Phys Ther* 39, 2 (2015), 111-118. http://dx.doi.org/10.1097/npt.0000000000000085
33. Gitendra Uswatte, Edward Taub, David Morris, Mary Vignolo and Karen McCulloch. Reliability and Validity of the Upper-Extremity Motor Activity Log-14 for Measuring Real-World Arm Use. *Stroke* 36, 11 (2005), 2493-2496.
34. Marijke Vandermaesen, Tom de Weyer, Kris Luyten and Karin Coninx. 2014. Physicube: Providing Tangible Interaction in a Pervasive Upper-Limb Rehabilitation System. In *Proceedings of Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. ACM, 2540936, 85-92. http://dx.doi.org/10.1145/2540930.2540936
35. Michael W Whittle. *Gait Analysis: An Introduction*. Butterworth-Heinemann (Edinburgh), 2014.
36. Markus Windolf, Nils Götzen and Michael Morlock. Systematic Accuracy and Precision Analysis of Video Motion Capturing Systems—Exemplified on the Vicon-460 System. *Journal of Biomechanics* 41, 12 (2008), 2776-2780.

http://dx.doi.org/http://dx.doi.org/10.1016/j.jbiomech.2008.06.024