Towards the Design of a Ring Sensor-based mHealth System to Achieve Optimal Motor Function in Stroke Survivors

YOOJUNG KIM, Seoul National University, Republic of Korea
HEE-TAE JUNG, University of Massachusetts Amherst, United States
JOONWOO PARK, Smilegreen Child Development Center, Republic of Korea
YANGSOO KIM, Heeyeon Rehabilitation Hospital, Republic of Korea
NATHAN RAMASARMA, ArcSecond Inc., United States
PAOLO BONATO, Harvard Medical School, Spaulding Rehabilitation Hospital, United States
EUN KYOUNG CHOE*, University of Maryland, College Park, United States
SUNGHOON IVAN LEE*, University of Massachusetts Amherst, United States

Maximizing the motor practice in stroke survivors' living environments may significantly improve the functional recovery of their stroke-affected upper-limb. A wearable system that can continuously monitor upper-limb performance has been considered as an effective clinical solution for its potential to provide patient-centered, data-driven feedback to improve the motor dosage. Towards that end, we investigate a system leveraging a pair of finger-worn, ring-type accelerometers capable of monitoring both gross-arm and fine-hand movements that are clinically relevant to the performance of daily activities. In this work, we conduct a mixed-methods study to (1) quantitatively evaluate the efficacy of finger-worn accelerometers in measuring clinically relevant information regarding stroke survivors' upper-limb performance, and (2) qualitatively investigate design requirements for the self-monitoring system, based on data collected from 25 stroke survivors and seven occupational therapists. Our quantitative findings demonstrate strong face and convergent validity of the finger-worn accelerometers, and its responsiveness to changes in motor behavior. Our qualitative findings provide a detailed account of the current rehabilitation process while highlighting several challenges that therapists and stroke survivors face. This study offers promising directions for the design of a self-monitoring system that can encourage the affected limb use during stroke survivors' daily living.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing**; *Ubiquitous and mobile computing systems and tools*;

Additional Key Words and Phrases: Ring accelerometers, finger-worn accelerometers, stroke survivor, upper limb, hemiparesis, stroke rehabilitation, self-monitoring, mixed-methods study

*Co-corresponding authors.

Authors' addresses: Yoojung Kim, Seoul National University, Seoul, Republic of Korea, tendtoyj@snu.ac.kr; Hee-Tae Jung, University of Massachusetts Amherst, Amherst, Massachusetts, United States, hjung@cs.umass.edu; Joonwoo Park, Smilegreen Child Development Center, Daegu, Republic of Korea, otpjw@naver.com; Yangsoo Kim, Heeyeon Rehabilitation Hospital, Changwon, Republic of Korea, ysk@silver4u.net; Nathan Ramasarma, ArcSecond Inc. San Diego, California, United States, nathan@arcsecond.co; Paolo Bonato, Harvard Medical School, Spaulding Rehabilitation Hospital, Charlestown, Massachusetts, United States, pbonato@mgh.harvard.edu; Eun Kyoung Choe, University of Maryland, College Park, College Park, Maryland, United States, choe@umd.edu; Sunghoon Ivan Lee, University of Massachusetts Amherst, Amherst, Massachusetts, United States, silee@cs.umass.edu.

2474-9567/2019/12-ART138 $15.00
https://doi.org/10.1145/3369817

ACM Reference Format:
Yoojung Kim, Hee-Tae Jung, Joonwoo Park, Yangsoo Kim, Nathan Ramasarma, Paolo Bonato, Eun Kyoung Choe, and Sunghoon Ivan Lee. 2019. Towards the Design of a Ring Sensor-based mHealth System to Achieve Optimal Motor Function in Stroke Survivors. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 3, 4, Article 138 (December 2019), 26 pages. https://doi.org/10.1145/3369817

1 INTRODUCTION

Each year, nearly 800,000 individuals in the United States suffer from a stroke—a major cause of severe disability [5]. Approximately 75% of stroke survivors experience long-term motor impairments in the upper-limb, which significantly affects their performance of Activities of Daily Living (ADL) [20], thereby leading to lower health-related quality of life [18]. Post-stroke upper-limb impairments are marked by weakness with subsequently diminished dexterity and limited ability to perform reaching, transport, and grasping movements [64]. More importantly, impairments in the upper-limb can be prominent in one of the two limbs—stroke-affected vs. unaffected (or less affected)—which is a unique characteristic (referred to as *hemiparesis*) associated with stroke (or more generally, brain injuries) [33].

Most stroke survivors demonstrate considerable functional recovery within the first few weeks after the brain injury (i.e., spontaneous recovery), then reach a stable, yet still improvable phase of recovery [7]. The residual motor impairments in stroke survivors in their chronic phase (i.e., several years after the injury) could be possibly explained by a phenomenon referred to as *learned non-use* [28]. Due to the imbalance in the motor function between the two upper-limbs, stroke survivors tend to favor the use of the unaffected limb over the affected limb. As stroke survivors rely more and more on the unaffected limb, they progressively learn not to use the stroke-affected limb and lose its motor ability that may be recovered from the early-stage (i.e., acute) rehabilitation process [68]. This learned non-use significantly impedes the rehabilitation of the affected upper-limb [28].

To minimize the negative effects of learned non-use on functional recovery, stroke survivors are encouraged to continue making use of the stroke-affected upper-limb during ADLs [23], in addition to conventional rehabilitation exercises that focus on range-of-motion (ROM) and functional capabilities [4]. A large body of scientific evidence shows that a high dosage of motor practice in the affected limb during ADLs, despite the considerable difficulty, stimulates neuroplasticity and motor function recovery [77]. However, stroke survivors' adherence to high-dosage motor performance tends to be poor because of the inconvenience, forgetfulness, and lacking motivation and accountability [17, 72]. As stroke survivors spend much time in their home settings post discharge, they need an effective in-home rehabilitation support to maximize the motor practice in the affected limb (where the dosage level needs to be personalized based on the impairment level). In this light, a mobile-health (mHealth) intervention equipped with low-burden self-monitoring holds promise for promoting high-dosage affected upper-limb use. Wearable technologies have been considered as a potential solution to improve the functional level of the affected upper-limb. Due to their ability to continuously monitor upper-limb performance, wearable technologies can provide personalized and data-driven feedback and reminder, which facilitate a translation to the stroke survivors' daily life in an inexpensive, less-stringent, patient-friendly, and safe manner [8, 24, 40]. Over the past decade, wrist-worn accelerometer has gained acceptance as a low-cost, objective monitoring tool to quantify real-world upper-limb use during ADLs [2, 35, 47, 70]. Unfortunately, wrist-worn accelerometer-based solutions—despite growing clinical interests—have shown a number of limitations that prohibit their widespread adaptation in the clinic [23]. Wrist-worn accelerometers capture only the contributions of the arm and forearm (i.e., gross-arm movements) without measuring the contributions of the hand (i.e., fine-hand movements), which is more relevant to the essential upper-limb functions in performing ADLs [55]. As a result, wrist-worn accelerometers have been criticized for the overestimation of movement intensity and inability to capture small changes in the upper-limb performance over time [37].

In this work, we investigate to utilize finger-worn, ring-type accelerometers to design and develop an mHealth technology that will encourage the use of the stroke-affected limb during the performance of ADLs. The finger-worn accelerometers, contrary to wrist-worn accelerometers that mainly capture gross-arm movements, are capable of capturing the contributions of both gross-arm and fine-hand movements that reflect more meaningful, goal-direct use of the upper-limbs [1, 23]. In the following scenario, we envision how the mHealth system based on finger-worn accelerometers would assist stroke survivors in the home and during the therapy sessions:

> *Carol, a 64-year-old woman, survived from a stroke three months ago and is left with right hemiparesis. After three months in a hospital receiving intensive rehabilitation therapies, Carol has regained some of the lost motor function despite left with residual impairments. In preparing for Carol's discharge, her therapist, John, emphasizes the use of the affected right arm and hand during everyday activities as much time as possible in addition to the everyday at-home rehabilitation program that he prescribed to Carol. John suggests using an at-home monitoring system with finger-worn sensors that can track the duration, intensity, and ratio of both limb use throughout the day and provide feedback to Carol and John so that they can closely monitor the progress of the recovery and set weekly goals. One week later, Carol and John review the first-week data during a remote therapy session. They find that Carol uses her right limb only 20% of waking hours. Based on this information, they set the weekly goal to increase 5% of right limb use. During the daytime, Carol receives a data-driven notification based on her recent right limb use: "You have used your right limb 18% so far today and 5% during the past hour. Use your right limb more to reach your goal of 25%!" Every night, Carol receives a summary notification showing the day's performance. After a few weeks, Carol and John meet again to review the summarized data and find that Carol particularly avoids using her right limb in the morning. John teaches and prescribes a new set of movement techniques for Carol to practice at home.*

As a first step in pursuit of our vision, we conducted a mixed-methods study to (1) quantitatively investigate the feasibility of using finger-worn accelerometers to evaluate stroke survivors' upper-limb performance and to (2) qualitatively examine design requirements for stroke survivors' in-home self-monitoring system. More specifically, in the quantitative part of this study, we establish face and convergent validity of finger-worn accelerometers in 22 stroke survivors with mild-to-moderate motor impairments based on a set of ADLs performed in a laboratory setting. We also validate finger-worn accelerometers' responsiveness to changes in the upper-limb use pattern when participants were asked to increase their stroke-affected limb use, demonstrating the sensors' ability to continuously monitor the adherence and effectiveness of the envisioned self-monitoring system. In the qualitative part of the study, we identify how therapists and stroke survivors personalize rehabilitation goals (i.e., the optimal functional level), what efforts they make to achieve the goals, and what challenges they encounter throughout the current rehabilitation process based on semi-structured interviews with seven Occupational Therapists (OTs) and 25 stroke survivors. Building on these findings from both studies, we offer design implications for stroke survivors' self-monitoring system, focusing on how such a system can provide data-driven therapy, support meaningful rehabilitation goals, and promote collaboration between clinicians and patients. This work serves a step towards developing an mHealth system that can help attain the personalized, optimal motor function in stroke survivors.

2 RELATED WORK

2.1 Technologies for Remote Rehabilitation in Stroke Survivors

Technologies to enable remote rehabilitation in stroke survivors' home and community settings have been of great interest to researchers and clinicians. A variety of approaches have been investigated to support remote rehabilitation exercises, including (1) wearable and mobile device-based [22, 35], (2) camera-based (e.g., Microsoft Kinect) [46, 74], (3) augmented or virtual reality-based [57, 63], and (4) robot-assisted approaches [30, 78]. Although these technologies facilitate frequent, high-dosage motor practices in patients' living environments in a cost-effective manner (e.g., without the presence of therapists), they do not support a ubiquitous solution to improve their stroke-affected limb use during ADLs (see the discussion of the Constraint-Induced Movement Therapy below), which have been noted to be much needed to improve motor ability in stroke survivors [23, 40]. Furthermore, many of the equipment-based (e.g., robots or virtual reality equipment) technologies require substantial training for stroke survivors, who are often elderly and not tech-savvy.

In clinical research, a treatment method named Constraint-Induced Movement Therapy (CIMT) has emerged as one of the most effective regimens to improve outcomes of the affected upper-limb [77]. CIMT is a form of rehabilitation therapy that forces the use of the stroke-affected limb by restraining the unaffected limb using a mitt or a half glove [77]. The success of CIMT has been understood to be owing to its ubiquity, that is, continuously forcing stroke survivors to use their affected limb during ADLs [40]. However, despite its effectiveness, CIMT has not been incorporated into daily clinical practice because (1) limb-constraint raises safety concerns for stroke survivors with impaired balance and (2) both stroke survivors and clinicians reported poor compliance due to the intensity of the therapy [16, 72]. To address these limitations, we want to leverage wearable technologies to continuously promote stroke-affected limb use in a safe and user-friendly manner.

2.2 Wearable Technologies for Remote Monitoring of Gross-Arm Movements in Stroke Survivors

Over the past decade, wrist-worn accelerometers have gained acceptance as a low-cost, objective tool to quantify real-world upper-limb use during ADLs [23, 47]. With its ability to continuously monitor upper-limb performance, personalized and data-driven feedback provided from wearable technologies have the potential to attain the therapeutic benefits of CIMT, and the cost advantages and convenience of at-home training. Wrist-worn accelerometers are often placed bilaterally to capture the activities of both limbs and compare their relative use (e.g., stroke-affected limb vs. unaffected limb use) [2, 66]. The measures of upper-limb performance that have been widely investigated (mostly via cross-sectional studies) can be roughly categorized into: (1) the intensity of limb use [1, 2, 44, 70], (2) the time duration of limb use [32, 62, 65], and (3) the ratio of activity between the two limbs [31, 44, 62, 70]. The intensity of limb use is computed by summing up the acceleration magnitudes, which represents the overall intensity of limb activity. Studies have investigated the intensity of unilateral (affected side only) as well as bilateral (both limbs combined) limb activities [1]. The duration refers to the time period the stroke survivor is actively using the affected upper-limb, where active vs. inactive periods are determined based on an acceleration magnitude threshold (i.e., the limb is moving vs. not moving). The threshold value often varies from one study to another (e.g., one or two activity counts [3, 67], an arbitrary measure of human activity). The ratio of activity between the two upper-limbs describes the movement characteristics of the affected upper-limb with respect to the unaffected limb [23]. The ratio can be computed based on the intensity or use duration of the two limbs. Some studies have also investigated the ability of wrist-worn accelerometers to capture longitudinal changes in stroke survivors' functional ability (e.g., after receiving a rehabilitation treatment), supporting that wearable devices could be used to track the recovery trajectories[12, 66, 69]. Uswatte and colleagues showed that the change in activity ratio between the affected vs. unaffected limbs demonstrates significant correlations to changes in the clinically accepted measures of upper-limb performance after receiving CIMT [66, 69]. More recently, Chen and colleagues showed that the intensity of the affected limb use demonstrate acceptable responsiveness to changes in functional ability after a four-week-long upper-limb rehabilitation intervention [12]. However, as discussed in the previous section, wrist-worn sensors are limited in capturing fine-hand movements that are more relevant to the meaningful use of the upper-limb during the performance of ADLs [55]. In a recent review article [23], this limitation of wrist-worn sensors has been identified as one of the major barriers for current wearable solutions to be translated into clinical practice.

Previous studies have proposed different technologies to monitor the contributions of hand and finger during ADLs. A number of studies have proposed instrumented gloves with embedded sensors [22]. However, continuously wearing gloves during daily living can be cumbersome and challenging, especially for stroke survivors with motor impairments to repeatedly don and doff the gloves—possibly without the help of caregivers—throughout the ADLs (e.g., washing hands, washing dishes, showering). Friedman and colleagues introduced a system leveraging a magnetic ring whose movements can be captured by a wrist-worn device equipped with a magnetometer [19]. However, the system requires stroke survivors to wear both the wrist-worn and finger-worn devices, which may negatively affect their adherence to the system as previous studies emphasized that general patients (especially the elderly population) prefer to wear a minimum number of wearable devices [6]. Lee and colleagues recently deployed two stand-alone bilaterally-worn finger-worn accelerometers in young neurologically intact, able-bodied individuals to capture the degree of use preference of the dominant vs. non-dominant upper limbs (i.e., handedness) during ADLs in free-living settings [36]. The authors also introduced a new measure of real-world upper-limb performance (i.e., the difference in the duration of active use between the two limbs) and showed a significant correlation to the self-reported handedness scores. However, there exist no studies to date that have investigated the use of finger-worn accelerometers to monitor the performance of upper-limb use in stroke survivors.

2.3 Wearable and Mobile Technologies to Promote the Use of the Stroke-Affected Limb

Researchers have designed and developed mHealth interventions leveraging wearable sensing to encourage the use of the stroke-affected limb [8, 25, 40, 43]. These interventions commonly consist of all or some combinations of self-monitoring, feedback, reminder, cue, and goal setting, which are known to be critical in inducing behavior change. One of the most important design aspects in self-monitoring technology is the design of feedback and feedback delivery mechanism. Beursgens and colleagues designed Us'em, which is composed of two wrist-worn accelerometers to compute the ratio of movement between the stroke-affected vs. unaffected limbs [8]. On one of the wrist-worn devices, Us'em provides visual feedback of the use ratio over several days. Although the researchers demonstrated that the concept of wearable technology that monitors and provides feedback on limb usage is credible as a treatment device, all participants noted that the wrist-worn devices were too bulky to wear all the time, while the feedback design was limited by the small screen of the wrist-worn device. More recently, Held and colleagues [24] designed a wearable system, namely ARYS, composed of two wrist-worn devices and an accompanying Android mobile app and proposed to test the effects of feedback through a between-subjects study. The feedback of both limb use is shown on the mobile app display through a figurative representation ("Tree of Recovery") with scores. As this is work-in-progress, the effects of the aesthetic and gamified feedback on stroke survivors' limb use during ADLs will be tested in the future.

Sending cues and reminders via wearables and mobile devices can motivate stroke survivors to enhance the rehabilitation of the affected upper-limb [25, 40, 43]. Holden and colleagues designed CueS, which sends vibrotactile cues every hour throughout the day for stroke survivors to nudge them to perform target exercise movements [25]. Similarly, Luster and colleagues [40] developed a vibrotactile device, which delivers frequent (every 30 seconds) vibrotactile cues through a wristband, but only when a person is performing a five-minute target task. In both settings, stroke survivors expressed positive opinions about the vibrotactile cues in motivating them to use an unaffected limb. To further examine cue modalities, Micallef and colleagues developed a system, namely Aide-Memoire Stroke (AIMS), and studied how people perceive and prefer different devices and reminder modalities (i.e., visual, vibration, audio, speech) [43]. The authors reported that the design of the reminders for stroke survivors should be attuned to their unique needs and disease characteristics. For example, stroke survivors preferred repeated and salient reminders because it takes time for them to notice and process the information [43]. Although these prior studies provide insights for designing and integrating effective cues and reminders,

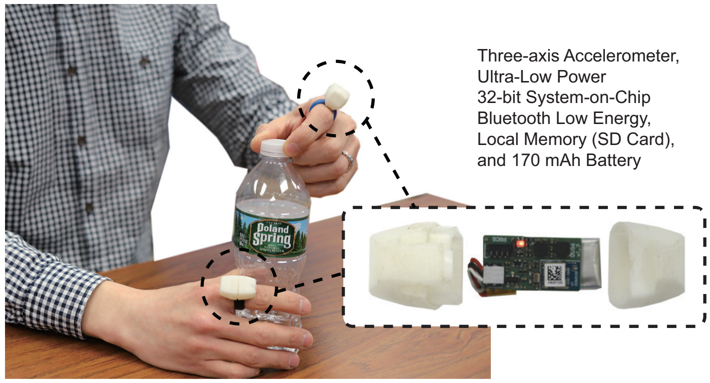

Fig. 1. The finger-worn accelerometers used in our study, which could capture three-axis accelerometer data at a sampling rate of 100 Hz.

identifying the optimal combination of reminder contents and modality warrants further studies. Moreover, while these prior studies focus on promoting stroke survivors' use of an affected limb during pre-defined, targeted rehabilitation exercises, we aim to explore the design of cues and reminders in stroke survivors' ADL contexts where continuous monitoring of fine-grained limb performance may be possible through finger-worn sensors.

3 METHODS

To mitigate the aforementioned limitations of existing work, we envision an mHealth system that can continuously monitor the contributions of both gross-arm and fine-hand movements during the performance of ADLs. In this section, we examine the feasibility of finger-worn accelerometers in generating accurate feedback, which may be used to encourage stroke-affected limb use. Specifically, we discuss our mixed-methods to (1) validate the clinical efficacy of our finger-worn sensor (i.e., quantitative analysis) and (2) identify design opportunities for the self-monitoring mHealth system leveraging the finger-worn sensors (i.e., qualitative analysis).

3.1 Finger-worn, Ring Accelerometers

Fig. 1 shows the picture of the finger-worn accelerometer used in this study. The wearable device contains a three-axis accelerometer, ultra low-power system-on-chip with Bluetooth Low Energy (BLE) capability, a local data storage (a micro-SD card), and a 170 mAh battery, encapsulated in a waterproof enclosure. The sampling rate of the accelerometer data was 100 Hz. The device could be secured to the index finger using a rubber ring band that comes in different sizes to fit individuals with varying body shapes.

The battery life of the body sensor network (i.e., two finger-worn sensors and a smartphone) was approximately 24 hours when the sensors transmitted accelerometer data to the smartphone via BLE, supporting that the system could be operable throughout a day. However, for this in-laboratory experiments, we stored the captured accelerometer data in the internal micro-SD cards for simplicity (see Section 3.3.3 for details about data synchronization).

3.2 Recruitment

We recruited seven OTs and 25 stroke survivors with residual upper-limb hemiparesis from Heeyeon Rehabilitation Hospital in South Korea between July and August 2018. We placed a recruitment blurb on public desks in the study site to recruit both groups of participants. The OTs (3 females) were 28 ± 4 years old (mean ± standard deviation) with 5 ± 3 years of practice. The stroke survivors (16 females) were 67 ± 12 years old and 14 ± 10 months post stroke. The inclusion criteria for the OTs required that they (1) are 18 years old or older, (2) are full-time employees of Heeyeon Rehabilitation Hospital at the time of data collection, and (3) have more than three months of experience as an OT at the time of data collection. The inclusion criteria for stroke survivors entailed that participants were (1) 18 years old or older, (2) have mild or better cognitive function measured by the Mini Mental State Examination (i.e., 19 points or greater out of the 30 points of the scale), and (3) have the latest assessment of mild-to-moderate upper-limb impairment level obtained using the Fugl-Meyer Assessment (FMA) scale (i.e., score between 15 and 55 of the total points of 65). There was no compensation for participating in this study. The study procedure was reviewed and approved by the University of Amherst's Institutional Review Board (IRB) as well as from the hospital site.

3.3 Data Collection Procedure

3.3.1 Clinical Evaluation on Stroke Survivors. Stroke survivor participants were first asked to self-report the Motor Activity Log (MAL), a standardized clinical tool to measure how much and how well stroke survivors use their stroke-affected upper-limb outside of the laboratory settings [10]. The MAL is a self-reported outcome composed of 30 items of various ADLs (e.g., turning on a light switch, washing hand, brushing teeth). For each item, participants are instructed to provide two scales, namely the (1) Amount of Use (AoU) scale and (2) Quality of Movement (QoM) scale. The MAL-AoU is a six-point ordinal scale (0-5) evaluating participants' amount of the stroke-affected limb use in terms of time duration (e.g., as much as pre-stroke, rarely, not used). The MAL-QoM is also a six-point scale (0-5) evaluating the quality of stroke-affected limb movements in terms of speed and accuracy (e.g., normal as pre-stroke, very slowly or with difficulty, not used). The average MAL-AoU and MAL-QoM scores computed over the 30 items are used to represent the comprehensive level of motor performance. Participants were then evaluated for their impairment level and quality of movements by a trained research therapist using the FMA and Functional Ability Scale (FAS), respectively. For both assessment tools, higher scores represent better health condition in stroke survivors (i.e., lower impairment level for the FMA and greater movement quality for the FAS). Readers are referred to the work by Sanford and colleagues [56] and Wolf and colleagues [76] for more detailed information regarding the FMA and FAS, respectively. It is noteworthy that, to compute the FAS score, we employed a subset of four (out of originally 15) motor tasks that were previously shown to be sufficient to reflect the total FAS score [50] (i.e., forearm to table, extend elbow, hand to table, and reach and retrieve). The movement quality scores of the four motor tasks were summed and normalized to the maximum possible score to represent the overall quality of movements.

In this study, the MAL-AoU was used as the *primary clinical outcome* to validate the convergence of the objective measures that are derived from our wearable device since both tools (i.e., MAL-AoU and wearable devices) aim to capture the amount of the stroke-affected upper-limb use during the performance of ADLs. The rest of the clinical measures—self-reported movement quality (MAL-QoL), and therapist's evaluation of movement quality (FAS) and upper-limb impairment level (FMA)—that are indirectly related to the motor function of the affected limb were used as the *secondary clinical outcomes*.

3.3.2 Semi-Structured Interviews with Stroke Survivors. We then conducted semi-structured interviews with the 25 stroke survivors. The second author interviewed all participants in person. An external OT who was a 30-year-old male with ten years of experience accompanied the second author to provide the necessary background and further explanation of clinical terms regarding rehabilitation practices. The interviews lasted from five to 30 minutes (average 15 minutes). We designed the interview protocol to understand the enablers and barriers that stroke survivors experience during current rehabilitation practices. We asked stroke survivors questions about their rehabilitation goals (e.g., *What do you want to achieve through engaging in rehabilitation therapy? Why?*). We then asked about their current experience of using the affected limb (e.g., *What activities do you think are*

Table 1. A summary of motor tasks of ADLs involving different levels of upper-limb laterality, required motor skills, and intensity, performed by our study participants.

Motor Task	Upper-Limb Laterality	Required Motor Skills
Walking	Completely Bilateral	Gross-arm
Sit-to-stand transition	Completely Bilateral	Gross-arm
Putting on a sock	Mostly Bilateral	Mostly gross-arm
Putting lotion on hands	Mostly Bilateral	Mostly gross-arm
Buttoning shirts	Mostly Bilateral	Mostly fine-hand
Drinking from a water bottle	Mostly Bilateral	Both gross-arm and fine-hand

affected by the stroke? How do you currently do such activities? and *How do you feel when doing such activities?*). Finally, we asked about the challenges they experience in both in-person therapy and at home (e.g., *What is the major barrier that prevents you from using your affected limb during ADLs?*).

3.3.3 Performance of Activities of Daily Living in the Experimental Setting. Stroke survivors were then asked to bilaterally place the above-mentioned wearable sensors on their index fingers. For our experiments, participants were also equipped with two wrist-worn accelerometers (MTw Awinda, XSens, The Netherlands) for comparative analyses to previous studies that were established on wrist-worn accelerometers. Participants were then instructed to perform a series of six motor tasks that require different levels of limb laterality (bilateral vs. unilateral), motor skills (gross-arm vs. fine-hand), and intensity, which are summarized in Table 1. These motor tasks have been also similarly used in prior studies that investigated the validation of wearable devices for capturing upper-limb performance in laboratory settings [1, 36, 39]. For *walking*, participants walked on an approximately 10 *m* trail at a self-paced speed, turned around, and walked back to the original position. For *sit-to-stand transition*, participants were asked to sit on a chair and stand-up. Both walking and sit-to-stand were included in our study to represent motor tasks that involve completely bilateral and gross upper-limb movements (e.g., arm swing). For *putting on a sock*, participants were instructed to pick up a sock (unilateral, fine-hand) and put it on their preferred foot (bilateral, gross-arm). For *putting on lotion*, participants were asked to push the dispensing pump to place lotion on one hand (partially unilateral, gross-arm) and rub two hands to thoroughly spread the lotion (bilateral, fine-hand or gross-arm depending on the impairment level). Although these two motor tasks involved some degree of unilateral limb use, most of the performance required bilateral, gross-arm movements. For *buttoning shirts*, participants were asked to button up a shirt with four buttons, aiming to capture bilateral, fine-hand movements. For *drinking*, participants were asked to reach out to a water bottle (unilateral, gross-arm), unscrew the bottle cap (unilateral, find hand), and drink from it (unilateral, gross-arm). It is noteworthy that most ADLs performed by humans involve both upper-limbs and there exist only a very few activities that solely require a single limb use [1, 23]. Seven participants (all moderately impaired) did not perform sit-to-stand and putting on socks, and eight moderate participants did not perform walking due to safety reasons (e.g., potential for a fall). All participants successfully performed the remaining motor tasks.

Participants repeated motor tasks twice except for walking and sit-to-stand, which are completely bilateral in nature. In the first attempt, participants were asked to perform the motor tasks in a naturalistic manner as if they would perform in their real-world scenarios. In the second attempt, we asked participants to repeat the motor tasks by maximizing the use of the stroke-affected limb. The accelerometer data were collected and stored in the local memory of the sensors. Participants were asked to clap three time before and after each motor task, which were used to manually synchronize the data from the four sensors.

3.3.4 Semi-Structured Interviews with Occupational Therapists. To complement stroke survivors' experience, we also conducted semi-structured interviews with seven OTs in the hospital. The second author again interviewed all participants in their preferred time (e.g., breaktime) and location (e.g., an office or a hallway where there were a desk and chairs). We defined our interview protocol for OTs to investigate the current practices, motivation strategies, and opportunities for a self-monitoring system at home. We asked OT participants about their current practices including goal setting process and types of exercise with questions (e.g., *How do you set an individual stroke survivor's goals? How do you tailor therapy sessions for an individual patient?*). We also asked about their strategies to motivate stroke survivors (e.g., *How do you motivate your patients? How do you monitor your patients' progress? How do you communicate with them outside the therapy sessions?*). Lastly, we asked them about opportunities to adopt new technology in designing remote rehabilitation systems to help stroke survivors.

3.4 Quantitative Data Analysis

Based on the data collected from our finger-worn accelerometers, the primary objectives of the quantitative data analysis include (1) understanding the behavior of our finger-worn accelerometers when stroke survivors are performing various types of ADLs in a controlled environment, (2) demonstrating face and convergent validity of the sensor-based measures of upper-limb performance, (3) investigate the responsiveness of the finger-worn accelerometers to the changes in the upper-limb performance when asked to maximize the stroke-affected limb use, and (4) comparing the performance of our finger-worn accelerometers to the wrist-worn accelerometers that have been widely studied in the field.

We first discuss how the accelerometer data were processed to generate different measures of upper-limb performance and how we demonstrate the face and convergent validity of our finger-worn sensor. Face validity represents the subjective evaluation of the degree to which a measurement is analyzed for its ability to capture contents as it purports to measure [15]. Convergent validity represents the objective evaluation of the degree to which two measures that are theoretically related (i.e., our finger-worn accelerometer-based measure vs. the clinically accepted measure: MAL-AoU) are actually related [15]. We used the Pearson correlation coefficient to evaluate the convergent validity [36]. We note that wearable sensor data collected from three of the 25 stroke survivors were removed from the analyses because at least one of the sensors were malfunctioning and did not successfully collect data. Among the 22 stroke survivors (15 females, 66 ± 13 years old, and 11 ± 8 months post stroke) whose data were included in the analyses, nine had moderate upper-limb impairments and 13 had mild impairments according to the FMA.

First, the acceleration magnitude was derived from the three-axis acceleration information: $|a_a[n]| = \sqrt{a^2_{af,x}[n] + a^2_{af,y}[n] + a^2_{af,z}[n]} - g$ and $|a_u[n]| = \sqrt{a^2_{un,x}[n] + a^2_{un,y}[n] + a^2_{un,z}[n])} - g$ for the acceleromter on the affected and unaffected limbs respectively, where n represents each data point sampled at 100 Hz and g represents gravity ($\approx$ 9.8 m/s^2). Then, the mean acceleration was computed for one-second long epochs: $|\overline{a}_a[t]| = \sum_{n=t}^{t+99} |a_a[n]|$ and $|\overline{a}_u[t]| = \sum_{n=t}^{t+99} |a_u[n]|$, where $t = 1, 2, 3, \cdots$ seconds.

To demonstrate the face validity of the behavior of our finger-worn sensors during the natural performance of different ADLs, a two-dimensional plot between (1) the ratio of use intensity between the two limbs (i.e., laterality) $r[t] = \ln(|\overline{a}_a[t]|/|\overline{a}_u[t]|)$ and (2) bilateral intensity $|\overline{a}_b[t]| = |\overline{a}_a[t]| + |\overline{a}_u[t]|$ was used (see Fig. 2a for an example). This visualization has been widely accepted in the literature to demonstrate the face validity of wearable-based solutions for upper-limb performance assessment [1, 23, 36]. It is noteworthy that the ratio measure $r[t]$ was log-transformed in order to make the measurement symmetric for the opposite signs [1, 36, 70]. Because face validity focuses on understanding the sensor behavior during the performance of ADLs involving different limb laterality and intensity, as previously shown in Table 1, we computed the mean and standard deviation of the two measures (i.e., $r[t]$ and $|\overline{a}_b[t]|$) across the study participants for each motor task (see Fig. 2b for an example). This analysis aims to provide the comprehensive understanding about which limb and what intensity do stroke survivors use—on average—to naturally perform different ADLs. We also investigate the changes in the motor behavior when stroke survivors were asked to maximize their affected limb use.

Convergent validity focuses on evaluating the proposed finger-worn sensor's ability to continuously monitor and quantify real-world upper-limb performance during ADLs by investigating the agreement to other clinically established measures (i.e., MAL-AoU as our primary measure). Because the MAL-AoU provides a measure that summarizes the use of the affected limb during real-world ADLs, we consider the six motor tasks that participants performed in the natural manner to represent their own performance of real-world ADLs. In other words, in this analysis—unlike face validity in which we aim to understand the sensor behavior during a specific set of motor tasks resembling ADLs—we do not assume that we know *a priori* types of ADLs that participants perform or analytically detect the occurrences of the ADLs (e.g., activity detection via machine learning algorithms). Rather, we consider the accelerometer data collected during the motor tasks as a continuous time-series without contextual information regarding the performed ADLs. We investigate a variety of measures that have been studied in the field to summarize the upper-limb performance, such as (1) the mean bilateral intensity throughout the monitoring period [70]: $M_1 = \frac{\sum_{t=1}^{T} |\overline{a}_b[t]|}{T}$, where T is the monitoring duration in seconds; (2) the mean intensity of the affected limb [54]: $M_2 = \frac{\sum_{t=1}^{T} |\overline{a}_a[t]|}{T}$; (3) the duration percentage for the active use of the affected limb [1, 62]: $M_3 = \frac{|t \in \{|\overline{a}_a[t]| > \beta\}|}{T}$, where $|t \in \{\cdot\}|$ represents the number of epochs (seconds) that satisfy the condition specified in $\{\cdot\}$ and β is the threshold to defined the active use of the limb. In our work, β was derived by placing the sensor stationary on a table, measuring the mean μ_s and standard deviation σ_s of the accelerometer magnitude, and computing $\beta = \mu_s + 2.96 \times \sigma_s \approx 0.10\ g$; (4) the mean ratio of the limb intensity [31, 38, 61, 70, 73]: $M_4 = \frac{\sum_{t=1}^{T} |r[t]|}{T}$; (5) the ratio of duration of active use between the two limbs [3, 32, 36, 62, 66]: $M_5 = \ln\left(\frac{|t \in \{|\overline{a}_a[t]| > \beta\}|}{T}\right) - \ln\left(\frac{|t \in \{|\overline{a}_u[t]| > \beta\}|}{T}\right)$.

We also introduce a new measure of upper-limb performance that quantifies how often—i.e., the time duration that—stroke survivors use two limbs together (bilaterally) to perform ADLs rather than relying on the stroke-affected (unilateral) limb. This was motivated by the fact that most real-world ADLs require both limbs as we discussed earlier [1, 23] and our findings also corroborate that stroke survivors with mild upper-limb impairment tend to perform ADLs using both limbs while those with moderate impairment rely more on the unaffected limb (see Fig. 3). The new measure computes the duration percentage of active bilateral use:

$$M_6 = \frac{|t \in \{|\overline{a}_b[t]| > 2\beta, |r[t]| < \delta\}|}{T},$$

where "$|r[t]| < \delta$" represents the condition for capturing bilateral limb use, and "$|\overline{a}_b[t]| > 2\beta$" represents the condition for capturing the active bilateral use with sufficient intensity (i.e., $2\beta \approx 0.20\ g$). The value of δ was found empirically using the Leave-One-Subject-Out Cross Validation (LOSOCV) technique. That is, while one subject's sensor and clinical data were designated as the testing set, the data from the remaining subjects were used as the training set to find the optimal value of δ for the testing subject. In each iteration of the LOSOCV, we performed a linear heuristic search on the value of δ from 0.3 (empirically chosen that well separates unilateral vs. bilateral limb use in more impaired stroke survivors according to Fig. 3b) to the maximum possible value of $|r[t]|$ with an increment of 0.05. The value of δ that yielded the maximum Pearson correlation coefficient to the target clinical measure (e.g., MAL-AoU) on the training dataset was selected as the optimal value for the testing subject. This process was repeated for all subjects (to be designated as the testing subjects), which provides a fair, unbiased (as opposed to optimistic) means to evaluate the performance of M_6 by completely isolating the testing dataset for finding the optimal value of δ.

In summary, M_1 and M_2 focus on measuring the intensity of limb use (as categorized in Section 2.2), M_4 and M_5 measure the ratio of activities between the two limbs, and M_3 and M_6 respectively measure the relative time duration of the affected limb use and both limbs. It is also noteworthy that T, which represents the monitoring duration, can be customized to support continuous monitoring of upper-limb performance throughout the day.

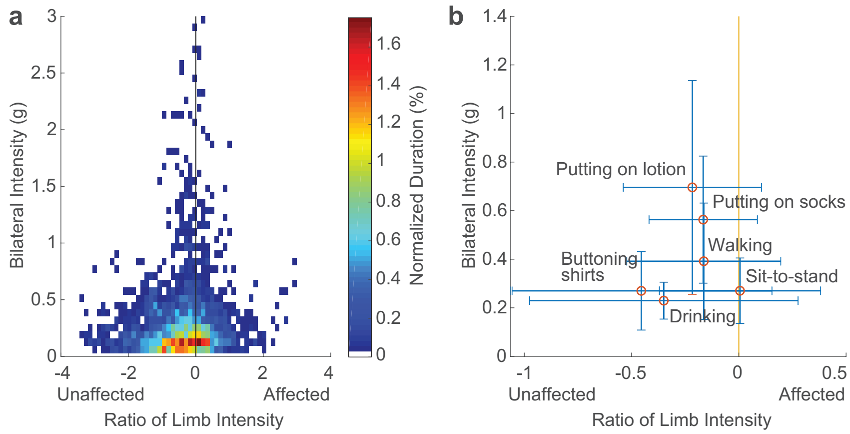

Fig. 2. (a) A 2D density heatmap that summarizes the frequency of epochs of upper-limb movements in terms of the ratio of limb intensity ($r[t]$) and the bilateral limb intensity ($|\overline{a}_b[t]|$). (b) A scatter plot of the mean and standard deviation of the ratio $r[t]$ and bilateral intensity $|\overline{a}_b[t]|$ per motor task across the study participants.

For example, if T is set to one hour, the mHealth system could generate feedback to stroke survivors summarizing their upper-limb performance every hour.

3.5 Qualitative Data Analysis

The primary objective of the qualitative data analysis is to identify opportunities for the design of stroke survivors' remote self-monitoring system leveraging the finger-worn accelerometers. Specifically, the qualitative analysis focuses on (1) understanding how therapists employ the rehabilitation therapy in the clinic (e.g., goal setting, goal adjustment, progress monitoring, and associated challenges), (2) collecting initial reactions of therapists and stroke survivors on self-monitoring of limb use in the home, and (3) providing practical implications and insights for designing self-monitoring technology to provide personalized, data-driven therapy and aid in collaboration between therapist and stroke survivors.

All interviews were audio recorded, which were later transcribed, translated, and analyzed using the thematic approach [9]. At first, three authors individually analyzed the transcriptions of seven therapists and three stroke survivors using open coding. Then, all authors contributed to the affinity sessions to build coding scheme. After three rounds of iteration of open coding and discussion, all authors reached the saturation of codes and agreed on the coding scheme. The final coding scheme included four main codes and 12 sub-codes. The first author coded the rest of interview data according to the coding scheme. Then, by combining similar codes, the first author and third author conducted axial coding (i.e., making connections between codes and sub-codes), yielding larger themes from the data. Lastly, all authors refined and integrated those themes into four major themes.

4 QUANTITATIVE FINDINGS

4.1 Face Validity of Finger-Worn Accelerometers

Fig. 2a and b summarize participants' natural performance of motor tasks using the ratio of limb intensity ($r[t]$) in the x-axis and the bilateral limb intensity ($|\overline{a}_b[t]|$) in the y-axis, which are used to demonstrate the face validity of our finger-worn accelerometers. More specifically, Fig. 2a represents the 2D density heatmap (i.e., histogram) that summarizes the frequency of one-second long epochs for each value combination of $r[t]$ and $|\overline{a}_b[t]|$. The maximum and minimum values of both axes were divided into 50 bins of equal lengths. Blue colors represent

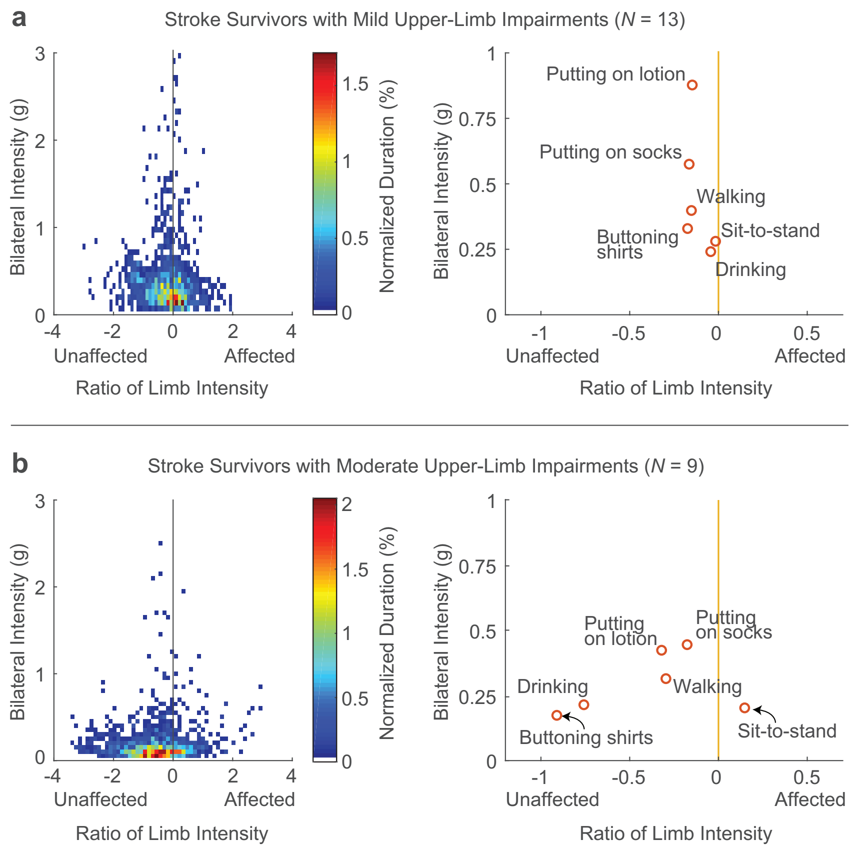

Fig. 3. The 2D density heatmap (left) and scatter plot for different tasks (right) for (a) participants with moderate upper-limb impairments and (b) participants with mild upper-limb impairments. Note that the standard deviation information in the scatter plots was omitted to simplify and better demonstrate the difference in motor patterns in two different groups.

lower frequencies, whereas red colors represent higher frequencies. The colors were mapped to the normalized time duration (in %) with respect to the summed length of all the epochs. Fig. 2a shows that most epochs were located in the region where $r[t] < 0$ and $|\overline{a}_b[t]| < 0.25\ g$, which indicates that the participated stroke survivors spent more time generating low-intensity movements with their unaffected limb to perform the motor tasks. This result is comparable to a number of prior studies that investigated the density plot on wrist-worn accelerometer data obtained from the naturalistic settings (e.g., 24 hours of monitoring). Hayward and colleagues [23] and Lang and colleagues [31] reported that stroke survivors show an asymmetric use pattern that is skewed towards the unaffected upper-limb. On the other hand, both work reported that neurologically intact, healthy individuals show a symmetric pattern centered around $r[t] = 0$, indicating that healthy individuals utilize both the dominant and non-dominant upper-limbs together to perform ADLs. Furthermore, both work showed that stroke survivors produced the warmer glow in the bottom of the y-axis (which again well-aligns with our findings), while healthy individuals produced it in the middle of the y-axis, showing that healthy individuals generate higher-intensity movements compare to stroke survivors in general.

Fig. 2b summarizes the results of Fig. 2a by first computing the mean values of $r[t]$ and $|\overline{a}_b[t]|$ for each motor task for each participant, then computing the means and standard deviations across the participants. The mean $r[t]$ values in Fig. 2b show the patterns of limb laterality that we hypothesized in Table 1. For example, the mean values of $r[t]$ show incremental unilateral limb use pattern from walking, sit-to-stand, putting on socks, putting on lotion, drinking, and buttoning. A number of interesting observations were made during the data collection. First, the intensity of the unaffected limb use was greater than that of the affected limb (i.e., the average $r[t]$ was less than 0) during walking because the affected limb in stroke survivors was often tightly attached to the torso due to muscle spasticity—a common symptom in stroke [49]—while the unaffected limb was more naturally swinging during walking. Consequently, the intensity of the affected limb was often slightly lower than the unaffected limb. Second, the buttoning activity was designed to capture bilateral, fine-hand movements, but our results show that stroke survivors significantly relied on their unaffected limb to perform the motor task. This is because the motor recovery occurs from the proximal components (e.g., upper arm) of the upper limb to the distal components (hand) [58]. In other words, the recovery of fine-hand function usually occurs at the later stage of the rehabilitation process compared to gross-arm function, and most of our study participants, specifically those with moderate impairments, did not have good fine-hand ability to perform the buttoning task with their affected limb (see also Fig. 3). Lastly, the large variations in the mean values of $r[t]$ and $|\overline{a}_b[t]|$ across participants indicate that participants showed large variations in movement patterns to perform the motor tasks, which agrees with previously reported findings [1, 23, 36, 60]. The results presented in Fig. 2a and b collectively demonstrate the face validity of the finger-worn accelerometers in stroke survivors.

Fig. 3a and b compare the natural performance of motor tasks in participants with mild (n = 13) and moderate (n = 9) motor impairments, respectively. Participants with mild impairments showed more symmetric and high-intensity use of the limbs when compared to moderately impaired participants. In other words, mild participants exhibited the pattern of motor performance that was more similar to the healthy population (as described in the previous paragraph) [1, 23, 36, 60]. On the other hand, moderately impaired participants substantially relied on their low-intensity unaffected limb movements to perform the motor tasks, especially buttoning shirts and drinking from a water bottle that involved some degree of fine-hand motor skills. The results depicted in Fig. 3 demonstrate the finger-worn accelerometer's face validity for its responsiveness to the motor impairment level in stroke survivors.

4.2 Finger-Worn Accelerometers' Responsiveness to Changes in Motor Behavior

Fig. 4 compares the upper-limb performance when participants performed the motor tasks in a naturalistic manner vs. after they were asked to maximize the use of their affected limb. The 2D density plots clearly show that participants increased the affected limb use (i.e., shifted towards the affected side on the x-axis) after receiving the prompting message. The scatter plots on the right also show that participants increased the use of their affected limb to perform the motor tasks, especially buttoning shirts and drinking from a water bottle that involved substantial amount of unilateral movements. Statistical analysis showed that all motor tasks, except putting on socks, showed significant improvements in the relative use of the stroke-affected limb (paired t-test, $p < 0.05$), which supports the responsiveness of the finger-worn accelerometers to the changes in upper-limb behavior after participants were asked to maximize the use of the affected limb. Furthermore, although the prompting message was conveyed verbally in the experimental setting, our results support the potential of and motivate the design of an mHealth system that can provide self-monitoring feedback accompanied with such prompting messages to improve stroke survivors' functional level in the affected limb. However, it is worth noting that most participants with moderate impairments had to make great efforts to perform the motor tasks when they were asked to maximize their affected limb use. Some participants had to repeatedly try to open up the bottle cap or to button the shirt, and some even gave up on completing the motor tasks. Although participants indeed

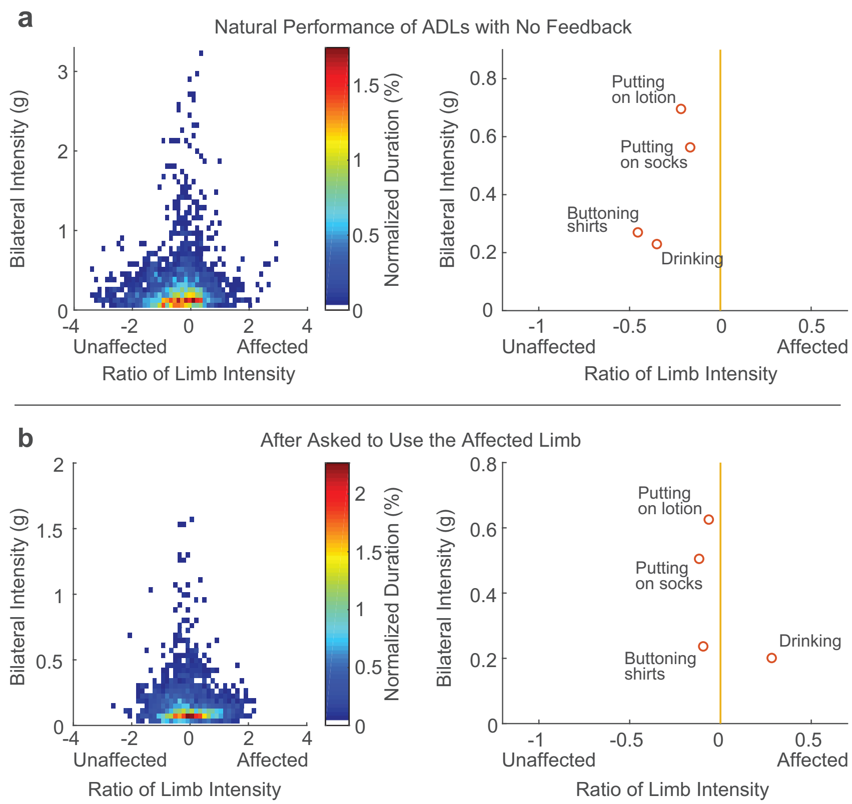

Fig. 4. The 2D density heatmap (left) and scatter plot for different motor tasks (right) when participants performed (a) in a naturailistic manner vs. (b) after being asked to maximize the use of their affected limb.

significantly improved the motor dosage of their affected limb after receiving the prompting message, it does not seem practical to assume that stroke survivors with moderate impairment level will make such an effort when an mHealth system delivers the message in their naturalistic settings. On the other hand, participants with mild impairments could increase the motor dosage of their affected limb with minimal efforts. One of the major reasons that stroke survivors do not use their affected limb includes that they simply forget as they become accustomed (or habitual) to use more of their unaffected limb in ubiquitous settings (see Section 5.3 for our findings). As such, stroke survivors with mild impairment would be an ideal target user group for an mHealth system that can capture people's motor performance and nudge them via reminders.

4.3 Convergent Validity of Finger-Worn Accelerometers

Table 2 reports strong convergent validity between the six different sensor-based measures of real-world upper-limb performance considered in this work (see Section 3.4) and the clinical measures (see Section 3.3.1). Although all sensor-based measures reported statistically significant Pearson correlations to the primary measure of real-world upper-limb performance (i.e., MAL-AoU), M_6 (i.e., duration percentage of active bilateral use) yielded the best correlation coefficient of 0.83. Fig. 5 shows the scatter plot, where one data point was identified as an outlier according to Cook's distance [11]. The linear fit shown in Fig. 5, however, was computed including the outlier.

Table 2. A summary of convergent validity between the sensor-based measures of upper-limb performance vs. the primary clinical measure of upper-limb performance (i.e., MAL-AoU) and secondary clinical measure of the movement quality (i.e., MAL-QoM and FAS) and impairment level (i.e., FMA) in the upper-limb.

Sensor-Based Measures		Clinical Measure			
		Primary	Secondary		
Category	Notation	MAL-AoU	MAL-QoM	FMA	FAS
Intensity	M_1	0.51*	0.41	0.56**	0.45*
	M_2	0.63**	0.55**	0.65**	0.54**
Duration	M_3	0.69**	0.60**	0.56**	0.64**
Ratio	M_4	0.69**	0.75**	0.68**	0.68**
	M_5	0.73**	0.74**	0.72**	0.80**
Proposed Measure	M_6	0.83**	0.72**	0.65**	0.60**
Maximum correlation		0.83**	0.75**	0.72**	0.80**

$^*p < 0.05$, $^{**}p < 0.01$.

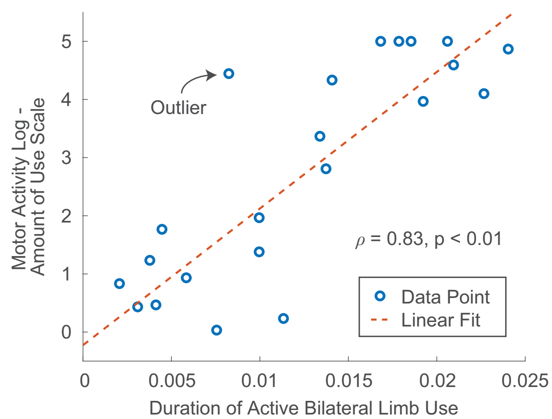

Fig. 5. Scatter plot between a sensor-based measure (i.e., duration percentage of active bilateral use) vs. the primary clinical measure of real-world upper-limb use (i.e., MAL-AoU). The Pearson analysis showed a statistically significant correlation ($p < 0.01$) with a coefficient of 0.83.

Furthermore, it is noteworthy that the values of δ for M_6 determined through the iterations of LOSOCV were consistent with small variations (i.e., 0.62 ± 0.065), which demonstrates that the measure could capture reliable patterns of bilateral limb use across the participants (i.e., not biased towards a specific participant). On the other hand, M_5, which focuses on measuring how often stroke survivors use the affected limb with respect to the unaffected limb, produced the highest correlation coefficients to other secondary measures, especially the FMA and FAS that evaluate the impairment level and movement quality of the "affected limb", respectively.

Table 3 compares the convergent validity of finger-worn vs. wrist-worn accelerometers by reporting the maximum correlation coefficients achieved for each clinical score. The measures derived from the finger-worn sensor yielded comparable, yet stronger, convergent validity to the clinical measures of real-world upper-limb performance, movement quality, and impairment level. The correlations reported in this work are comparable to prior work that employed wrist-worn accelerometers. The correlation coefficients between the wrist-worn sensor-based measures from existing work and the MAL-AoU vary from 0.47 to 0.60, and those for the MAL-QoM vary from 0.52 to 0.66 [38, 47, 61, 66, 70, 73]. Similarly, wrist-worn accelerometer-based measures have shown correlations between 0.46 and 0.60 for the FMA [38, 47, 62]. No prior work has compared accelerometer intensity-based measures to the quality of movements obtained by using the FAS. Note, however, that the correlations

Table 3. Comparison of convergent validity for finger-worn vs. wrist-worn accelerometers using the ratio measures (i.e., M_4, M_5, and M_6) that yielded best correlations to the clinical measures.

Sensor Location	**Maximum Correlation**			
	MAL-AoU	**MAL-QoM**	**FMA**	**FAS**
Finger	0.83^{**}	0.75^{**}	0.72^{**}	0.80^{**}
Wrist	0.76^{**}	0.73^{**}	0.70^{**}	0.69^{**}

$^{*}p < 0.05$, $^{**}p < 0.01$.

reported in this work should not be directly compared to the aforementioned results of existing work. Although our work has investigated the convergent validity in a set of motor tasks involving various levels of limb laterality, motor skills, and intensity, most of the previous works have computed the measures based on data collected in real-world settings (e.g., 24 hours).

5 QUALITATIVE FINDINGS

Based on the quantitative results demonstrating the clinical validity of the finger-worn sensor system and its ability to continuously monitor stroke survivors' upper-limb behavior, in this section, we aim to establish design requirements of a self-monitoring system that can provide personalized and data-driven feedback to improve the motor dosage of the affected limb in stroke survivors' naturalistic environments. To that end, we describe how therapists employ rehabilitation in the clinic, including goal setting, goal adjustment, and strategies to help stroke survivors achieve the goals. We also report stroke survivors' goals and challenges in the current rehabilitation practices. We note that the data reported in this section are based on the interviews with therapists and stroke survivors who were going through in-the-clinic therapy sessions. While the findings are based on their *current* experience of rehabilitation therapy, we believe that these findings will serve as a basis for the design of stroke survivors' self-monitoring system that leverages finger-worn sensors.

5.1 Goal Setting and Adjustment

Goal setting is the first step in the rehabilitation process. Goals are largely driven by the stroke survivor's and therapist's priorities, and it is common that each party expresses the goals in different ways using different languages. Therapists tend to focus on *functional improvement* goals expressed in clinical metrics or performance-related (e.g., muscle strength) metrics that are easily measurable. Before setting concrete goals, therapists first assess the current functional or impairment level of a stroke survivor using validated metrics (e.g., FMA, ROM, ADL score), and look for exhibition of compensatory behaviors. Depending on each stroke survivor's case, therapists additionally examine the *fine-hand motor function* illustrated as follows: *"In terms of functions, this patient is in a very good condition, comparing to other patients. Instead, in fine-hand motor function, the thumb doesn't move very well. [...] I keep checking out [the patient's] fine-hand motor functions."* (OT-5). After reviewing current functional abilities, therapists set goals based on each stroke survivor's status. Such practice is exemplified in OT-3's comment: *"I usually help patients regain range of motion, improve strength, then build muscle strength."*

In contrast to therapists, stroke survivors elicit and express *aspirational goals* conveying why they want to get better and what they desire to do after they gain functional improvement. These goals contain a mix of desired ADLs and personal activities. The most prominent goal is to go back to their normal life and engage in household chores, such as *cooking for family* (P-4, P-20, P-24, P-25), *cleaning the house* (P-3, P-24) or *doing laundry* (P-1). Similarly, some goals are related to doing things that they used to do in their free time before the stroke, such as meeting friends (P-4, P-10, P-13), fishing (P-24), dancing (P-12), seeing grandchildren (P-18), and hiking (P-10). Another common goal is to get back to work, despite the wide range of jobs—from painter to running own business (e.g., store, orchard). These aspirational goals reflect stroke survivors' lived experience, not the clinical metrics, and therefore, may not directly be translated into functional goals.

Therapists are aware that the stroke survivor's and therapist's goals are different and sometimes in conflict with one another. Some therapists expressed that they should consider what the patient wants as a top priority, even if the stroke survivor's goals clash with the ideal functional goals of the therapists. OT-1 stated, *"It [the rehabilitation goal] depends on what the patient wants. If the patient wants to go back home as soon as possible due to the financial situation, thereby wanting to gain [the minimal level of] physical abilities, I honor that, even if the posture would be bad."*

The goals agreed upon and determined at the beginning of the rehabilitation process change depending on each patient's recovery trajectory over time. Therapists try to actively adjust the regimen rather than stick to the initial plan. OT-1 remarked, *"If patients rapidly get better, I give them more challenging goals [...] If patients couldn't do it, I lower the goal and look into why the goal didn't work. I check out if the approach or the goal was good enough, or whether the patients did their best."* One way to adjust the goal is to divide the goal into sub-goals, which encourages the stroke survivor to gradually achieve both. OT-4 illustrated a successful case, in which he divided up one big goal into two-tiered goals so that the stroke survivor ended up achieving them. OT-4 said, *"She [the patient] wanted to grab it [the object] and then move it. At first, she was not able to grip it at all. So, I thought she should work on grabbing first, even if she couldn't move it. So, [I said to her,] 'Let's try to grab this. Moving it is the next thing.' She ended up achieving it [grabbing the object] and now she's working on moving the object."*

5.2 Steps to Achieve Goals

To help stroke survivors achieve the rehabilitation goals, therapists design various therapeutic exercises and activities for each stroke survivor and teach them during the in-person therapy sessions. For example, OT-6 reported that the activity of picking up a coin on the floor can help improve both gross-arm (e.g., stooping down the upper body) and fine-hand (e.g., use fingers) motor functions. There were also other activities that involve everyday objects (e.g., clothespin, button, bottle) to improve fine motor function. For those who need to be trained in using both limbs, therapists instruct them to do bilateral activities, such as opening a bottle cap or buttoning, similarly to the motor tasks in Table 1 that we investigated earlier in the paper.

In addition to the aforementioned activities taught in the therapy sessions, therapists reported that they prescribe patients in-home exercises and household chores to maximize the motor dosage outside the clinical setting. The prescribed activities are simple enough for stroke survivors to repeat several times on their own, such as holding bottles (OT-2) or trays (P-24), pouring water into a glass (P-24), moving objects from one side to the other side (OT-7), and wringing out a towel (P-24). OT-6 noted that some ADLs such as dishwashing may be a good in-home rehabilitation activity—although it may be too challenging for some—because it requires using different parts of the body. The benefits and drawbacks of dishwashing are illustrated in OT-6's description: *"I recommend doing the dishes [to stroke survivors] because it helps exercise their legs. [...] It includes all types of activities, like lifting plates, using hands, and using the upper limb. [...] In addition to the risk of falling, [...] when wearing gloves or shoes, stroke survivors might become dull so that they miss a plate and break it."*

Stroke survivors should repetitively practice such activities for a long time to improve the functional level of the affected upper-limb. However, motivating them to do so is challenging after discharge. OT-7 noted, *"Many stroke survivors are discharged from the hospital once they regain lower limb function, and thus to be able to walk. They say they will exercise their upper limbs from home but most of them don't."* Unlike in-clinic therapy sessions, stroke survivors experience a lack of knowledge and accountability when exercising alone at home. They sometimes forget what exercise to do and how to do it. P-20 said, *"My [occupational] therapist said that I should do some kinds of hand exercise. [...] He told me that I should do it a lot but I forgot what it was."* Although some stroke survivors know what to do, they reported that they feel frustrated because it is difficult to do exercise without therapists' professional and in-person support (P-1, P-3, P-23). The presence of therapists may also influence the level of motivation. The following case of P-14 revealed this aspect:

> Interviewer (I): So, [as the therapist recommended,] do you walk a lot?
> P-14: I usually don't walk because it's still not comfortable but I do [walk] whenever I see my therapist.
> I: Could you tell me a reason why you don't walk when you don't see your therapist?
> P-14: It's [walking is] bothersome.

One way of motivating stroke survivors is to establish a trusted relationship (also referred to as *rapport*). OT-5 reported that one stroke survivor's attitude changed in a positive way after building trust. Explaining that building trust is a key to motivate stroke survivors to follow their instructions, OT-1 commented, *"If the patient has trust that the therapist can help them, [...] they will have a great motivation."* Showing how to make rapid progress is one way to build trust in a short time: *"There might be some [functional] aspects that I can help improve and exhibit to patients in a short time period. I usually try to show them such improvement as soon as possible. They might be excited and think like, 'I had not been able to do it for a year but now I suddenly became to be able to do it.' Then, they get motivated right away and start to trust me."*

5.3 Reminders and Cues

As mentioned earlier, stroke survivors can easily lose interests and lack accountability in rehabilitation at home. When asked how to address these issues in designing an mHealth system for stroke survivors, therapists suggested providing reminders (e.g., text-based notification) and cues (e.g., sounds, vibrations). With respect to reminder contents, therapists mentioned two types that they are already using or want to utilize in the future.

First, therapists currently use motivational messages to encourage patients to stay motivated in the rehabilitation process. Because rehabilitation usually takes a long time and requires a high-level commitment but the progress is often slow and invisible, patients are likely to be discouraged. During the interview, many stroke survivor participants showed strong signs of depression (P-3, P-8, P-16, P-19, P-21, P-23) and helplessness (P-6, P-9, P-10, P-15, P-16, P-23). Therapists suggested that giving motivational messages tied to stroke survivors' aspirational goals may inspire them to engage in the rehabilitation process. OT-4 reported an example of a stroke survivor who runs an apple orchard: *"He [the patient] thought he was not able to do certain activities but from my view, he was fully able to do it. He was discouraged, so I said, 'You should go back and pick fruits.' Then, he was motivated again and tried his best. I think he realized that he really wanted to go back and grow his fruits."*

Second, therapists suggested that providing personalized cues based on the upper-limb performance data would be helpful because stroke survivors often forget to use the affected limb at home. P-8, whose left side is affected, reported that he habitually uses his right hand (due to his right-handedness) unless he consciously tries to use the left hand. Furthermore, some stroke survivors unconsciously use the unaffected limb at home, which may cause an overload of the unaffected limb. P-12 said, *"I used the right hand too much and it was overloaded. [...] When I met a woman whose hand was paralyzed, I was afraid that I would become like her."* As a way of encouraging the use of the affected limb, OT-2 proposed to send audio cues based on the actual limb usage. OT-2 said, *"One of my patients doesn't use his left hand at all at home. So, it would be great to provide cues that ask the patient to use his left hand in some specific situations."*

Participants also discussed several delivery mechanisms of the reminders and cues. Some therapists expected that personalized verbal and auditory cues can be an effective way to deliver the contents. OT-1 stated that the tone of voice may be more critical than the content of the message itself because a certain tone of voice can make some stroke survivors focus on the muscle movement and strength. Similarly, OT-5 and OT-6 mentioned that some stroke survivors better react to provoking words than to soothing words. OT-5 said, *"If I softly tell him to do exercise, he usually doesn't do it. [...] This kind of patients are likely to be motivated by some provoking words like, 'Can you really do this? Perhaps this is too much for you?' [...] When I say things like that, they try very hard."*

However, most therapists said that relying solely on cues and reminders may promote therapeutically undesirable behaviors (e.g., compensatory movements) and that visual instructions could aid in teaching stroke survivors how to make clinically appropriate movements. To provide instructions in an effective manner, OT-5 proposed to utilize visual media, such as videos or televisions, especially in the home environment. This finding also suggests the need to carefully identify an appropriate target audience for remote rehabilitation and self-monitoring—those who already learned how to move and exercise in correct forms but need reminders and cues to do it on their own, which well-aligns with our quantitative findings and discussions regarding the target population in Section 4.2.

5.4 Involving Formal & Informal Caregivers

During the in-clinic rehabilitation sessions, therapists deliver personalized therapy for each stroke survivor, which involves deciding on what strategies to use or what goals to focus. Therapists stated that each stroke survivor is different and their condition may change from day to day, which requires therapists to attune to those differences and changes and react to them by fine-tuning the therapy session and by varying the level of assistance they provide to each stroke survivor. OT participants (OT-5, OT-6, OT-7) strongly felt that their role cannot be replaced by family members or other informal caregivers because they lack professional rehabilitation knowledge. Consider the following example given by OT-1: "*[...] most of patients lift their arms high with interlocked fingers. The downside of that exercise is, if the right arm has hemiparesis, the right arm would pull the left arm, since right arm can't do the task. It will damage joints. However, patients think that is the part of exercise.*" When OT-1 sees stroke survivors doing exercise with bad form, he stops them and fixes the posture. However, family members cannot provide such assistance, which may lead to a reinforcement of compensatory behaviors.

Although informal caregivers may not provide the kinds of rehabilitation guidance that therapists provide, therapists mentioned several ways in which informal caregivers could help stroke survivors in the home. First, informal caregivers may offer "simple" exercise guidance provided that they have the necessary training with a therapist. Drawing an analogy of a person taking measurements of another person, OT-4 said that having another set of eyes to check the stroke survivor's posture might be better than the stroke survivor checking his/her own. Furthermore, family members can motivate stroke survivors when they exercise together. In P-15's case, the stroke survivor would do a finger (fine-hand) exercise only when his family does the exercise together with him: *"I can't do it well on my own. I mostly do with my family."* Informal caregivers could also remind the stroke survivor to use an affected limb in daily living—for example, when turning the faucet on or off—because stroke survivors tend to forget to use the affected limb. While such reminders could be easily seen as nagging, some stroke survivor participants did not mind getting frequent reminders from caregivers, especially when they have a good rapport. Because family members or other informal caregivers spend much more time with stroke survivors than therapists do, therapists thought that involving family members in the rehabilitation process under the guidance of clinicians would be a good idea.

6 DESIGN IMPLICATIONS

In Section 4, we demonstrated strong evidence for the finger-worn accelerometer to be a viable means to measure continuous upper-limb performance. Furthermore, in Section 5, we provided an understanding of how therapists and stroke survivors currently engage in the rehabilitation practice as a starting point to design a self-monitoring system for stroke survivors. Drawn from these findings, we offer four design implications: (1) provide data-driven therapy, (2) support both functional and aspirational goals, (3) promote collaboration between clinicians and patients, and (4) design for acceptability. In all of these cases, we envision using the self-monitoring system to *augment* the in-person therapy, rather than replacing it. Therapists play an integral role in the stroke rehabilitation and they shall continue to do so in the ecosystem of the self-monitoring technology.

6.1 Provide Data-driven Therapy

With the advancement and prevalence of mobile and wearable sensors, self-monitoring technologies have shown great promise in chronic condition management (e.g., diabetes, weight loss, irritable bowel syndrome, mental health, Parkinson's disease) by helping clinician's decision making, increasing patient's self-awareness, and enabling personalized interventions [75]. Similar to these approaches, we believe that self-monitoring technology capable of detecting fine-grained upper-limb performance can facilitate personalized, data-driven therapy for stroke survivors.

Our quantitative findings show that finger-worn accelerometers have great potential to continuously monitor and generate clinically relevant measures of upper-limb performance during the performance of ADLs. In Table 2, we showed that different measures of movement intensity (M_1 and M_2), active unilateral/bilateral limb-use duration (M_3 and M_6), and ratio of use between the two limbs (M_4 and M_5) can provide statistically significant correlations to clinically accepted measures of real-world upper-limb performance (i.e., MAL), movement quality (i.e., FAS), and impairment level (i.e., FMA). We also showed that the measures of the ratio of intensity between the two limbs and the bilateral limb intensity could together be responsive to the motor impairment level (i.e., Fig. 3) and changes in motor performance (i.e., Fig. 4) in stroke survivors. We believe that these measures of different dimensions of upper-limb performance (i.e., intensity, duration, and ratio) could be collectively used to represent the stroke survivor's comprehensive motor performance (rather than relying on a single measure), because the use patterns of the upper-limbs during ADLs are highly variable within and across individuals [3, 23, 60] and the patterns of functional recovery in stroke survivors are also highly heterogeneous[29].

As we demonstrated a good face validity and convergent validity of the finger-worn accelerometers, a logical next step would be to work with therapists and stroke survivors to explore ways to utilize these fine-grained, multi-dimensional limb performance data for the rehabilitation purposes in the home setting. Although several studies have explored design requirements to utilize self-monitoring data in various clinical contexts [45, 53, 75], we need to create a system that is suitable and applicable for stroke rehabilitation, which has not yet been thoroughly studied. We suspect that the kind of feedback that stroke survivors prefer would be different from that of therapists, and as such, we should involve these stakeholders to learn their preferred level of data summary, metrics, and data granularity to help them make sense of the limb performance data.

For stroke survivors, finger-worn accelerometers can enhance the visibility of the upper-limb functional level—whether an affected or unaffected limb is under- or overused—which may be effective in addressing the issue of *learned non-use* that stroke survivors often encounter. The learned non-use can be aggravated post-discharge, when stroke survivors spend most of their time without therapists' watch. Therefore, we envision a self-monitoring system that continuously monitors the use of both limbs and shows personalized feedback to help achieve the balanced ratio of both limb uses. The feedback for stroke survivors would convey the measures of upper-limb performance (e.g., from M_1 to M_6) in an easy-to-understand textual or graphical format in a daily or weekly basis, compare his/her current performance to the past performance, and suggest an adjusted goal for the forthcoming monitoring cycle. While such feedback may be valuable for therapists to understand stroke survivors' activities in detail, therapists may largely be interested in M_5 and M_6, the measures that are highly correlated to and thereby could be easily translated into the clinically accepted measures (e.g., MAL-AoU and FMA), which therapists routinely use in their clinical practice. Having these data readily accessible would allow therapists to quickly understand patients' status and progress, based on which they can flexibly adjust goals and prescribe relevant exercise, as we described in the motivating scenario.

Furthermore, when the system detects the imbalance ratio of the uses between the two limbs, it can proactively send reminders to encourage stroke survivors to take steps to achieve more balanced ratio, as several studies have reported that healthy individuals use both limbs approximately equivalently with relatively high-intensity (although measured using wrist-worn sensors or using finger-worn sensors in young adults) [23, 26, 31, 36]. Such personalized reminders are different from existing approaches, which often send fixed reminders or cues at a set time (e.g., every hour) [25]. Identifying the optimal frequency, timing, and modalities of delivering these personalized reminders, however, warrants future research.

6.2 Support Both Functional and Aspirational Goals

The difference between clinicians' and patients' goals and priorities have been reported in other clinical contexts (e.g., [21]), where overarching health goals are often determined by healthcare providers. Our qualitative findings revealed that how therapists describe goals are markedly different from how stroke survivors describe goals: therapists focus on the functional goals based on their years of clinical practice, whereas stroke survivors focus on the aspirational goals reflecting their lived experience [41]. Functional goals can be expressed in the form of validated metrics, and achieving these goals is considered clinical improvement. Although therapists' functional goals are trackable and less ambiguous than aspirational goals, they are disconnected with the aspirational goals and cannot easily be translated into the language of the stroke survivors. However, aspirational goals are equally important to functional goals and can serve as a strong motivator for stroke survivors. Unfortunately, these two types of goals sometimes conflict with one another. In our findings, one stroke survivor participant wanted to get back home as soon as possible (aspirational goal), at the expense of good posture and performance (functional goal) that can be achieved over a long-term period. Supporting to capture, mediate, or follow up these two different goal types have not been examined in the prior work [25, 40, 43], which we see as important design considerations for a self-monitoring system for stroke survivors and therapists.

Capturing both functional (quantitative aspect) and aspirational (qualitative aspect) goals can be supported cohesively via the semi-automated tracking approach [13] embodied in the envisioned mHealth system. Leveraging both manual and automated data collection methods, this approach aims to lower the capture burdens (e.g., through the finger-worn accelerometers) while at the same time collect data that are typically difficult to track automatically (e.g., aspirational goals captured via free-form texts). Capturing both types of goals can be integrated in the configuration stage of the self-monitoring system, which requires both therapists and stroke survivors to explicitly and consciously think about what to achieve (functional goal) and why to achieve (aspirational goal). Capturing these goals can later be used to motivate stroke survivors to continue making use of the stroke-affected upper-limb during ADLs. For example, the envisioned self-monitoring system can overlay the functional goal on the stroke survivor's progress trajectory such that stroke survivors can review their progress in comparison to the functional goal. Furthermore, aspirational goals can be sent as a prompt to foster self-reflection and boost stroke survivors' motivation to continue exercise in place of therapists, whose role was often to remind why they should engage in making use of the stroke-affected limb.

6.3 Promote Collaboration between Clinicians and Patients

Shared decision making in healthcare (i.e., clinicians and patients make decisions together using the best available evidence) could enhance patient knowledge and foster active patient engagement [52]. However, in our interviews, we found that therapists most often drive the goal setting, as well as the design and delivery of the rehabilitation sessions. On the other hand, stroke survivors remain as passive recipients of the therapy. Although stroke survivors (patients) occasionally converse with therapists (clinicians), there was a lack of involvement from the patients who were feeling a deep sense of helplessness. Stroke survivors are likely to be alienated from treatment decision making because they often encounter obstacles to explicitly articulating their experiences of illness. Although patients can bring in different expertise (e.g., experience of illness, social circumstances, attitude to risk, values) from that of clinicians (e.g., diagnosis, disease aetiology, prognosis, treatment options) [14], eliciting and leveraging patients' expertise is challenging due to their limited knowledge about rehabilitation regimen or limited cognitive abilities. Furthermore, stroke survivors with severe cognitive impairment may feel this gap much larger because they often suffer from language disorders including dysphasia.

To bridge the knowledge and communication gap, the self-monitoring system can serve as a collaboration medium for therapists and stroke survivors. Currently, there is no system that enables therapists to remotely monitor stroke survivors' limb performance and recovery trajectory. As such, they cannot effectively adjust goals, exercise prescription, and rehabilitation regimen at large once stroke survivors are discharged. Thus, a data-driven approach with our finger-worn sensor can be useful to resolve this problem by filling in the knowledge gaps of the therapists to understand each stroke survivors' motivation level and limb performance over time. As we mentioned in Section 5.2, dishwashing can be a good rehabilitation exercise, but it must be carefully adjusted according to each patient's condition to lower the risk of injury. Therapists and stroke survivors may discuss if the progress is enough to practice dishwashing or if there are any positive or negative impacts on the limb use by reviewing the finger-worn sensor data.

From the patients' side, self-monitoring data could enable patients to talk more about themselves during the in-person therapy and have the potential to put patients and clinicians on an equal footing [42, 79]. In fact, self-monitoring data can facilitate discussion between clinicians and patients during the in-person or remote therapy sessions [27, 42, 79]. A dashboard containing patient's goals, prescribed activities, and limb-usage data could scaffold the process of expressing patients' thoughts and feelings, as well as for therapists to understand patients' status and recovery trajectory. Such design could also help therapists and patients validate the effectiveness of the current rehabilitation regimen and discuss the next rehabilitation goals.

6.4 Design for Acceptability

People abandon self-monitoring systems and assistive technologies at high rates when these devices do not reflect personal values, preferences, and social contexts [34, 51]. As such, we should learn and consider these aspects when designing a rehabilitation system to promote its long-term acceptability. People's general attitudes toward wearable sensors (i.e., non stroke-specific) have been studied. Older adults are acceptable to a wearable sensor (for general health monitoring) that is lighter or equal to the weight of a watch and smaller [48]. They also prefer a sensor embedded in a watch or ring as they do not want to be seen wearing a health monitoring device [59]. We have also seen conflicting findings from previous research where stroke survivors noted that wearing wrist-worn devices (one on each limb) was uncomfortable and stigmatizing [8]. We do not know what aspects of the design—some elements of the form factor, or having to wear two wrist-worn sensors—led to the stigmatization, which warrants us to further investigate what elements (e.g., size, color, aesthetics of the ring, number of devices) contribute to stigmatization, if any.

In our study, we deployed the finger-worn sensors only for a short duration (i.e., on average, 30 minutes in a laboratory setting). While participants did not complain of its usability or comment on the possibility of stigmatization during the interview, their feelings and experience with the wearable sensors will likely be different in their naturalistic environments [71], which remains a topic we plan to explore through a real-world deployment study. To this end, we will work with a professional designer to refine the form factor of the finger-worn sensor to balance the needs to house the battery and sensor units while improving the overall form factor of the ring for usability, aesthetics, and acceptance.

7 LIMITATIONS, FUTURE WORK, AND CONCLUSION

Several limitations of this study deserve further discussions. First, we validated the finger-worn accelerometers in an experimental (hospital) setting with an aim to understand and observe the behavior of the sensors (and thus the interpretation of the collected data) during stroke survivors' performance of ADLs. However, although the experiments were conducted in a hospital setting, participants performed the ADLs in their naturalistic manners—as if they would perform in real-world environments—without any instructions from research staff, supporting the validity of the findings reported in this work. Our immediate future research plans include deploying the sensors in a semi-experimental (e.g., simulated home) or free-living (e.g., real home) settings to monitor stroke survivors' more naturalistic motor performance. Second, as we discussed in Section 6.4, the design of the finger-worn devices used in this work needs further refinement for the field deployment. Prior studies support stroke survivors' strong preferences on the aesthetics and socially-acceptable wearable form factors [8, 23, 25]. All the electronic components of the current finger-worn prototype are enclosed in a 3D-printed capsule and attached to a silicon ring hand, as shown in Fig. 1, which can be quite bulky and prominent in appearance. Currently, our team is developing an embedded sensor system on a flexible PCB board with a ring-shaped battery, such that the electronic components can be packaged into a smaller, ring-like form-factor with minimal protrusion. Lastly, our study was based in a single site (i.e., [Anonymous] Hostpital in South Korea) and might not reflect findings from other geographic regions and cultures. Likewise, our qualitative findings might not represent more diverse perspectives of therapists and stroke survivors. Future work includes establishing concrete needs and parameters for self-monitoring technologies by situating stroke survivors in naturalistic environments and by providing concrete design probes to collect contextualized feedback. The next phase is to design and build a self-monitoring system reflecting each participant groups' requirements including desired data types, ways of visualization, and the layout of the screen, which will later be empirically evaluated via in-laboratory and field deployment studies.

In this work, we demonstrated—for the first time—the clinical efficacy of finger-worn accelerometers in stroke survivors for its face and convergent validity, as well as its responsiveness to feedback to increase their affected limb use. Our quantitative findings support that finger-worn accelerometers can be used to continuously monitor stroke survivors' goal-direct, meaningful use of their upper-limbs based on its ability to capture both gross-arm and fine-hand movements. Furthermore, our qualitative findings provide a detailed account of the current rehabilitation process while highlighting several challenges that therapists and stroke survivors face. These findings offer promising directions for the design of a self-monitoring system that can encourage the affected limb use with data-driven and patient-centered feedback during stroke survivors' daily living. This work contributes to bridging gaps in the state-of-the-art research findings in wearable computing, rehabilitation sciences, and human-computer interactions, and initiate valuable clinical translation. The envisioned mHealth system to increase the stroke-affected limb use in remote settings will be particularly useful in cases where a high-dosage physical and occupational therapy is not feasible (i.e., rural areas), which can form the basis of a wide range of future investigations and research opportunities in rehabilitation for hemiparesis.

ACKNOWLEDGMENTS

This work was partly supported by the 2018 Seed Grants from the Center for Personalized Health Monitoring at the University of Massachusetts Amherst.

REFERENCES

[1] Ryan R Bailey, Joseph W Klaesner, and Catherine E Lang. 2014. An accelerometry-based methodology for assessment of real-world bilateral upper extremity activity. *PloS one* 9, 7 (2014), e103135.

[2] Ryan R Bailey, Joseph W Klaesner, and Catherine E Lang. 2015. Quantifying real-world upper-limb activity in nondisabled adults and adults with chronic stroke. *Neurorehabilitation and neural repair* 29, 10 (2015), 969–978.

[3] Ryan R Bailey and Catherine E Lang. 2014. Upper extremity activity in adults: referent values using accelerometry. *Journal of rehabilitation research and development* 50, 9 (2014), 1213.

[4] Susan Barreca, Steven L Wolf, Susan Fasoli, and Richard Bohannon. 2003. Treatment interventions for the paretic upper limb of stroke survivors: a critical review. *Neurorehabilitation and neural repair* 17, 4 (2003), 220–226.

[5] Emelia J Benjamin, Paul Muntner, and Márcio Sommer Bittencourt. 2019. Heart disease and stroke statistics-2019 update: A report from the American Heart Association. *Circulation* 139, 10 (2019), e56–e528.

[6] JHM Bergmann and AH McGregor. 2011. Body-worn sensor design: what do patients and clinicians want? *Annals of biomedical engineering* 39, 9 (2011), 2299–2312.

[7] Julie Bernhardt, Kathryn S Hayward, Gert Kwakkel, Nick S Ward, Steven L Wolf, Karen Borschmann, John W Krakauer, Lara A Boyd, S Thomas Carmichael, Dale Corbett, et al. 2017. Agreed definitions and a shared vision for new standards in stroke recovery research: the stroke recovery and rehabilitation roundtable taskforce. *International Journal of Stroke* 12, 5 (2017), 444–450.

[8] 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 *CHI'11 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1279–1284.

[9] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2 (2006), 77–101.

[10] Tamara Bushnik. 2011. Motor Activity Log. In *Encyclopedia of Clinical Neuropsychology*. Springer, 1664–1665.

[11] Samprit Chatterjee and Ali S Hadi. 2009. *Sensitivity analysis in linear regression*. Vol. 327. John Wiley & Sons.

[12] Hao-ling Chen, Keh-chung Lin, Yu-wei Hsieh, Ching-yi Wu, Rong-jiuan Liing, and Chia-ling Chen. 2018. A study of predictive validity, responsiveness, and minimal clinically important difference of arm accelerometer in real-world activity of patients with chronic stroke. *Clinical rehabilitation* 32, 1 (2018), 75–83.

[13] Eun Kyoung Choe, Saeed Abdullah, Mashfiqui Rabbi, Edison Thomaz, Daniel A Epstein, Felicia Cordeiro, Matthew Kay, Gregory D Abowd, Tanzeem Choudhury, James Fogarty, et al. 2017. Semi-automated tracking: a balanced approach for self-monitoring applications. *IEEE Pervasive Computing* 16, 1 (2017), 74–84.

[14] Angela Coulter and Alf Collins. 2011. Making shared decision-making a reality. *London: King's Fund* (2011).

[15] Leanne S Cowin, Cecily Hengstberger-Sims, Sandy C Eagar, Linda Gregory, Sharon Andrew, and John Rolley. 2008. Competency measurements: testing convergent validity for two measures. *Journal of advanced nursing* 64, 3 (2008), 272–277.

[16] Leah Daniel, Whitney Howard, Danielle Braun, and Stephen J Page. 2012. Opinions of constraint-induced movement therapy among therapists in southwestern Ohio. *Topics in stroke rehabilitation* 19, 3 (2012), 268–275.

[17] Stefan Rennick Egglestone, Lesley Axelrod, Thomas Nind, Ruth Turk, Anna Wilkinson, Jane Burridge, Geraldine Fitzpatrick, Sue Mawson, Zoe Robertson, Ann Marie Hughes, et al. 2009. A design framework for a home-based stroke rehabilitation system: Identifying the key components. In *2009 3rd International Conference on Pervasive Computing Technologies for Healthcare*. IEEE, 1–8.

[18] Iza Faria-Fortini, Stella Maris Michaelsen, Janine Gomes Cassiano, and Luci Fuscaldi Teixeira-Salmela. 2011. Upper extremity function in stroke subjects: relationships between the international classification of functioning, disability, and health domains. *Journal of Hand Therapy* 24, 3 (2011), 257–265.

[19] Nizan Friedman, Justin B Rowe, David J Reinkensmeyer, and Mark Bachman. 2014. The manumeter: a wearable device for monitoring daily use of the wrist and fingers. *IEEE journal of biomedical and health informatics* 18, 6 (2014), 1804–1812.

[20] JM Geddes, Jon Fear, Alan Tennant, Ann Pickering, Micky Hillman, and M Anne Chamberlain. 1996. Prevalence of self reported stroke in a population in northern England. *Journal of Epidemiology & Community Health* 50, 2 (1996), 140–143.

[21] Shefali Haldar, Sonali R. Mishra, Maher Khelifi, Ari H. Pollack, and Wanda Pratt. 2019. Beyond the Patient Portal: Supporting Needs of Hospitalized Patients. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 366, 14 pages. https://doi.org/10.1145/3290605.3300596

[22] James Hallam. 2015. Haptic mirror therapy glove: aiding the treatment of a paretic limb after a stroke. In *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers*. ACM, 459–464.

[23] Kathryn S Hayward, Janice J Eng, Lara A Boyd, Bimal Lakhani, Julie Bernhardt, and Catherine E Lang. 2016. Exploring the role of accelerometers in the measurement of real world upper-limb use after stroke. *Brain Impairment* 17, 1 (2016), 16–33.

[24] Jeremia PO Held, Andreas R Luft, and Janne M Veerbeek. 2018. Encouragement-induced real-World upper limb use after Stroke by a tracking and Feedback device: a Study Protocol for a Multi-Center, assessor-Blinded, randomized Controlled trial. *Frontiers in neurology* 9 (2018), 13.

[25] Amey Holden, Róisín McNaney, Madeline Balaam, Robin Thompson, Nils Hammerla, Thomas Ploetz, Dan Jackson, Christopher Price, Lianne Brkic, and Patrick Olivier. 2015. CueS: cueing for upper limb rehabilitation in stroke. In *Proceedings of the 2015 British HCI Conference*. ACM, 18–25.

[26] Sharon L Kilbreath and Robert C Heard. 2005. Frequency of hand use in healthy older persons. *Australian Journal of Physiotherapy* 51, 2 (2005), 119–122.

[27] Yoojung Kim, Eunyoung Heo, Hyunjeong Lee, Sookyoung Ji, Jueun Choi, Jeong-Whun Kim, Joongseek Lee, and Sooyoung Yoo. 2017. Prescribing 10,000 Steps Like Aspirin: Designing a Novel Interface for Data-Driven Medical Consultations. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 5787–5799. https://doi.org/10.1145/3025453.3025570

[28] Annett Kunkel, Bruno Kopp, Gudrun Müller, Kersten Villringer, Arno Villringer, Edward Taub, and Herta Flor. 1999. Constraint-induced movement therapy for motor recovery in chronic stroke patients. *Archives of physical medicine and rehabilitation* 80, 6 (1999), 624–628.

[29] Gert Kwakkel, Boudewijn Kollen, and Eline Lindeman. 2004. Understanding the pattern of functional recovery after stroke: facts and theories. *Restorative neurology and neuroscience* 22, 3-5 (2004), 281–299.

[30] Gert Kwakkel, Boudewijn J Kollen, and Hermano I Krebs. 2008. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabilitation and neural repair* 22, 2 (2008), 111–121.
[31] Catherine E Lang, Kimberly J Waddell, Joseph W Klaesner, and Marghuretta D Bland. 2017. A method for quantifying upper limb performance in daily life using accelerometers. *JoVE (Journal of Visualized Experiments)* 122 (2017), e55673.
[32] Catherine E Lang, Joanne M Wagner, Dorothy F Edwards, and Alexander W Dromerick. 2007. Upper extremity use in people with hemiparesis in the first few weeks after stroke. *Journal of Neurologic Physical Therapy* 31, 2 (2007), 56–63.
[33] Peter Langhorne, Julie Bernhardt, and Gert Kwakkel. 2011. Stroke rehabilitation. *The Lancet* 377, 9778 (2011), 1693–1702.
[34] Amanda Lazar, Christian Koehler, Joshua Tanenbaum, and David H Nguyen. 2015. Why we use and abandon smart devices. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 635–646.
[35] Sunghoon I Lee, Catherine P Adans-Dester, Matteo Grimaldi, Ariel V Dowling, Peter C Horak, Randie M Black-Schaffer, Paolo Bonato, and Joseph T Gwin. 2018. Enabling stroke rehabilitation in home and community settings: a wearable sensor-based approach for upper-limb motor training. *IEEE Journal of Translational Engineering in Health and Medicine* 6 (2018), 1–11.
[36] Sunghoon Ivan Lee, Xin Liu, Smita Rajan, Nathan Ramasarma, Eun Kyoung Choe, and Paolo Bonato. 2019. A novel upper-limb function measure derived from finger-worn sensor data collected in a free-living setting. *PloS one* 14, 3 (2019), e0212484.
[37] Kaspar Leuenberger, Roman Gonzenbach, Susanne Wachter, Andreas Luft, and Roger Gassert. 2017. A method to qualitatively assess arm use in stroke survivors in the home environment. *Medical & biological engineering & computing* 55, 1 (2017), 141–150.
[38] Wan-wen Liao, Ching-yi Wu, Yu-wei Hsieh, Keh-chung Lin, and Wan-ying Chang. 2012. Effects of robot-assisted upper limb rehabilitation on daily function and real-world arm activity in patients with chronic stroke: a randomized controlled trial. *Clinical Rehabilitation* 26, 2 (2012), 111–120.
[39] Xin Liu, Smita Rajan, Nathan Ramasarma, Paolo Bonato, and Sunghoon Ivan Lee. 2019. The Use of A Finger-Worn Accelerometer for Monitoring of Hand Use in Ambulatory Settings. *IEEE journal of biomedical and health informatics* 23, 2 (2019), 599–606.
[40] Eric L Luster, Troy McDaniel, Bijan Fakhri, Jim Davis, Morris Goldberg, Shantanu Bala, and Sethuraman Panchanathan. 2013. Vibrotactile cueing using wearable computers for overcoming learned non-use in chronic stroke. In *Proceedings of the 7th International Conference on Pervasive Computing Technologies for Healthcare*. ICST (Institute for Computer Sciences, Social-Informatics and ..., 378–381.
[41] Niall Maclean, Pandora Pound, Charles Wolfe, and Anthony Rudd. 2000. Qualitative analysis of stroke patients' motivation for rehabilitation. *Bmj* 321, 7268 (2000), 1051–1054.
[42] Helena M Mentis, Anita Komlodi, Katrina Schrader, Michael Phipps, Ann Gruber-Baldini, Karen Yarbrough, and Lisa Shulman. 2017. Crafting a view of self-tracking data in the clinical visit. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 5800–5812.
[43] Nicholas Micallef, Lynne Baillie, and Stephen Uzor. 2016. Time to exercise!: an aide-memoire stroke app for post-stroke arm rehabilitation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, 112–123.
[44] Marian E Michielsen, Ruud W Selles, Henk J Stam, Gerard M Ribbers, and Johannes B Bussmann. 2012. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Archives of physical medicine and rehabilitation* 93, 11 (2012), 1975–1981.
[45] Sonali R. Mishra, Andrew D. Miller, Shefali Haldar, Maher Khelifi, Jordan Eschler, Rashmi G. Elera, Ari H. Pollack, and Wanda Pratt. 2018. Supporting Collaborative Health Tracking in the Hospital: Patients' Perspectives. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 650, 14 pages. https://doi.org/10.1145/3173574.3174224
[46] Hossein Mousavi Hondori and Maryam Khademi. 2014. A review on technical and clinical impact of microsoft kinect on physical therapy and rehabilitation. *Journal of medical engineering* 2014 (2014).
[47] Marika Noorkõiv, Helen Rodgers, and Christopher I Price. 2014. Accelerometer measurement of upper extremity movement after stroke: a systematic review of clinical studies. *Journal of neuroengineering and rehabilitation* 11, 1 (2014), 144.
[48] Norbert Noury, A Galay, J Pasquier, and M Ballussaud. 2008. Preliminary investigation into the use of autonomous fall detectors. In *2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2828–2831.
[49] NJ O'dwyer, L Ada, and PD Neilson. 1996. Spasticity and muscle contracture following stroke. *Brain* 119, 5 (1996), 1737–1749.
[50] Shyamal Patel, Richard Hughes, Todd Hester, Joel Stein, Metin Akay, Jennifer G Dy, and Paolo Bonato. 2010. A novel approach to monitor rehabilitation outcomes in stroke survivors using wearable technology. *Proc. IEEE* 98, 3 (2010), 450–461.
[51] Betsy Phillips and Hongxin Zhao. 1993. Predictors of assistive technology abandonment. *Assistive technology* 5, 1 (1993), 36–45.
[52] Wullianallur Raghupathi and Viju Raghupathi. 2014. Big data analytics in healthcare: promise and potential. *Health information science and systems* 2, 1 (2014), 3.
[53] Shriti Raj, Joyce M Lee, Ashley Garrity, and Mark W Newman. 2019. Clinical Data in Context: Towards Sensemaking Tools for Interpreting Personal Health Data. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 3, 1 (2019), 22.
[54] Debbie Rand and Janice J Eng. 2012. Disparity between functional recovery and daily use of the upper and lower extremities during subacute stroke rehabilitation. *Neurorehabilitation and neural repair* 26, 1 (2012), 76–84.
[55] Justin B Rowe, Nizan Friedman, Vicky Chan, Steven C Cramer, Mark Bachman, and David J Reinkensmeyer. 2014. The variable relationship between arm and hand use: a rationale for using finger magnetometry to complement wrist accelerometry when measuring

daily use of the upper extremity. In *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 4087–4090.
[56] Julie Sanford, Julie Moreland, Laurie R Swanson, Paul W Stratford, and Carolyn Gowland. 1993. Reliability of the Fugl-Meyer assessment for testing motor performance in patients following stroke. *Physical therapy* 73, 7 (1993), 447–454.
[57] Gustavo Saposnik, Robert Teasell, Muhammad Mamdani, Judith Hall, William McIlroy, Donna Cheung, Kevin E Thorpe, Leonardo G Cohen, and Mark Bayley. 2010. Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation: a pilot randomized clinical trial and proof of principle. *Stroke* 41, 7 (2010), 1477–1484.
[58] Fátima de NAP Shelton and Michael J Reding. 2001. Effect of lesion location on upper limb motor recovery after stroke. *Stroke* 32, 1 (2001), 107–112.
[59] Robert Steele, Amanda Lo, Chris Secombe, and Yuk Kuen Wong. 2009. Elderly persons' perception and acceptance of using wireless sensor networks to assist healthcare. *International journal of medical informatics* 78, 12 (2009), 788–801.
[60] Nicholas Stergiou and Leslie M Decker. 2011. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Human movement science* 30, 5 (2011), 869–888.
[61] Edward Taub, Gitendra Uswatte, Mary H Bowman, Victor W Mark, Adriana Delgado, Camille Bryson, David Morris, and Staci Bishop-McKay. 2013. Constraint-induced movement therapy combined with conventional neurorehabilitation techniques in chronic stroke patients with plegic hands: a case series. *Archives of physical medicine and rehabilitation* 94, 1 (2013), 86–94.
[62] Gyrd Thrane, Nina Emaus, Torunn Askim, and Audny Anke. 2011. Arm use in patients with subacute stroke monitored by accelerometry: association with motor impairment and influence on self-dependence. *Journal of rehabilitation medicine* 43, 4 (2011), 299–304.
[63] Shanbao Tong. 2016. Virtual Reality: The New Era of Rehabilitation Engineering [From the Regional Editor]. *IEEE pulse* 7, 3 (2016), 5–5.
[64] Jarugool Tretriluxana, James Gordon, Beth E Fisher, and Carolee J Winstein. 2009. Hemisphere specific impairments in reach-to-grasp control after stroke: effects of object size. *Neurorehabilitation and neural repair* 23, 7 (2009), 679–691.
[65] MA Urbin, Ryan R Bailey, and Catherine E Lang. 2015. Validity of body-worn sensor acceleration metrics to index upper extremity function in hemiparetic stroke. *Journal of neurologic physical therapy: JNPT* 39, 2 (2015), 111.
[66] Gitendra Uswatte, Carol Giuliani, Carolee Winstein, Angelique Zeringue, Laura Hobbs, and Steven L Wolf. 2006. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Archives of physical medicine and rehabilitation* 87, 10 (2006), 1340–1345.
[67] Gitendra Uswatte, Wolfgang HR Miltner, Benjamin Foo, Maneesh Varma, Scott Moran, and Edward Taub. 2000. Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. *Stroke* 31, 3 (2000), 662–667.
[68] Gitendra Uswatte and Edward Taub. 2005. Implications of the learned nonuse formulation for measuring rehabilitation outcomes: Lessons from constraint-induced movement therapy. *Rehabilitation psychology* 50, 1 (2005), 34.
[69] Gitendra Uswatte, Edward Taub, David Morris, Mary Vignolo, and Karen McCulloch. 2005. Reliability and validity of the upper-extremity Motor Activity Log-14 for measuring real-world arm use. *Stroke* 36, 11 (2005), 2493–2496.
[70] Sanne C van der Pas, Jeanine A Verbunt, Dorien E Breukelaar, Rachma van Woerden, and Henk A Seelen. 2011. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Archives of physical medicine and rehabilitation* 92, 9 (2011), 1437–1442.
[71] Viswanath Venkatesh and Hillol Bala. 2008. Technology acceptance model 3 and a research agenda on interventions. *Decision sciences* 39, 2 (2008), 273–315.
[72] Ricardo Viana and Robert Teasell. 2012. Barriers to the implementation of constraint-induced movement therapy into practice. *Topics in stroke rehabilitation* 19, 2 (2012), 104–114.
[73] Tien-ni Wang, Keh-chung Lin, Ching-yi Wu, Chia-ying Chung, Yu-cheng Pei, and Yu-kuei Teng. 2011. Validity, responsiveness, and clinically important difference of the ABILHAND questionnaire in patients with stroke. *Archives of physical medicine and rehabilitation* 92, 7 (2011), 1086–1091.
[74] David Webster and Ozkan Celik. 2014. Systematic review of Kinect applications in elderly care and stroke rehabilitation. *Journal of neuroengineering and rehabilitation* 11, 1 (2014), 108.
[75] Peter West, Max Van Kleek, Richard Giordano, Mark J Weal, and Nigel Shadbolt. 2018. Common barriers to the use of patient-generated data across clinical settings. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 484.
[76] Steven L Wolf, Pamela A Catlin, Michael Ellis, Audrey Link Archer, Bryn Morgan, and Aimee Piacentino. 2001. Assessing Wolf motor function test as outcome measure for research in patients after stroke. *Stroke* 32, 7 (2001), 1635–1639.
[77] Steven L Wolf, Carolee J Winstein, J Philip Miller, Edward Taub, Gitendra Uswatte, David Morris, Carol Giuliani, Kathye E Light, Deborah Nichols-Larsen, Excite Investigators, et al. 2006. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial. *Jama* 296, 17 (2006), 2095–2104.
[78] Hong Kai Yap, Jeong Hoon Lim, Fatima Nasrallah, and Chen-Hua Yeow. 2017. Design and preliminary feasibility study of a soft robotic glove for hand function assistance in stroke survivors. *Frontiers in neuroscience* 11 (2017), 547.
[79] Haining Zhu, Joanna Colgan, Madhu Reddy, and Eun Kyoung Choe. 2016. Sharing patient-generated data in clinical practices: an interview study. In *AMIA Annual Symposium Proceedings*, Vol. 2016. American Medical Informatics Association, 1303.