Studying the Use and Utility of an Indoor Location Tracking System for Non-experts

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Abstract. Indoor location tracking systems have been a major focus of ubiquitous computing research, and they have much promise to help in collecting objective, real time data for applications and supporting studies. However, due to their typically difficult and time consuming installation process, few have explored the extent to which they can be used by non-experts. In this research, we studied how one location tracking system, PowerLine Positioning, could be used by non-technology expert rehabilitation researchers to study the mobility patterns of wheelchair users in their homes. We determined that indoor location tracking systems are not only usable by non-experts, but they can also be useful in allowing them to achieve their own research goals of obtaining objective mobility data. Based on the results, we provide areas for future exploration and implications for designers of location-based and other types of sensing systems which aim to be end-user deployable.

Keywords: Location, indoor location sensing, end-user deployable, accessibility, wheelchair users, PowerLine Positioning, user study.

1 Introduction and Motivation

The ability to sense a person's location, both indoors and outside, has been a long-term goal of technology designers in pervasive and ubiquitous computing. The promise of knowing precisely where a person may be at any given time has many potential uses, from context-aware computing, to location-based services [19], to tracking and monitoring behavior [3, 4, 24]. A number of researchers, both within the ubicomp community and beyond, have an interest in using location tracking systems as a means of collecting data they can use for assessing people's behaviors, activities, and whereabouts. This may be useful for application designers who wish to provide location-based services, but also for researchers hoping to better understand people's behaviors using a more objective means.

One difficulty with current sensing systems, especially indoor location sensing, is that the systems typically require extensive setup and have significant installation burdens on end-users [4]. Thus, their use often requires an expert to help install the application or requires significant training on the part of the end-user. These aspects

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limit the number of locations that a sensing system may be deployed as well as the number of people that can be studied. Because of these factors, the usefulness and utility of location sensing systems by non-technical users has been underexplored.

In this research, we wanted to determine whether the promise of easy-to-deploy indoor location systems could live up to the usefulness predicted by many location system designers. Thus, we explored whether one indoor location tracking system, designed to be easy-to-deploy and low-cost, could be used by a set of non-expert users to achieve their goals for location tracking research. In particular, we studied a group of rehabilitation researchers who used the PowerLine Positioning (PLP) [25] system to track the mobility patterns of wheelchair users within their homes to augment interviews having the goal of uncovering accessibility barriers and everyday life experiences. In particular, we focused on how well end-users were able to install, calibrate, and use PLP in the homes of the wheelchair users they wanted to study. We also studied the usefulness of PLP in achieving the goals of the researchers by identifying whether researchers were able to uncover more information about accessibility barriers by using PLP in combination with interviews than interviews alone. Overall, we found that PLP was easy to deploy and maintain by the rehabilitation researchers and helped them to uncover more barriers to accessibility in the wheelchair users' homes than interviews alone.

The research we present in this paper helps motivate one particular need for indoor location tracking systems as well as show how a ubiquitous sensing system can be designed to support use by the non-expert end-user. We provide a number of implications that other technology designers can use to design their systems to be both usable and useful by end-users. These implications can also be used for the design of sensing systems beyond just location tracking. This helps bring the field of ubiquitous computing closer to achieving the goal of sensing on a larger scale by creating guidelines for easy-to-deploy and maintain sensing systems.

The rest of this paper is organized as follows. We begin with a discussion of the related work, where we describe what motivated this work and where this work fits within the larger scheme of the pervasive computing literature. We next describe the design of our study, including details about the PowerLine Positioning technology we had users deploy in this study as well as the research questions the rehabilitation researchers wanted to address. Next, we describe the details of the study findings, including data on the ease of use and usefulness of the technology for the rehabilitation researchers. We follow the findings with a discussion of the results and describe implications and lessons learned from this process and then end with the conclusion.

2 Related Work

In this section, we outline the related work for this research and how it builds upon existing technology and studies. In particular, we discuss indoor location tracking systems and their challenges for domestic use, studying human activity in the home, and studying end-user deployment of sensing systems.

2.1 Indoor Location Tracking Systems and Their Challenges

Indoor positioning has been a very active area of research in pervasive and ubiquitous computing for the past decade, and many commercial systems are beginning to emerge. Several characteristics distinguish different solutions, such as the underlying signaling technology, line-of-sight requirements, accuracy, and cost of scaling the solution over space and over number of items [31]. The first indoor solutions introduced new infrastructure to support localization [1, 14, 22, 27]. Despite some success, as indicated by commercialized products [10, 12, 16, 30, 32], the cost and effort of installation are major drawbacks to wide-scale deployment, particularly in domestic settings. Thus, new projects in location-based systems research reuse existing infrastructure to ease the burden of deployment and lower the cost. The earliest demonstrations leveraged 802.11 access points [6, 8], and more recent examples explore Bluetooth [20] and wireless telephony infrastructure, such as GSM [19, 23] or FM transmission towers [18]. A concern is that individuals may not be able to control the characteristics of this infrastructure and the operational parameters of the infrastructure may change without warning, resulting in the need to recalibrate. The desire to control the infrastructure and to scale inexpensively inspired the work on the PowerLine Positioning system [25], which we used in this research.

Deployment time and ease-of-use are other essential considerations for indoor location systems, especially for studies in domestic settings. Investigators have limited time they can spend in a participant's home, thus the entire installation process must be as short as possible. In addition, technical expertise can also vary greatly, so an easy-to-use solution is always desirable. One way to address this challenge is to minimize the number of components used in the system, which is the case of the PLP system. Studies have also shown that homeowners are concerned with the appearance of their home after adding any additional instrumentation [7, 15]. PLP's minimal components made it an ideal system for us to use in this study.

2.2 Studying Human Activity in the Home

With the advent of new, affordable technologies, there has been a trend in research to shift from building technology to supporting office and home life. Abowd and Mynatt point out a need for studying domestic settings to inform the design of new technologies [1]. Edwards and Grinter echo similar sentiments in that people are using technologies in new and interesting ways in the home [11]. Thus, a key research problem for designing for the home is first to study the home's everyday workings, such as how people live in the home, what they do, and the role that technologies play.

The initial foray in studying the home has been with ethnography. For example, Crabtree *et al*. present a series of ethnographic studies that aimed to uncover communication routines and how people use particular spaces in the home [9]. They provide guidelines for placing technology in appropriate locations in the home. More recent work has looked at collecting emprical evidence for studying the domestic space. For example, Intille *et al.* presents techniques for acquiring data about people, their behavior, and their use of technology in a natural setting [17].

With the proliferation of portable electronic devices in the home, researchers are interested in studying the complex interactions between household residents and their devices. Aipperspach *et al.* [3, 4] looked at using sensor-based visual records of the physical movement of people and devices to facilitate in-depth discussion during interviews, but they also report challenges in installing the Ubisense location tracking system, which impacted the number deployments. Rowan and Mynatt installed strain sensors on the underside of the first floor of an elder's home to deploy their Digital Family Portrait application [28]. By detecting the weight of a person standing on the floor, these sensors allow the Digital Family Portrait to portray movement information in the home.

Tapia, *et al.* describe MITes (MIT environmental sensors), which are low-cost, wireless devices for collecting real-time data of human activities in natural settings [29]. The system includes five wearable sensors: on body acceleration, heart rate, ultra-violet radiation exposure, RFID reader wristband, and location beacons. Patel *et al.* demonstrated the use of Bluetooth for tracking the proximity of users to their mobile phone to study their affinity to their mobile phone and reasons for separation [24]. Philipose, *et al.* present the use of an RFID-enabled glove to monitor activities of daily living [26]. A person wearing the glove interacts with RFID-tagged objects, and the system recognizes activities based on interactions with objects. Thus, many of the current sensing approaches aim to address particular behaviors and location is often implicitly inferred. Just sensing alone cannot always gather meaningful information on people's activities, and thus must be coupled with an annotation or survey procedure. This line of research shows a need for developing and testing robust, scalable sensing systems for the home, as we have done with this work. In addition, we highlight the value of augmenting self-report with real-time location sensing data.

2.3 Studying End-User Sensor Deployments

Researchers have explored the acceptance of sensors in the home as well as end-user deployment considerations, which provided us with some guidelines for designing our location tracking solution. Hirsch, *et al.* examined the social and psychological factors that influence the design of elder care sensing systems and applications [15]. Among their findings is a concern that technology may be rejected if it detracts from the aesthetics of the home. Beckmann, *et al.* presented a study of end-user sensor installation and reaction to sensors in the home [7]. They had end-users install vibration sensors, in-line electricity monitoring sensors, motion detectors, cameras, and microphones. They found that end-users made a variety of errors, often due to the directional requirements of sensors or uncertainty over exactly where a sensor needs to be positioned. They also found many negative reactions to the intrusion of sensors into the living space, including objections to the potential for damage caused by the adhesive used for installation, concerns that sensors were placed in locations accessible by children or pets, and objections to the placement of cameras and microphones in the home. We use some of these principles in the design of our deployable system in addition to offering new insights in building non-expert or end-user deployable location tracking solutions for home.

3 Study Design

In this section, we describe the overall design of our study. We begin with the motivation and design of the rehabilitation researchers' study and the questions they aimed to answer, describe our method for studying them, and then discuss the technology we used to support the rehabilitation researchers. The overall aim of this our study was to answer the following research questions:

- Can an indoor location tracking system be easy enough to deploy for non-experts, and what is the typical deployment time for a standard home?
- Can an indoor location tracking system provide objective, empirical data for location-based studies in the home?
- Does using automatically-sensed location and mobility data facilitate a richer interview process that produces higher quality data?

3.1 Motivation for Studying Mobility of Wheelchair Users in the Home

Increased activity and participation for people with disabilities is a goal of the U.S. Americans with Disabilities Act (ADA) [5] and the New Freedom Initiative [21]. The aim is to reduce environmental barriers and increase access to assistive technologies in order to increase the ability of people with disabilities to integrate into the community, have a sense of autonomy, and lower dependence on societal resources. The assumption for this population is that wheelchairs are necessary for mobility, and mobility is the means to performing activities and community participation. However, in order to dress, eat, or bathe in a wheelchair, the home environment needs to be accessible (*e.g.,* wide enough doorways, wheelable ground surfaces, *etc.*). Studying and understanding the mobility patterns of wheelchair users in their homes can provide useful insights on where environmental barriers exist, how better to design assistive devices, and how to improve the architecture of homes and offices. However, collecting this data is a difficult task.

New technological methods are needed to understand activity and participation in the everyday lives of wheelchairs users, especially in the home. The development of objective indoor measures is critical to understanding how people use mobility devices in the home and can be used to document where, when, and how people are using these devices. In addition, it can help understand how specific environments in the home can facilitate or hinder a person's use of a particular device or the performance of a specific activity. In the rehabilitation research community, current measurement of indoor activities among wheelchair users in the home has been limited to self-report questionnaires, such as the Home Accessibility Survey [13]. Disability researchers have also used diaries to gather mobility problems when they occur. However, researchers have found that many incidents are missed with both of these methods. Indoor tracking technology can provide simple, automatic, and objective data about the activity and participation of individuals in a space.

Table 1 shows some the types of questions that researchers are interested in gathering about wheelchair users. The questions are based on current literature in the area. For each question, we briefly highlight how automatic location tracking can play an important role alone and when used in combination with interviews.

Table 1. Questions the rehabilitation researchers are interested in and how location tracking technology can help answer them

1.	**Where do people go to perform what activity?**
	Location data can show where people tend to spend a lot of time, and the interview can probe the participants about what activity is going on at those times.
2.	**How do people who use mobility devices make use of spaces in the home, and how does it differ from non-disabled family members?**
	Location data can show traces of where disabled and non-disabled members tend to go.
3.	**What mobility devices do people use for a particular activity (*e.g.,* walker to enter the bathroom, shower chair in the bath, and wheelchair in the hallway)?**
	Tagging all mobility aids will give information about which are used in which parts of the home. Participants can be queried about particular situations to determine the reason for the transition.
4.	**What is the frequency and duration of mobility device (*e.g.,* walker, cane, wheelchair, *etc.*) use in each room?**
	Location data can provide this information automatically and more accurately than self-report.
5.	**What routes do individuals take throughout the home? How have people adapted their homes (or not) and how does that impact mobility device use?**
	Location data can be aggregated to show time varying route information for each individual. The interview process can potentially reveal why certain routes are taken, such as the result of an environmental barrier.
6.	**What parts of the home are completely inaccessible?**
	Location data can show the parts of the house where people rarely go, and the interview can determine the reasons (e.g., inaccessible or just not used).
7.	**What are key facilitators in people's homes (*e.g.,* caregivers, devices, furniture, *etc.*)?**
	Location data can show the routes people take and if an aid was used. If it is not shown being used, then during the interview the participant can be probed about other types of mobility assistance they may use (e.g., help from a family member).

In large clinical trials, it is often necessary to recruit participants in distant locations. In addition, because of the individual's mobility disability, they may have limited ability to deploy any technology themselves. A deployable system has to be comprised of minimal components that can be installed by anyone, such as by a caregiver or family member. Presumably, researchers would conduct many simultaneous studies to produce a rich and generalizeable result, which argues for a cost-effective and easy-to-deploy solution. PowerLine Positioning is an appealing choice to address this need, where the infrastructure requirements are two plug-in modules, and the calibration step consists of a house walkthrough.

3.2 Technology Used in Study

The indoor location tracking system we chose for this study is the PowerLine Positioning system we previously developed [25]. PowerLine Positioning is an affordable, whole-house indoor localization system that works in the vast majority of households, scales cost-effectively to support the tracking of multiple objects simultaneously, and does not require the installation of any new infrastructure. The solution requires the installation of two small, plug-in modules at the extreme ends of the home (*e.g.,* the upstairs northwest corner and the basement southeast corner). These modules inject a mid-frequency signal throughout the electrical system of the home. Simple receivers, or positioning tags, listen for these signals radiated off the power line and wirelessly transmit their positioning readings back to the environment.

We re-engineered and built a deployable version of the PLP system, which conforms to the U.S. FCC Part 15 regulations. In addition, we incorporated a multi-staged tuned tag design (see Figure 1) and used different power line transmission frequencies: 500 kHz and 600 kHZ (see Figure 2). This new design yielded better performance and resolution (86% classification at 1-meter regions) in our test deployments.

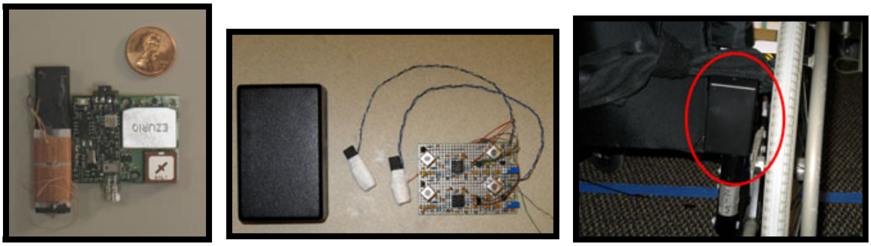

Fig. 1. Left: Redesigned and deployable PowerLine Positioning tags. **Middle:** The encasement used for larger devices, such as wheelchair and walkers. The larger case housed a higher capacity battery. **Right:** The tag installed on a user's wheelchair.

The new location tags we developed featured a zigbee wireless backchannel that reported a 16-bit unique ID, two 12-bit signal values, and a single bit indicating if the button on the tag is pressed back to the basestation in the home. The RF receiver connected to the personal computer was able to able receive data from up to 25 tags (base station limitation). An application running on the laptop parsed the data, handled the fingerprinting algorithm, and provided location services to the visualizer. The tag had an on/off switch and a single position push button. The button was used to indicate a special action to the remote computer, which was used to indicate that the tag is in site survey or calibration mode. The tags also incorporate motion detection, so the tag will go into a sleep mode if no motion is present for 30 seconds and reactivate itself on the next motion event. This approach greatly reduced the overall power consumption of the tag. With the tag duty cycling 40% of the time, the tag could easily last the entire duration of the study using a 750 mAh lithium ion battery source.

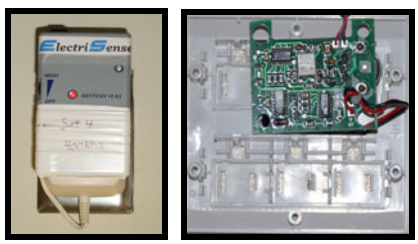

Fig. 2. Left: The signal generating plug-in modules. **Right**: Inside back cover of the outlet housing the signal generating circuitry.

To convey the location data for the interviews, we developed a simple visualization tool that used the data provided from PowerLine Positioning. The visualization allowed researchers to enter a timeframe and view either the concentration of activity levels in a given area in the house for a particular mobility aid or participant or view the routes that users or mobility aids traveled throughout the home (see Figure 3). The routes could also be animated to play back the exact path. The visualization tool provided a simple means to scan a large amount of location data in a meaningful way, by superimposing graphics on top of a floor map of the participant's home, drawn by rehabilitation researchers using a free online mapping tool.

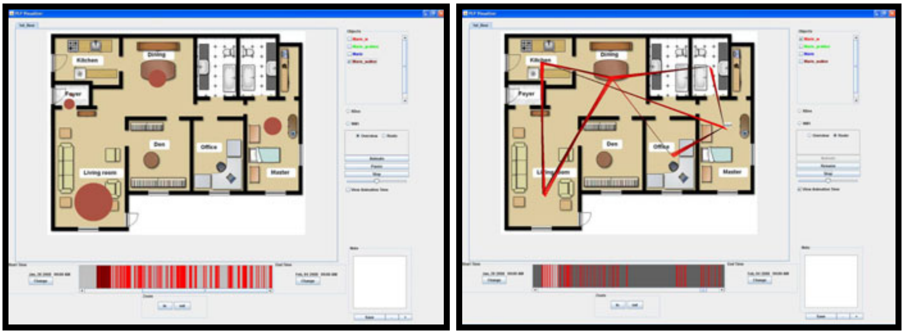

Fig. 3. Visualization of PowerLine Positioning data used during the interviews. **Left:** Size of red dot provides length of time tracked entities were at particular locations. Colored vertical bars represent movement of the corresponding entity. **Right:** Mobility traces or routes of the tracked objects and people. Black bounding bars on the timeline indicate how trail length shown on map. The routes are drawn as a line segment to show the origin and destination.

3.3 Study Details

The deployment study involved rehabilitation researchers studying the mobility patterns of four different households (see Table 2). The participants were recruited by the rehabilitation researchers and were selected through their patient pool of wheelchair users by sending out recruitment emails and letters. Each household was enrolled in the study for 6 weeks during which 7 interviews (3 current practice self-report and 4 prompted-recall) were administered on an approximately 1-week basis (see Table 3). Rehabilitation researchers also conducted interviews regarding the obtrusiveness and acceptance of the technology on the days of instrumentation installation and removal. The installation of PLP was carried out entirely by two rehabilitation researchers while we played only an observer role. The backgrounds of the researchers were in anthropology and design, and neither had previous experience with setting up or using location tracking systems. For each of the four deployments, a rehabilitation researcher installed PLP, and we also evaluated the installation and maintenance for each. We trained the two researchers prior to deployment, which involved a 30-minute tutorial and an installation example in a laboratory. During this tutorial, they were asked to install the system themselves under our supervision (setup and install the hardware for tracking 4 tags and calibrate the software). A PLP installation manual was also provided to the installers to read beforehand if they chose to do so. For the actual deployment, each of the two installers installed PLP in two homes. We timed how long each installation took and interviewed those conducting the installation to determine ease-of-use and problem spots during the installation.

For the study, we attached a location tag to each mobility device used and gave a tag to each member of the household. We built custom mounts that allow easy attachment to round surfaces, such as the frame of a wheelchair or a walker (see Figure 1). Individuals were asked to wear their tag around the neck on a lanyard. The batteries for each tracking tag were replaced or recharged during each weekly interview. However, we found that weekly recharging was unnecessary, because the tags ended up lasting over one month.

For the current practice self-report interviews, the researchers administered a Home Accessibility Survey [13], which is an interview process that captures the subject's knowledge, comfort, and satisfaction with their mobility aids and perceived environmental barriers to their mobility device usage during the past week. This tool is a hybrid survey the rehabilitation researchers created that synthesizes various well-known interview questions from the disability mobility community. Current research measures on environmental barriers in the home are limited to self-report and how barriers are subjectively experienced by the user. We maintained this process so that we could compare the self-report data with data gathered from the prompted semi-structured interviews based on the mobility pattern data provided by the tracking system. For the promoted-recall interviews, rehabilitation researchers reviewed the position traces using the visualization tool (captured with PowerLine Positioning, see Figure 3) with the participant from the previous day and "prompted" them with questions based on the mobility data. Because of the richer data, these interviews were typically limited to reviewing the participant's prior day. The interviews were scheduled such that different days of the week were gathered (*e.g.,* weekend vs. weekday). Table 3 shows the duration of the study and the interview schedule.

The aim was to compare the level of detail and quality of data researchers could obtain by using the sensed data as part of the interview process, in contrast to relying on self-report alone. For example, one metric of success was the determination of the number of environmental barriers to mobility for that person. Thus, we compared how many more barriers were found with the PLP-based interviews than self-report data to assess its effectiveness.

Table 2. Demographic information for each household of the wheelchair mobility participants

Household ID	Gender	Age	Profession	Mobility Aids Used	Years Using Chair	Home Size (ft^2/ m^2)	Number of Rooms in Home
1	M	38	IT Specialist	Powered wheelchair	30	1100/102	5
2	F	62	Consultant	Powered wheelchair, Walker, Grabber	26	1600/149	8
3	M	51	Public service business owner	Manual wheelchair, Manual sports wheelchair	28	1800/167	8
	F	48	Sales associate	N/A	N/A		
4	F	33	Product manager	Manual wheelchair, Walker	12	2400/223	10
	M	36	Engineer	N/A	N/A		

Other quantitative measures of activity gathered through the self-report questionnaire included metrics such as the length of time they spend out of the bed, the frequency that they move from one end of the home to the other, the percentage of the time participants spend using each mobility aid, and where they use the mobility aids. With the location data, we aimed to evaluate the accuracy of self-report responses using these objective measures. Finally, we interviewed the investigators conducting these studies to evaluate the ease-of-use of the pattern traces and their usefulness during the interview process.

A total of 6 different interviewers from the research team conducted the interviews with the four mobility participants (or households). For a given mobility participant, the interviewer that conducted the HAS-based interviews (current best practice) was different from the interviewer conducting the PLP-based interviews using the mobility traces. The reason for this was to ensure that the two interview processes did not bias each other. In order to address the issue of the differences between the two interviewers, we attempted to recruit interviewers that had similar experience levels both in conducting interviews and in the disability research community. In addition, we alternated the roles of the interviewer for each participant to counterbalance the interviews and varied when the non prompted-recall interview was administered during the 6-week period.

Table 3. Timeline of interviews conducted with members of each home during the course of the 6-week study. H = HAS-based interview, P = Prompted-recall, A = Interview on the acceptance and obtrusiveness of technology.

		Week of Study					
		1	**2**	**3**	**4**	**5**	**6**
Household	**H1**	H,A	P	H,P	P	H	P,A
	H2	P,A	H,P	P	H	P	H,A
	H3	H,A	P	H,P	P	H	P,A
	H4	P,A	H	P	H,P	P	H,A

One important consideration was the potential concern participants may have regarding privacy, especially in the home where it is a very personal space. Although the location data did not produce the same level of detail as video recordings, it was still important to be sensitive to what the participants were willing to reveal. We addressed this concern in two ways. The first was by giving the participants the ability to stop collecting location data at any moment by pressing the button on their location tag. Pressing the button again would restart data collection. The second was by creating a trusting relationship with the interviewer during the data review and interview process. This was accomplished by initially sharing with them their mobility trace data. Trust was also established by making participants a partner in the research process and having them drive the interview by asking them to walk through their day with the interviewer. The interviewer in turn asked more specific questions based on what the participant chose to reveal and what they saw from the mobility trace. In addition, the interviewers were instructed to be sensitive to questions and/or issues participants might find invasive and uncomfortable.

4 Results

In this section, we describe the findings from the study we conducted. We first describe the usability of the PowerLine Positioning system by the end-users. We then outline the results of the study on the usefulness of the PLP system in achieving the goals of the researchers, as compared to traditional data gathering means.

4.1 Usability of the PLP Tracking System by Non-experts

We assessed both the performance of the PowerLine Positioning system in these deployments as well as the ease of deployment by observing the installation procedure and interviewing the installers. Overall, both systems were successfully deployed in all four homes. We merely observed the installation procedure and did not directly assist them in the installation in any way. When the tracking system reported at least 95% accuracy from 20 random locations throughout the home, the installation process was concluded. PLP took an average about 32 minutes to install (H1 = 25, H2 = 29, H3 = 41, H4 = 33), which is encouraging considering the overhead other approaches would have had if there was additional hardware that needed to be installed in the home. This time includes the planning, physical installation, calibration, and testing of the system. Most of the time was attributed to the site survey or calibration. Homes 1 and 2 were installed by one person and Homes 3 and 4 by a second.

The installers appreciated the minimal amount of devices that needed to be deployed in the home since PLP required very little hardware that actually needed to be physically installed. During the study, the installers conducted performance tests when meeting with the participants for their interviews to determine whether recalibration was necessary. A recalibration was determined to be necessary if more than 10% of the tests failed to produce a correct position reading. Only one installer reported having to conduct another site survey (Home 1) in the middle of the study. The reason was during the interview process, she noticed two regions of the home were not being tracked, thus she needed to update the signal map with a denser survey. Home 1 required part of the living room and master bedroom to be resurveyed during the second week. The other 3 homes required no additional surveys.

To assess the researcher's proper maintenance and overall installation of PLP, we evaluated the overall accuracy of the system for the entire duration of the study. For this, we had the wheelchair users manually provide labeled ground truth data throughout the day by simply pressing a button on a wireless module placed at fixed location in the house (10 per home). We typically put these near frequented areas, such as the dining room table, office or computer desk, night stand, and coffee table. We asked them to simply press the button when they noticed it and had the opportunity. Since we knew the exact position of those buttons, we were able assess the performance of PLP (the classification accuracy for that sub-room) at those known locations. PLP correctly indicated the person's location (within a 2 meter circle) at the time the button was pressed. Over 97% (507 out of 523) of the button presses were identified correctly with PLP across all homes.

4.2 Utility of Indoor Location Tracking System

The four households that were enrolled in the study each had researchers conduct four PLP-based prompted-recall interviews and three prior practice self-report interviews. The prompted-recall interview consisted of a 1-hour meeting with each participant and a walkthrough of his or her previous day (two days if time allowed) using the PLP tracking data. The participants were allowed to dictate what was shown on the tracking interface to talk about any detail they chose, but the interviewers were instructed to follow the interview guide as much as possible. The tracking data was used to help prompt the participants about interesting situations that might have occurred with their mobility aid. In addition, the data was also used to encourage the participants to reflect on their usage of various mobility aids. The non-prompted interview was conducted using an adapted version of the rehabilitation researcher's current practice surveys (the HAS). These interviews also lasted about one hour, and the interviewers were asked to follow the interview guide. The interview was very similar to the prompted-recall interviews except that the tracking data was not available. The interviewers asked each participant to reflect on their previous two days during their interview, although they were not limited to that.

Each interview was audio-recorded, and the PLP tracking software logged when various features of the software were used. The interviewers also took notes during the interview. After the completion of the study, the interviews were transcribed for further analysis. We also analyzed the PLP tracking data to extract quantitative measures, such as time spent in each room, percentage of time spent in each room throughout the day, *etc.*, to compare against the participants' recall of that information.

The interview notes and transcripts were used to extract relevant statements and discussion points generated during the interviews, which in turn were used to produce themes that emerged from all the interviews relating to mobility problems. Two rehabilitation researchers independently categorized the statements in the transcripts and notes to determine the themes. The two coders produced a total of 19 themes, eight of which were common across the two coders. Thus, 11 unique themes were included after discussion and resolving overlaps between the different themes. A third independent coder re-categorized the statements using these 11 themes and we calculated inter-rater reliability using the categorizations from the three coders using two measures: observed agreement and Cohen's Kappa (see Table 4).

Table 4. Inter-rater reliability for each theme: (1) Observed agreement, measured by agreements divided by total number of statements coded and (2) Cohen's Kappa. Measures are between 0 and 1, with 1 indicating perfect agreement between coders.

Cluster	1	2	3	4	5	6	7	8	9	10	11
Observed Agreement	.96	1	.96	.98	.95	.95	1	.96	1	1	.95
Cohen's Kappa (k)	.92	.96	.83	.95	.79	.80	.96	.79	.94	.96	.80

The following themes emerged after the data analysis:

1. *Mechanical problems*: physical problems with the mobility aid itself, such as a broken wheel, faulty brake, *etc.*
2. *Mobility aid form factor or design problems*: the aid does not serve its purpose or intended function
3. *Doorway, hallway, or threshold barriers*: problem in locomotion in the home because of environmental barriers
4. *Reach problems*: items of interest being out of reach
5. *Level access problems*: includes accessing items that are hard to maneuver to, which can result from not being able to rotate the wheelchair, cluttered room, *etc.*
6. *Exercising*: tasks relating to regaining mobility strength, such as home physical therapy
7. *Safety concerns*: afraid of falling or not being confident enough to go to a particular region of the house or perform a particular task
8. *Person assistance*: task requires assistance from an able-bodied individual
9. *Floor conditions*: the characteristics of the floor contribute to mobility concerns, such as using a walker on carpet or slippery floors
10. *Self-conscious*: reluctant to show they used a mobility aid
11. *Medical procedures*: recent medical procedures or changes in health affecting overall mobility

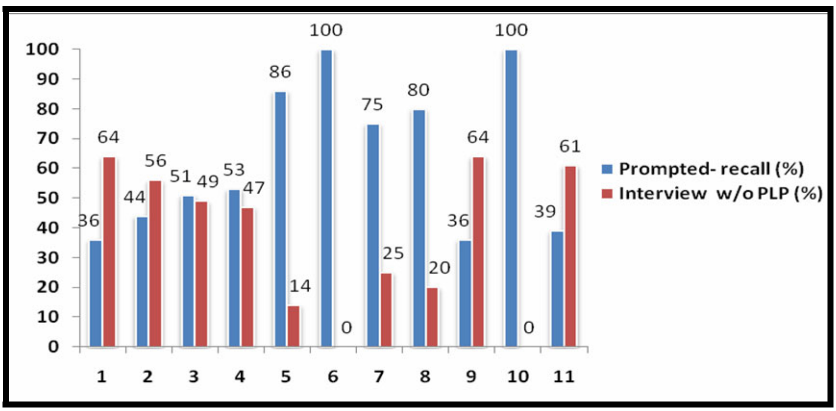

Fig. 4. Percentage of discussion points resulting from prompted-recall and non-promoted-recall interviews for each theme

Both interview methods (prompted-recall and non-prompted-recall) produced responses in 9 of the 11 themes (see Figure 4). However, two themes (Theme 6 and 10) only emerged from the prompted-recall data. In addition, a higher percentage of discussion points relating to Themes 5, 7, and 8 were produced from the prompted-recall data. Thus, there were some clear advantages to having the tracking data available during the interview process. For example, in the case of exercising, participants often talked about using a particular mobility aid for the purposes of strengthening their legs or muscles. However, it was not until participants actually saw their activity data did they recall this detail. Similarly, seeing their tracking data prompted discussions about other individuals having to help with a particular task. Participants also discussed situations where they did not take a particular route in their home or use a particular aid in certain parts of the home because they were afraid of falling (Theme 7). Another interesting result from the prompted-recall data was that participants not only talked about physical barriers in their environment, but also social pressures (Theme 10). For example, there was one instance where the data showed that a participant started to use a different aid that was not normally used. When she saw this, she stated that she did not want to her grandchildren to see her in a wheelchair, so she made a conscious effort to use the walker during their visit. Another participant reported using a manual wheelchair when his friend would come over, who also used a manual wheelchair.

In addition to counting the number of themes that emerged with each approach, a second coding scheme was introduced to rate the quality of the coded discussion points as determined by the needs of the rehabilitation researchers. Two coders rated each of the 113 statements or discussion points around that statement with a rating of 1 or 2. A value of 1 referred to a statement that was mentioned, but the participant did not engage in supporting details or examples during that discussion, while a value of 2 was given to a discussion point that involved the participant giving specific details. We also calculated a percentage agreement and Cohen's Kappa for the rating scheme for the 113 statements, which resulted in an observed agreement of .96 and a Cohen's Kappa of .88. The aim of this coding scheme was to determine the number of rich discussion points that resulted from using the prompted-recall method compared to the standard interview. In general, we saw a higher quality level of statements gathered using the prompted-recall ($\sigma = 1.85$) than we did with the interviews alone ($\sigma = 1.4$), which a two-tailed T-Test showed to be significant ($p < 0.01$). The higher rating of the prompted-recall interviews could be a result of the participants having something to explain or narrate when using the tracking data. In the self-report data, it was often the case that participants rarely remembered details around their actions during the prior days. One participant referred to the tracking data as, "the next best thing to a video camera without a camera," alluding to the usefulness of the context it offered during the interviews.

5 Discussion

The results of this study show that the use of an indoor location tracking system is feasible and acceptable for study participants and helps to meet the needs of non-experts. The study enabled us to uncover interesting results and implications for designers of other sensing systems, as well as those conducting studies of sensing systems in the home. Here we discuss the value of location-based sensing and the future avenues that can be explored, the implications we found for conducting these types of studies, and describe the limitations to this study.

5.1 Value of Sensing for Non-experts

One of the main contributions of this study was to show that location-based systems can be both usable and useful to non-experts. We believe this opens a number of doors for researchers and helps to validate much of the location-based technology research. Beyond the domain of sensing the location of wheelchair users, we believe there are other application areas that are made possible by this line of work. For example, research applications in eldercare [17] have made use of location data as a peace-of-mind application. These applications could be simplified and are feasible for end-users to deploy in their homes with the PowerLine Positioning system. Another potential application area is for architects who wish to study the use of built environments. Occupants could wear tags to allow designers to see which parts of homes are used and which are not to help determine how spaces could be redesigned or renovated to better use the space. Finally, this type of technology could benefit families of children with special needs, who could consider using indoor tracking systems to identify which rooms children are in when they exhibit different behaviors, which could help determine the causes of the behaviors and better address their needs.

5.2 Implications and Considerations

As a result of this work, we determined a number of implications for designers of future sensing systems for the installation and use by non-expert users and researchers who may want to use these techniques to study human behavior.

- *Visualization of Data* – One of the most important aspects of a sensing system designed for non-experts is an effective means of visualizing the data in a way that is relevant and easy to understand. The tools we built for visualization were rudimentary, and while they allowed the rehabilitation researchers to do the job, more design consideration could make the tools easier to use and understand. Understandable visualization of location data remains an area for exploration.
- *Initial Calibration* – During the site survey, the installers did not get feedback about the performance of their system until the very end of the calibration procedure. Providing feedback about the accuracy should be shown as they did the survey so they know if they need to do a denser survey to achieve the desired level of accuracy. This could help reduce installation time even further.
- *Interview Timing*– One thing rehabilitation researchers noticed about interviews with the prompted-recall data was that participants often became fascinated with viewing their own location traces, especially the first time they saw it. This may add to the length of the interview time during the first visit, since the participant may want to explore their own data. We do not think this is a negative aspect, but should be considered when scheduling prompted-recall interviews.
- *Re-calibration* – In the deployment of PLP for the non-experts, we instructed the installers to place a location tag in a fixed location that would serve as a means for measuring when the system would need to be calibrated. This manual checking worked in our study, but would be helpful if it sent a notification to the installers that a recalibration was necessary. This is especially important for longer-term installations.
- *Data Transparency to the Participants and Privacy* – Participants in the wheelchair mobility study appreciated that they were able to view their own data and see what the researchers could see about their movement patterns. This helped them feel more comfortable and reduce some of the concerns over privacy. We also provided a means for the participants to delete data after it was recorded if they chose, which gave them control over what was recorded. Although this feature was infrequently used, participants expressed comfort in its existence and that the PLP data was much less invasive than cameras.

- *Simplified Data Views* – At some times during the prompted interviews, the data became too overwhelming and confusing for the study participants. Providing ways for researchers to hide some of the complexity at times to make it more understandable to the participants may help make some of the interviews go more smoothly. However, viewing the full data set should always be an option to preserve the data transparency guideline provided above.
- *The Importance of Unobtrusiveness in Domestic Spaces* – Echoing some of the previous work in this space, the participants in the wheelchair mobility study expressed an appreciation for how minimally intrusive the PowerLine Positioning system was to the aesthetics of their home. Most participants agreed that this type of system could remain in their home indefinitely due to its unobtrusiveness.

5.3 Study and Technology Limitations

Although the results of this study were promising in showing the value of sensing and lead to a number of design implications, there were several limitations that we would like to discuss. First, the sample size studied was fairly small, and we were limited to only one group of rehabilitation researchers, who conducted pilot deployments in four households. Thus, the issue of scaling deployments to a large size is still an opportunity to explore. We believe that scaling this study to a larger set of users will be possible, since we found that non-experts were able to install the location-tracking system with minimal training and in about 30 minutes. They were also able to maintain it with very little external technical assistance. Although the non-experts only required minimal training, we would still like to get to the point where the sensing technology could be deployed without professional or expert help, such as by creating a comprehensive installation guide and demonstration video.

With regard to the technology, there were a few problems we encountered that could be improved. For example, positioning tags were still large and did not attach well to the smaller mobility aids, such as canes and grabbers. Thus, some data collected by the system may not be entirely accurate if location tags slip off. In addition, we believe that because PLP is nearly invisible, the non-experts had some difficulty establishing a good mental model of it. In the case of House 1, if they did not feel they were getting a good signal, they would move the plug-in modules to other plugs. Thus, we could provide a better sense of how the system works to end-users. Overall, compliance was still very high across all four participants and they all indicated no major challenges with the tags attached to their primary mobility aids.

6 Conclusion

In this paper, we discussed the usability and utility of a low-cost indoor location tracking system in the context of being used by non-technology expert rehabilitation researchers to study the mobility patterns of wheelchair users in their homes. We have encouraging results that such indoor location tracking systems are not only usable by non-experts, but they can also be useful in allowing non-experts to achieve their own research goals of finding more barriers to access and achieving higher quality, more detailed responses from participants. We hope to entice more work in applying ubiquitous computing technology and building tools to help researchers in other communities wanting to collect objective data about human activity and behavior. In addition, focusing on the non-expert deployability of these sensing technologies is going to be critical for attaining the scale for ubiquitous and pervasive computing we hope to achieve in the future.

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