Design and Evaluation of a Power Wheelchair-Based Self-tracking System to Prevent Pressure Ulcers

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Self-tracking technologies empower people to build self-knowledge and insights across many domains and individual user contexts. However, individuals with severe motor disabilities are largely excluded from personal informatics systems. To bridge this gap, we designed and developed a first-of-a-kind power wheelchair (PWC) based multi-modal self-tracking system to support individuals with a recent spinal cord injury to track their performance pressure reliefs—a very frequent self-care activity to prevent pressure ulcers. We deployed this system with nine in-patient participants of a rehabilitation hospital and qualitatively evaluated the feasibility through their interactions with audio, visual, and haptic reminder modalities through observations and interviews. Our deployment and evaluation demonstrate the feasibility of creating chairable self-tracking systems to help facilitate independence and self-awareness of their self-care activity and the potential for personal informatics systems to be effectively designed so that they are useful for this population.

Additional Key Words and Phrases: Spinal Cord Injury, Pressure Relief, Self-Care, Self-tracking Technologies

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1 INTRODUCTION

Self-tracking systems, such as Fitbits or smartwatches, are well-explored in the HCI research, and are popular pervasive consumer products. However, self-tracking technologies for underrepresented people, such as individuals with severe motor disabilities who depend on power wheelchairs (PWC) for mobility, remain underexplored within HCI and ubiquitous computing fields [54]. While some studies have examined the needs of manual wheelchair users [12, 14], the unique requirements of PWC users are broadly understudied [43, 53, 55]. Motor disabilities may arise from various causes, with spinal cord injuries (SCIs) being among the most common. SCIs often result from sudden traumatic incidents, such as motor vehicle accidents, violence, falls, or sports injuries, leading to either paraplegia (paralysis of the legs) or tetraplegia (paralysis of both arms and legs). Severe SCIs

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bring significant life changes, functional limitations, and disabilities, often requiring the use of power-operated wheelchairs (PWCs). Regardless of the injury level, individuals with spinal cord injuries (SCIs) must adhere to various lifelong self-care activities, which can be complex and often necessitate assistance from caregivers [8, 15]. These self-care activities range from weekly (e.g., exercise and physical therapy) to daily activities (e.g., catheterizing the bladder [1, 27, 44], bowel management [1, 27]), and hourly (e.g., respiratory self-care [27, 75], pain management [11, 27], and pressure relief (PR) [3, 36, 68]). Among these, PRs are most frequent, with clinical guidelines suggesting they should be performed every 20 minutes, which is approximately 30 to 50 times a day. PR involves redistributing or repositioning sitting pressure and tissue load to prevent pressure ulcers (PUs) [2, 74], which are a severe and life-threatening complication for individuals with SCIs [38]. PWC users use a tilt function of the chair to tilt backward, and need to be in the tilting position for two minutes. Despite the importance of performing regular PRs to prevent PUs, PR adherence is often inadequate [2, 72, 77], because PR is highly frequent activity and keeping track of this high frequency activity is challenging for people with no/less upper body functionality. Currently, PWC users with a severe SCI often lose track of PRs [53].

Several clinical research looked into different assistive technologies to reduce the risk of pressure ulcers (PUs) in individuals with a severe SCI, who use a PWC. Studies have explored methods such as assistive repositioning mechanisms [73, 74, 76], web-based monitoring [9], interface pressure mapping (IPM) for wheelchair seats [78, 81], educational materials [6, 60], electrical stimulation [5, 34], and telemedicine programs [61].However, none of these interventions were consistently successful in preventing PUs in this population. For instance, interventions, such as electrical stimulation to improve tissue tolerance, showed benefits but were unsustainable after discontinuation. Researchers also evaluated phone-based PR reminder systems [29], which initially improved adherence; however, adherence decreased once the reminders ceased. Further, for people using PWCs, phone-based reminders may be less effective due to limited access, particularly among those with reduced upper-body mobility [53, 57].

Recent HCI research has examined contextual challenges of performing such high-frequency self-care activities for people with a severe SCI, finding that self-tracking technologies could help support this population [8, 53]; however, designing effective interaction mechanism with those technologies is challenging. Carrington et al. [13] described that because of their limited arm and finger strength, PWC users often found devices difficult to reach and frequently need assistance from a caregiver for stowing, retrieving, or repositioning a device. Additionally, HCI literature demonstrated the multi-faceted challenges this population face due to different levels of functional abilities, comorbidities, or other disabilities soon after sustaining the injury [30, 40]. Taken together, recent work points to a clear opportunity to leverage self-tracking to better support people with SCIs, particularly in the domain of frequent self-care activities.

In this study, we designed and deployed "Tilt Tracker"—a first-of-its-kind PWC mounted self-tracking system—and tested the feasibility of such chairable self-tracking system to help individuals with a severe SCI improve their PR adherence in a rehabilitation hospital setting. We followed an iterative design process, rooted in relevant HCI literature and insights from 10 rehabilitation clinicians, including occupations and physical therapists, patient educations and a physician, who have many years of experience working with this population. Tilt Tracker automatically collects users' PR behavior and triggers reminder and feedback notifications through different modalities (e.g., haptic, audio, and visual). Data collection and notification delivery are completely integrated with the PWC—following Carrington et al' [13]'s chairable concept. Finally, we deployed and evaluated the system with nine inpatient participants in the rehabilitation hospital. We deployed Tilt Tracker for at least five days to nine participants' wheelchairs and observed their interaction using the system with different notification modalities and in different contexts; we also conducted multiple follow-up interviews with each participant to understand their experiences with Tilt Tracker.

Through our observation and interviews, we surfaced first-hand insights of our participants regarding the PWC-integrated self-tracking system. Results suggest that the reminders and notifications helped them to perform PRs independently and to be more mindful and aware of their PR behavior. Further, we gained additional insights regarding the challenges and opportunities to improve the future design of chairable systems, which has implications for designing for other PWC related activities.

Our findings provide the following contributions to ubiquitous computing, self-tracking, and accessibility literature for people who sustain severe spinal cord injuries and lose many of their physical abilities:

(1) We designed and developed a PWC-mounted self-tracking device, and evaluated the feasibility of such system to improve adherence to a high-frequency self-care activity.
(2) We examined the feasibility and effectiveness of different reminder and notification modalities for a chairable-system in a rehabilitation hospital.
(3) We demonstrated rigorous design implications for future chairable self-tracking systems and identify future opportunities to facilitate reflection on personal data through data exploration collaborating with stakeholders.

This work is an attempt to designing and developing a PWC-mounted self-tracking system incorporating the diverse needs and constraints of a highly underrepresented population—exploring different interactions with the system, and contextual issues associated with those interactions.

2 BACKGROUND AND RELATED WORK

In this section, we first establish the importance of performing PRs to prevent PUs, and the current challenges of PR adherence. Then, we present prior research efforts to design technology for improving PR adherence to contextualize our research goal within the design space of chairables and the self-tracking needs.

2.1 Preventing Pressure Ulcers: A Deadly Consequences of Spinal Cord Injury

Spinal cord injury (SCI) is a common traumatic event causing motor disability that happens suddenly due to motor vehicle accidents, acts of violence, falls, and sports and can cause paralysis of only legs (paraplegia) or both legs and arms (tetraplegia). Individuals who sustain a severe SCI undergo dramatic changes in their lives and develop a range of impairments and disabilities, often including limited motor control and sensation in their upper body. In addition, these functional disabilities often necessitate the use of power-operated wheelchairs (PWC) [13, 67]. Further, irrespective of the injury level, individuals need to follow several lifelong self-care activities [8]. In many cases these self-care activities are complex to perform [15].

Among all the post-SCI consequences, pressure ulcers (PUs) are the most commonly acquired deadly complications [16, 23, 71] resulting from localized tissue damage due to prolonged interface pressure while sitting [16, 23]. Approximately 24% of individuals develop PUs within the first year after an SCI, and 80% of those with an SCI experience at least one PU in their lifetime [2, 4, 58, 66] due to their life-long wheelchair usage and sitting in the same chair for long periods of time [2]. These serious wounds pose risks of infection [10], complications [65], and negatively impact quality of life [28].

One way to prevent pressure ulcers is regularly performing pressure reliefs. Pressure Relief (PR)—redistributing or repositioning the sitting pressure and tissue load [3, 36, 68]—are recommended to be performed three times an hour or approximately 30 to 50 times a day to avoid pressure ulcers.

Individuals perform PRs by changing their sitting position manually if they are able—or otherwise with the tilt function of their PWC—to redistribute the tissue load. PR is crucial to prevent pressure ulcers (PUs) [2, 74]—one of the most dangerous complications that individuals with an SCI can have [38]—where following both frequency and duration is important. Prior research found that PR adherence is typically inadequate [2, 72, 77]. Furthermore, PR performance is usually self-reported both to researchers and clinicians, which likely means that recall bias and response bias leads to unreliability in collected data [4, 37]. Thus, regularly performing PRs is very important, but adherence to these guidelines is difficult to measure and appears to be low.

2.2 Challenges to Routinize and Improve PR Adherence among Individuals with an SCI

Several clinical researchers developed and implemented assistive technologies to reduce the risk of PUs among individuals with SCIs. For instance, researchers looked at ways to reposition wheelchair users using assistive mechanisms to prevent PUs [73, 74, 76]. Stinson et al. [74] used an interface pressure mapping system for the wheelchair seat to record the interface pressure and examined an application of an ergonomically adapted computer-based activity to reduce interface pressure. The study found that those seated movements were not effective in reducing the interface pressures; thus non-effective to prevent pressure ulcers. Additionally, a variety of prevention tools have also been studied in clinical research on PU prevention, including educational materials [6, 60], interface pressure mapping (IPM) [78, 81], electrical stimulation for improvements in tissue tolerance [5, 34], and tele-medicine programs [61]. For instance, Bogie et al. [5] used the combination of implanted percutaneous electrodes and an external stimulator in high risk areas to increase muscle thickness, blood flow and pressure tolerance to reduce regional interface pressures. However, the tissue health deteriorated when the stimulation was discontinued [5]. Thus, none of these intervention resulted sustainable solution for PU prevention. Researchers also explored ways to improve the PR awareness using a phone-based PR reminder system [29]. The reminder system was initially successful for improving the PR adherence; however, it decreased again when the reminder system was removed. Further, a phone-based reminder system may not be successful to improve the PR adherence, particularly for people who use a PWC—with less/no upper-body functionality—due to their limited phone access [53].

Recent HCI research has explored self-care behaviors and related assistive technologies for individuals with an SCI [8, 53], and found that interaction with assistive technologies is limited and challenging for people with severe disabilities [8, 13, 41]. Although Motahar et al. [53] provided guidelines for improving PR adherence, they did not examine or evaluate them with a real-time technological solution. In addition, how these individuals behave when they begin adopting PR behavior soon after sustaining the injury remains unexplored. Prior work has found that interactions with assistive technologies while still in the rehabilitation hospital are challenging for this population [55], Therefore, which a technology-based solution to facilitate adoption of regular PR behaviors at the time when are first learning them, there are also many challenges or opportunities for pitfalls when deploying technology in a rehabilitation hospital setting.

In summary, although prior HCI research has established a solid foundation for understanding how we might improve PR adherence, a self-tracking system to facilitate this goal has yet to be explored. This work takes a step towards addressing that challenge by examining the feasibility of different reminder modes (vibration, LED light, and audio notification) in different contexts for individuals who use a PWC.

2.3 Feedback, Reflection, and Sense Making in Self-tracking Systems

Self-tracking technologies have enabled individuals to gain self-knowledge and insights into diverse fields, spanning physical activity [19, 31]), diet [25, 46], sleep [17, 82], mental health [56], personal finances [33], and alcohol consumption [50]. Research also explored self-tracking practices and self-care technologies for individuals with various chronic conditions [35, 49, 70]. These projects showed that engaging in self-tracking [48] can offer valuable support for users' well-being as these technologies allow users to collect and monitor their personal data. Additionally, reflecting, or getting feedback on the collected data can help facilitate self-awareness, as well as changing behavior.

In several research on self-tracking, reflection and feedback have been emphasized as essential components to facilitate self-knowledge and behavior change. Choe et al. [18]'s "Self-monitoring Model" emphasized that reflection occurs during the self-monitoring process while collecting the data and receiving feedback (e.g., reminders and other notifications). Similarly, Whooley et al. [79] explained that personal data tracking and behavior changes occur simultaneously through reflection, corroborating Schön's concept of reflection-in-action [69]. Thus, reflection and feedback are critical components for designing effective self-tracking systems to promote behavior changes. Unfortunately, while collecting self-tracked data and making use of that data for self-awareness or behavior change have both been shown to provide value in self-tracking systems, Kabir and Wiese [32] have detailed a broad set of design considerations that are barriers to and facilitators of collecting and using personal data in a personal informatics system.

In this work, we explore the feasibility of incorporating multi-modal feedback into PWC-based self-tracking systems (e.g., reminders and notifications) for people with severe motor disabilities, in order to improve adherence to self-care activities.

3 DESIGN AND DEVELOPMENT OF TILT TRACKER

The work of this paper results from a larger ongoing project that focuses on designing assistive technology with and for people who sustained severe SCIs and use PWCs. As a part of that project, we designed Tilt Tracker, and the design is informed by prior literature on self-tracking and accessibility, and insights provided by rehabilitation clinicians and therapists.We conducted semi-structured interviews with ten clinicians (inpatient and outpatient) who work with the target population. In this section, we first describe the interview protocols with the clinicians, report the findings from the interviews, then present these insights in the form of design goals incorporating prior research and the implementation details of the resulting system.

3.1 Author's Positionality Statement

Authors with varying levels of HCI research and rehabilitation expertise make up our team: a PhD student, a undergraduate student, a software engineer, a mechanical engineer, an occupational therapist, a medical specialist and a senior researcher who is a faculty member. Two of the authors have been involved in various levels of accessibility research with people with severe motor disabilities, including teaching accessibility and mentoring accessibility-related projects. One of the authors is also an expert in research with self-tracking technology and has been involved in personal informatics for several years. Both of the software engineer and the mechanical engineer have extended experience in working with rehabilitation technologies and PWCs. All these experiences likely shape our design, development and evaluation process in this study.

3.2 Semi-structured Interviews with the Clinicians

We conducted semi-structured interviews with 10 in-patient and out-patient clinicians (see Table 1) to explore their experiences with recently injured individuals regarding their self-care practices and relevant assitive technology usage during the rehabilitation period. We asked a total of nine questions to the clinicians, where only two specifically addressing potential technological interventions to improve PR adherence of individuals who are newly injured with a spinal cord injury and need to use a power wheelchair. The rest of the questions are targeted for different research questions; thus, we are not reporting them in this paper. Regarding PR adherence, all clinicians shared that training newly injured patients for pressure relief is challenging, particularly reminding them to perform this high frequency and critical self-care activity. Follow-up questions included how technology can be designed to improve the adherence. Clinician participants recalled and described examples of their training process and the possible technology solutions to overcome the challenges. Their extensive experience with patients with varying levels of SCI offered valuable insights into the potential design of technological solutions to enhance PR adherence. We conducted interviews in-person or over Zoom[83] video calls according to their preferences. We recorded the interviews with participants' consent.

3.2.1 Analysis. We transcribed interviews using Otter.ai [59], and employed reflexive thematic analysis [7] to analyze transcribed interview data. One author coded the data and regularly discussed the codes with the other authors. For the specific questions related to the pressure relief adherence challenges and possible technology solutions, our analysis process resulted in a total of 356 codes, including “mostly forget PRs”, “people loose track of time”, “alarms would be good for PRs”, and “technology should be unobtrusive”. After finishing the coding, we transferred the codes into a Miro [51] board for creating the affinity diagram all together. After several rounds of iteration, we grouped the codes into two main themes for the specific research question of this paper: *challenges to learn PR*, and *technological implications to improve PR adherence.*

Table 1. Details expertise of our ten clinician participants. We spoke with two OTs, five PTs, two patient educators, and a physician. * Inpatient: clinicians who see admitted patients in the rehabilitation hospital; outpatient: clinicians who treat patients who are discharged from hospital and stay at their home/assisted living facility

Clinician	Specialization	Stage of rehabilitation (inpatient or outpatient)	Years of experience working with people with severe SCI during rehabilitation
C1	Occupational Therapist	Inpatient	5 years
C2	Occupational Therapist	Inpatient	Three months
C3	Physician	Inpatient	22 years
C4	Patient educator	Inpatient	16 years
C5	Patient educator	Inpatient	9 years
C6	Physical Therapist	Outpatient	28 years
C7	Physical Therapist	Outpatient	13 years
C8	Physical Therapist	Inpatient	9 years
C9	Physical Therapist	Inpatient	11 years
C10	Physical Therapist	Outpatient	9 years

3.2.2 Recruitment Limitations in the Design Stage. We acknowledge the importance of participation of individuals with a recent SCI in the formative stages. Despite significant efforts to recruit these individuals, we encountered challenges to recruit participants from this vulnerable population pool for the initial stage of design of the system. We refer here to the extensively documented challenges associated with recruiting participants who have severe or multiple disabilities [30, 47, 53, 55]. When these efforts proved unsuccessful, we redirected our focus to the perspectives of their closest allies—rehabilitation hospital clinicians—who play a crucial role in training these individuals on PRs during post-injury rehabilitation [55]. Furthermore, we integrated these insights with prior literature to establish our design goals, drawing on research extensively engaging individuals who use power wheelchairs [43] or have severe SCIs [52, 53].

3.3 Insights from the Clinicians

3.3.1 Challenges to Learn PR. Both inpatient and outpatient clinicians observed that individuals frequently forget to perform PRs, often relying on their memory, which is not always sufficient. Many feel overwhelmed by the required frequency of PRs, and even when they remember, they may avoid performing them due to discomfort or fear, as tilting backward can be intimidating for some. Additionally, performing PRs independently can be challenging, as patients in rehabilitation often lack the capability to tilt on their own, resulting in extended periods spent without doing a PR. Furthermore, they rely on their caregivers to charge their power wheelchairs, which is essential for the tilt function to operate effectively during PRs. Cognitive barriers further impede adherence to PR routines for some. Further, some individuals do not adhere to PR guidelines or recognize their importance until they experience a pressure ulcer.

3.3.2 Technological Implications to Improve PR Adherence. Our interviews with clinicians provided crucial design guidelines for developing technology to enhance PR adherence among individuals during rehabilitation.

Form Factors: All clinician participants emphasized that PR reminders would be highly beneficial for newly injured individuals in rehabilitation settings to improve their PR adherence. They also mentioned that the number of PRs performed should be automatically recorded to reduce the burden on newly injured users and increasing awareness of consistent adherence. Self-reported PR data may not be reliable, as many individuals are on medications that can impact their cognitive awareness. Additionally, it is difficult for the newly injured patients in the rehabilitation hospital to keep track of this frequent activity (2 to 3 PRs per hour), and they rely on their caregivers and clinicians to help them track PRs. Consequently, an automated recording system would enhance accuracy and support their adherence without relying on memory or other people.

Clinicians also suggested that reminder technology should be integrated directly into the wheelchair for convenience. Reminders delivered via phone or wearable devices may be less practical due to the variability in these individuals' motor impairments, which may require assistance from others. Instead, clinicians suggested that, depending on the circumstances, haptic, visual, or audio notifications could all be effective, allowing individuals to engage in PR independently without requiring support from others. The positioning of the vibration reminder is particularly important for users with no, or low upper-body sensation. According to the clinicians, positioning the vibration reminder around the headrest area would be the most universally detectable by users, even with high level spinal cord injuries.

Frequency of Reminders: Clinicians also noted that reminder frequency should be minimized, with notifications delivered only when the user forgets or fails to perform the required PR. They explained that constant notifications for each PR will have a high likelihood of being ignored by users, potentially diminishing the reminders' effectiveness over time. By limiting the number of notifications, the reminders can be more effective, reduce user fatigue, and improve long-term adherence to PR routines. Several clinicians suggested that just-in-time reminders will help individuals to routinize and track their PR behaviors. Although clinicians sometimes suggest that patients should use traditional timers or phone-based recurrent alarms, these systems easily get out of sync with actual PR performance and, therefore, can become unreliable.

Interaction with Reminders: All clinician participants emphasized that wheelchair-integrated reminders must be natural, private, intuitive, and context-aware to effectively capture the user's attention. For instance, reminders should be discreet, ensuring they do not disturb or distract other people in the surrounding environment. Additionally, the interaction design should be optimized to accommodate the user's specific level of injury. Thus, reminders should be subtle yet perceptible, enabling individuals to respond independently and fostering adherence without impacting their surroundings.

3.4 Design Rationale of "Tilt Tracker"

We gathered insights from clinicians on the design of technology to enhance PR adherence among power wheelchair users. These insights were integrated with findings from prior research, and we present our resulting design goals for "Tilt Tracker" below.

3.4.1 Design Goal 1: Automated Collection of PR Data. Tracking and collecting PR data is crucial to enhancing PWC users' compliance with PR guidelines as well as helping stakeholders (e.g., clinicians, caregivers) monitor the patient's progress. However, obtaining this enormous amount of data via self-reporting is cumbersome and inaccurate. Although prior literature suggested that the formulation and execution of self-care routines can be effectively supported through semi-automated tracking [8], according to our clinician participants, PR data should be collected automatically, which is consistent with recommendations in the literature [18, 32]. Clinicians also reported that manually tracking of PR data can be subject to underreporting due to recall bias and response bias [4, 37]. Therefore, there is a clear need for an automated sensor-based PR tracking system.

3.4.2 Design Goal 2: Chairable Design Instead of Phone-based Design. According to prior literature, phones are not easily accessible for people with upper body impairment unless they are mounted directly on the PWC [13, 41]. Additionally, frequent mobile notifications will be burdensome and thus will be ignored [32, 80]. By being mounted directly on the PWC, a "chairable" approach that does not depend on a smartphone for tracking or feedback can address these issues with smartphone-based approaches.

3.4.3 Design Goal 3: Timed reminders. Clinicians recommended that the frequency of reminders be kept to a minimum to avoid overwhelming the user. A well-calibrated just-in-time PR reminder, could be made to only be triggered if PR is not performed on time and if the wheelchair is occupied, reducing the overall number of incorrect and unnecessary notifications [53].

3.4.4 Design Goal 4: Flexible Reminder Modalities. Prior literature identified that PWC users want to be reminded to do their PRs using different modalities; to effectively engage users, reminder notifications need to be natural, private, and appropriate for the situation. Additionally, clinician participants suggested that reminder interactions should be tailored according to the users' level of injury [41, 53, 57, 80]. Thus, different PWC-integrated modalities for PR reminders can be convenient and can facilitate users' needs [41]. Further, clinicians' suggestion on haptic, visual, or audio notifications and considerations of the positioning of the vibration reminder for users with severe SCI was not mentioned in previous work, which suggested vibration on the armrest [53].

3.4.5 Design Goal 5: Flexibility in Usage. According our clinician participants, individuals with severe SCI are often overwhelmed with new health tasks; therefore, the PR reminder system should be flexible, allowing reminders to be turned off and resumed as needed. [26]. This in turn can help users learn this new behavior at their own pace, and stay motivated to pursue self-care [24, 62].

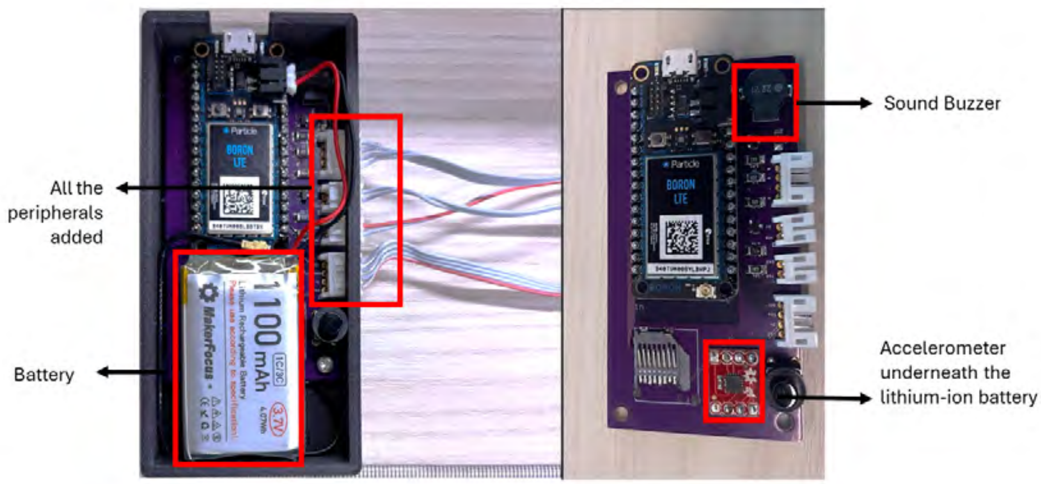
3.4.6 Design Goal 6: Minimize Charging Effort. Clinicians indicated that patients often forget to charge their PWC [52], and prior self-tracking literature has identified charging stand-alone devices as a barrier to self-tracking and thus leads to abandonment [32, 39]. Thus, it is important to minimize the power and charging requirements of the device, ideally with a solution which means that the user will not need to remember to charge the device at all.

3.5 System Design and Implementation

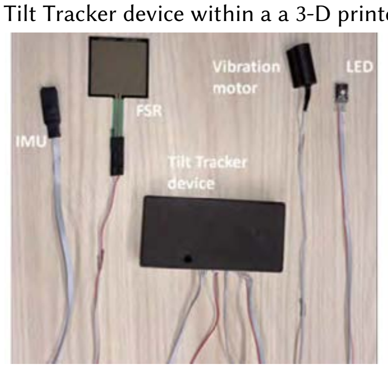
We used the design goals above to engage in an iterative design and implementation process for Tilt Tracker (See Figure 1). The system hardware of Tilt Tracker is mounted on the PWC itself, and there is a cloud backend that records all the PR data and provides the researchers access to the data. We describe the detailed system design and implementation in the following subsections.

3.5.1 Hardware. We implemented the current iteration of Tilt Tracker on the Particle Boron IoT Development Platform [1]. The Boron is equipped with a processor, cellular and Bluetooth radios, and I/O ports to connect to the Tilt Tracker peripherals. The rationale for using the Boron platform is its support for cellular data transmission over LTE networks, allowing PR data to be recorded in the cloud even when the user is outside and not connected to a WiFi network. The Boron board was also chosen partly due to its integrated charging circuitry for the battery. The Boron board, a 1100 mAh lithium ion battery, and an ADXL362 3-axis MEMS accelerometer[2] are

[1]https://docs.particle.io/boron/
[2]https://www.analog.com/media/en/technical-documentation/data-sheets/adxl362.pdf



(a) The Tilt Tracker device within a a 3-D printed box-case



(b) Input and output units are connected with the Tilt Tracker device

Fig. 1. This figure shows the final design of the Tilt Tracker device. Figure (a) shows the internal design of the device along with the accelerometer, sound buzzer and the battery connected with the Particle Boron. Figure (b) shows the input and output peripherals connected with the device.

all fit into a custom 3D printed box approximately the size of a smartphone, width: 4inch (10.2cm), and height: 1.85inch (4.7cm), which we attach to lower part of the backrest of the PWC with removable double-sided tape (see Figure 2). The lithium-ion battery enables the device to function by detecting seat occupancy and delivering PR reminders in situations where the user remains seated, but the wheelchair is powered off. Cables coming out of the box connect it to the USB port on the PWC for power, and to the remaining I/O devices.

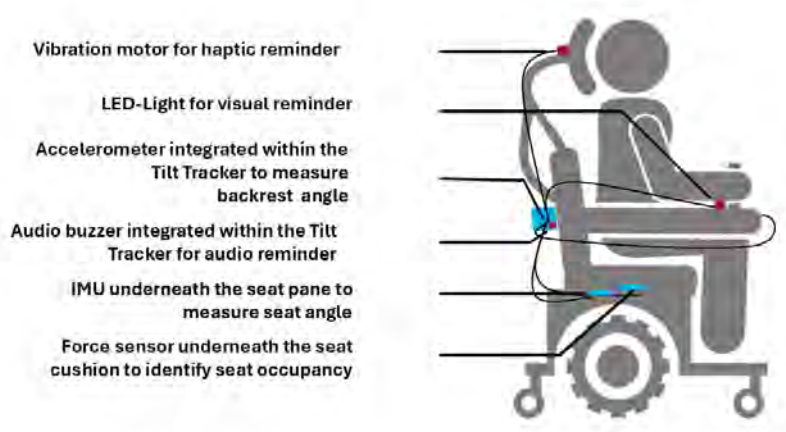


Fig. 2. This figure shows different peripherals of Tilt Tracker device attached to a PWC

In addition to the accelerometer located on the back of the chair, a DigiKey LSM9DS1 IMU [3] is attached under the seat pan. The combination of both accelerometer and IMU enable Tilt Tracker to detect whether the entire seat has been tilted using the sensor under the seat pan, and also whether the backrest has been adjusted using the difference between the two sensors (see Figure 3). Finally, we install a force-sensitive resistor (FSR)—Adafruit FSR 406 38mm square X 56 mm [4]—underneath the seat cushion to enable Tilt Tracker to infer wheelchair occupancy.

We attached three additional peripherals to enable Tilt Tracker to deliver reminders through various modalities. We attached a small vibration motor [5] the back of the headrest, an LED (DigiKey LED RGB 6PLCC SMD) [6] adjacent to the joystick area at the end of the armrest, and a piezo buzzer (DigiKey BUZZER MAGNETIC 3.5V 12MM TH) [7] mounted inside the 3D printed box that can deliver audio reminders. Additionally, we integrated a small button on the outside of the case (see Figure 2). Pressing the button toggles the Tilt Tracker on and off, which enables clinicians or caregivers to turn off or turn on reminders upon users' request, using an audible notification to indicate the on/off state. Further, pressing the button four times will put the device into a sleep mode, and another press returns it to normal operating mode. Notably, data collection will be paused while the device is in sleep mode, whereas PR performance data will still be collected when the notifications are turned off. Figure 2 shows the Tilt Tracker sensors installed on a PWC.

3.5.2 Software and Operation. The software that operates the Tilt Tracker device runs on the Boron board and was implemented in C++. Additionally, the cloud backend provides researchers with access to the recorded PR data, enables configuration of some of the parameters of the device, and facilitates data collection and analysis. At a high level, the software records data when the angle of the seat pan or seat back goes beyond a minimum threshold. This approach helps to filter noise in the sensor data from, for example, driving the PWC. It infers that

[3]https://www.digikey.com/en/products/detail/sparkfun-electronics/SEN-13944/6193601
[4]https://cdn-shop.adafruit.com/datasheets/FSR400Series_PD.pdf
[5]https://cdn.sparkfun.com/assets/a/0/b/b/1/DS-16036.pdf
[6]http://tinyurl.com/mr4c8d3c
[7]http://tinyurl.com/9drca6ys

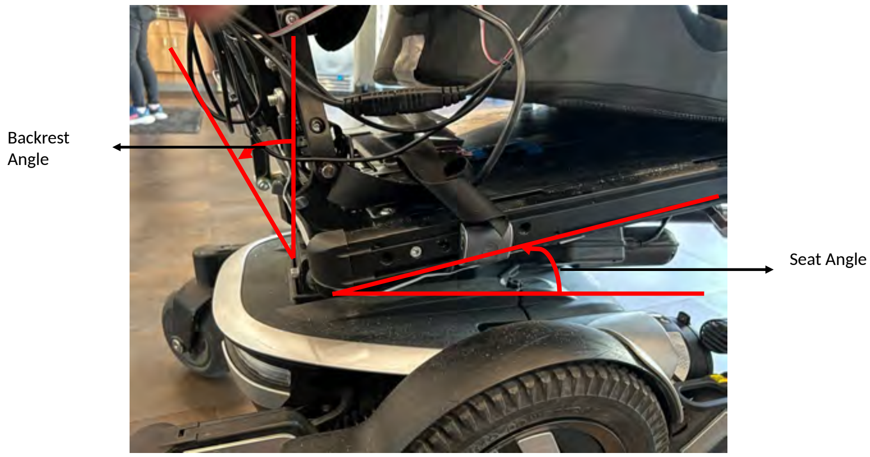


Fig. 3. The figure shows how the seat and backrest angles are calculated to measure users' PR.

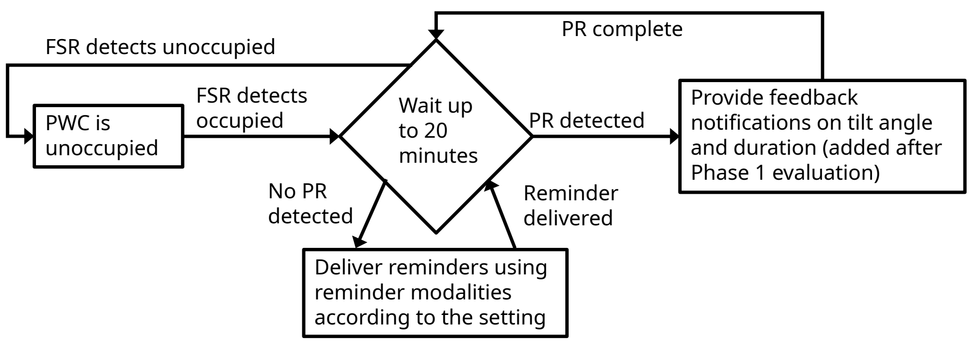


Fig. 4. The figure shows the logic diagram of Tilt Tracker device

a potential PR has been started if the seat pan has been tilted back at least 20 °and that the backrest has been tilted to at least 115 °(see Figure 3). There will be no reminders triggered as long as the user initiates a PR within 20 minutes. As the user completes the PR and returns to an upright position, it will start the countdown for the next 20 minutes. Figure 4 diagrams this logic.

A reminder is triggered for each missed PR if sufficient tilting is not detected within a 20 minute period. Reminders can be delivered using any of the three output modalities described above: vibration, LED light, and audio notification. The output modalities used can be configured in software. All data related to wheelchair occupancy, tilting angles, reminders mode, and trigger history are transmitted over the cellular network in batches and preserved in the cloud database.

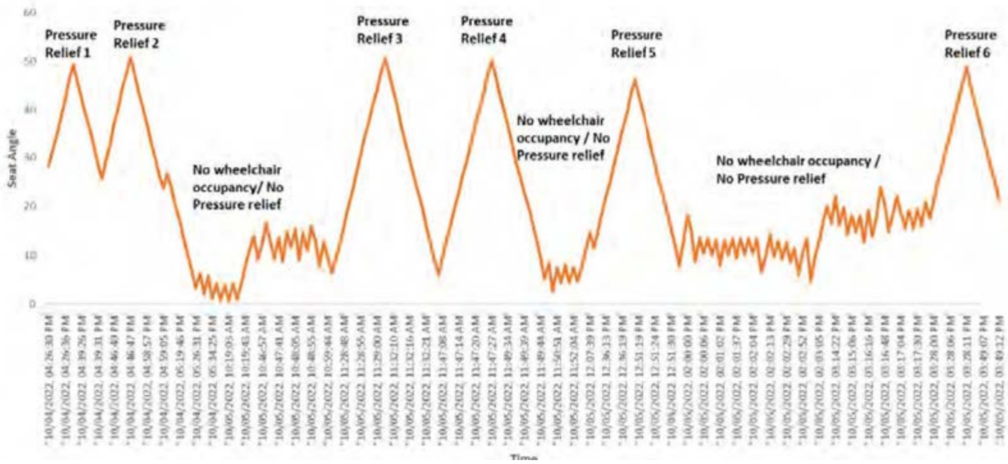


Fig. 5. Partial sample PR data that Tilt Tracker captured for P1: time of the day, angle of the seat, and time durations when the wheelchair was not occupied.

4 TILT TRACKER DEPLOYMENT AND EVALUATION

We deployed and evaluated the Tilt Tracker device with nine participants who had sustained a severe SCI, use a PWC, and were current inpatients in a rehabilitation hospital. We chose to deploy and evaluate this initial version of Tilt Tracker in the rehabilitation hospital setting because the clinicians we spoke with indicated that developing strong PR habits while still in the hospital improves the likelihood of long-term adherence to PR recommendations. Thus, having strong training on PR behavior in the rehabilitation hospital lays an important foundation for their future.

Our deployment and evaluation happened in two phases (see sections 4.4 and 4.7) with some iterative design improvements made between phases. We also followed methodological accommodations appropriate for participants with different disabilities and comorbidities during device installation, observation, and interviews, which are further described in those sections below.

4.1 Recruitment

We recruited ten inpatients in the rehabilitation hospital who had sustained a severe SCI (single or multiple cervical injuries) from October 2022 to July, 2023, and deployed the Tilt Tracker device on their wheelchairs. Participants were identified by the rehabilitation clinicians with the following inclusion criteria: (1) sustained a recent SCI and was recommended to use a PWC for mobility; and (2) has sufficient cognitive ability, which is important to understand the PR process and guidelines. Additionally, one participant who qualified to participate was unable to continue with the study because of problems with the installation of Tilt Tracker with their cushion; the type of cushion he used in his wheelchair was impeding the FSR, making it impossible to infer wheelchair occupancy. We obtained verbal consent from all participants, because they all lacked the hand and finger dexterity to sign the consent form. Thus, A witness signature was also obtained from a clinician or caregiver who was present during the consent process. The study participation was completely voluntary, and no compensation was provided. Our study protocol was approved by our Institutional Review Board (IRB).

Recruitment Limitation during Deployment: We acknowledge the limited number of study participants for the Tilt Tracker deployment, similar to the recruitment during design phase (see section 3.2.2). One reason is the small pool of potential participants who sustained a severe SCI and admitted in the rehabilitation hospital. Additionally, there are well-documented challenges of recruitment from such population [55] and multiple barriers, including speech, or respiratory impairment, that individuals with severe and multiple disabilities encounter to participate in research [30, 47]. We encountered similar challenges in recruiting participants. Despite the challenges, we succeeded in recruiting participants as a representative sample of this population. Future research can conduct such deployment study in post-rehabilitation, or with participants staying in assisted living.

4.2 Study Protocol

Our study protocol followed the following steps: First, Tilt Tracker device installation on participant's PWC. Second, informing and demonstrating the participant about the features of the system. Third, observing the participant in different context. Forth, Follow-up interviews after each observation session. Fifth, Conducting the exit interview with the participant.

4.2.1 Device Installation. Two researchers installed the device on each participant's PWC. The device was installed when participants were out of their chair, early in the morning before their daily schedule began, or late in the evening after they have finished their daily activities and have transferred to their bed. After installation, we demonstrated the device's functionality to the participant and their caregivers. That demonstration included showing all of the reminder modalities, enabling/disabling reminders, putting the device into sleep mode and keeping the USB plug connected. We asked the participants if they prefer one of the reminder modalities on the first day of installation.

We had to install the device more than once for several participants as their recommended type of PWC changed during the study period. Clinicians often change patient's PWC according to their frequent changes in functional capabilities and interaction needs. For instance, the initial PWC provided to P1—where we installed the Tilt Tracker device—had a regular joystick. Clinicians determined that P1 was less capable of operating that type of joystick, particularly when it came to pushing the joystick forward and backward to tilt the chair. Thus, P1 received a new PWC with a "buddy-button" that allows her to tilt down or tilt up with a single touch of a button. With that replacement, we had to re-install the Tilt Tracker device in her new PWC.

4.2.2 Demonstrating the features. Upon installing the Tilt Tracker device on the participant's PWC, we demonstrated all three modes of reminder to the participant and asked which mode they would prefer. Later, for each observation session, we varied the mode of the reminders to observe participants' interaction with those specific reminder modalities. We made that variation with the consent of the participant.

4.2.3 Observations. We aimed to deploy the Tilt Tracker device with each participant for five to seven days and conduct a combination of observations of participants using Tilt Tracker followed by interviews after each observation sessions focused on understanding their experience using the system. We conducted observations in different contexts, including alone without anyone else in the room, with family and friends in their rooms, moving through the corridors and elevators, engaged in various activities (watching television, speaking on the telephone, eating), as well as participating in a therapy session in the hospital therapy facility. However, we had to extend the deployment time for several participants due to their health conditions. For instance, P2 had multiple AD (autonomic dysreflexia) episodes during the deployment period, and did not use his PWC for several days; thus, we had to reschedule the observation sessions five times. Similarly, we had to reschedule the observations twice because P5's neck injury got worse and she did not use her PWC for several days. Since P4 was infected with COVID, we had to wait for a week in order to complete the observations.

We conducted a total of 35 hours observation (M = 3.95 hours) to examine participants' interactions with different reminder modalities. We observed whether the participants noticed the reminders, how they responded to the reminders (did or did not perform PRs), and the impact of additional factors like location, social context, or levels of disabilities on the response behavior. The first author conducted all the observations and collected field notes. Participants had the device installed on their PWC and used them even when we were not observing them.

4.2.4 Follow-up interviews. We conducted follow-up interviews with participants immediately following each observation session. During the follow-up interviews, we asked them about the notifications they saw during the observation session, their opinion of those notifications and reminders, and whether those opinions were based on any contextual factors. In addition, we followed up on their PR-related activities that we observed. This included their reasons for not performing PR in different situations (e.g. in the corridor or during meals), as well as their opinions regarding those situations. Follow-up interviews lasted approximately 4 to 15 minutes ($M = 10.5$ minutes). During interviews, we found some participants (P5, P7, P9) to be fatigued and answering questions with brief responses, such as "I did not see", "I heard the sound", "I don't know". Several previous studies have reported such fatigue and tiredness of this population during research [30]. Further, P3 and P6 had slight speech impairment. Thus, in both cases of fatigue and speech impairment, we tended to avoid more elaborate questions, and let them answer briefly in an effort to accommodate their fatigue.

4.2.5 Exit interviews. The last day of observation, we conducted exit interviews with all participants to obtain their overall impression of the Tilt Tracker. They were asked about their perception of PR, the challenges they face in performing PRs, their experience with Tilt Tracker device, their opinion regarding different reminder modalities/interactions/challenges, and their expectations for the future. The exit interviews lasted from 7 to 20 minutes. We audio recorded all interviews with participants' consent.

4.3 Data Analysis

We transcribed all interviews from Phase 1 and Phase 2 using an automated transcription service (Otter.ai [59]). We then employed reflexive thematic analysis [7] to analyze transcribed interview data and observation field notes. We started by reading through the interview transcripts and performed open coding of the transcripts and field notes. As we coded, we sought to identify codes that accurately represented the content of the raw qualitative data. The data were coded by two authors and they progressively discussed the codes with the other author. There were 144 codes resulting from Phase 1 and 376 codes resulting from Phase 2 interviews. After finishing the coding, the codes were transferred into a Miro [51] board, and the authors worked together to create an affinity diagram. After several rounds of iteration, we finalized five themes from Phase 1 deployment data: (1) effectiveness of the PR reminders, (2) challenges with the reminders, (3) more features to enhance effectiveness, (4) uncertainty of the tilt angle, and (5) uncertainty of the tilt duration. We discuss our findings in next section. Likewise, we found four themes from Phase 2 analysis: (1) acknowledgments of the effectiveness of PR reminders, (2) pros and cons of reminders, (3) contextual challenges, and (4) different data delivery amount, frequency and mode. We discuss our findings in next section.

4.4 Deployment and Evaluation: Phase 1

Our deployment and system evaluation happened in two phases. In phase 1, we deployed the device with four inpatient participants, recruited from October 2022 to February 2023 in the rehabilitation hospital. During the Phase 1 deployment, we observed that reminder modalities were effective; however, participants encountered several crucial challenges while interacting with the Tilt Tracker device. We describe our findings from the Phase 1 deployment below.

4.4.1 Reminders Were Effective to Remind about PRs in Most Cases . All participants acknowledged that the reminders generally served effectively, helping to reminding them about performing PRs. For instance, P3, who used a stopwatch for his PR before getting the Tilt Tracker deployment, stated that this reminder feature would "replace" the stopwatch for him. Similarly, P2 shared that the reminder notifications helped him keep track of if he was performing his PRs regularly.

The audio reminder, in particular, was effective in most instances. P2 mentioned that if he is in the room alone, he would prefer the audio. Similarly, P4 stated that:

> *I noticed the sound the most [...] I would prefer the sound probably, that was best for me. (P3)*

Participants also mentioned that the vibration motor mounted on the headrest was an effective and noticeable PR reminder, as they could always feel it. For instance, P1 shared that she could both feel and hear to the vibration, as she often keeps her head on the headrest due to her neck injury. P2 emphasized that vibration mode would be more convenient in a quiet place. Further, P4 highlighted that vibration would be less distracting for people around him:

> *I could tell that it was like, notifying me. But it wasn't like honking a horn or distracting somebody else. And consistently, I could feel it, versus either seeing it or hearing it. So the feel of the vibration was much more apparent. (P4)*

In addition, participants also agreed that LED light can be an effective way to remind them about the PRs, particularly in a noisy place where it is hard to notice the audio (P3, P4), or during meetings (P3), or in quite places like library (P1).

4.4.2 Reminders Were Not Noticable in Some Contexts. While Phase 1 participants acknowledged that the reminder notifications were useful for helping them remember their PRs, they encountered several issues to notice the reminders. We observed that audio notifications were insufficiently loud in various contexts within the rehabilitation hospital. For instance, according to P1, the audio volume was not loud enough to alert her while watching television. Similarly, P2 reported that the audio notifications were not discernible among the other alarms in the hospital. P2 shared one incident when OTs notified him in the rehabilitation gymnasium area when an audio notification was triggered that he did not notice.

Similarly, participants mentioned a reminder through only the LED light is likely to be missed because people do not often look down at the armrest (P2, P3, P4). Likewise, due to neck injuries, participants were unable to notice the LED light notifications located adjacent to the joystick area. Additionally, watching TV or speaking with someone usually requires that participants look up, so again they may not notice the light reminder. As P4 explained:

> *...because a lot of times you are not looking down and you do not see that [LED light], but [...] I can feel the others [vibration and audio]. (P4)*

In addition, our observation of participants (P1, P3, P4) revealed that their PWC armrests were frequently kept upright during therapy sessions. As a result, if the LED light reminder was triggered, the participant was unaware of it.

With all those challenges, participants (P3, P4) shared their interest to have the option to change the reminder modalities according to their preference. For instance, P4 particularity expressed his interest to have a way to select the reminder modalities according to the contexts:

> *you should be able to have an option to which one you want to use, but all three are acceptable. [...] all three [vibration, audio and light] of those would work really good hand in hand. (P4)*

Similarly, P3 is also interested to have the option to "switch" the reminder modality according to the surrounding contest:

> *if you could be able to switch maybe to the light instead of the sound ... if you're, say you're in a meeting or something you'd prefer having the light versus sound. (P3)*

Even when participants noticed the reminder, some were unable to perform a PR due to limited available space. For instance, we observed P4 noticing a reminder during a therapy session, but ignoring it. He shared his hesitation regarding the congested space in the follow-up interview:

> *When I was in the PT (physical therapy) area downstairs, a lot of people, remember...it's just too many people in the area. You have people walking around. You have people, you know, so it's congested. (P4)*

To avoid performing PRs in crowded or constrained environments, we found participants P1 and P4 performing PRs proactively before leaving their rooms. Similarly, we observed that P3 ignored the PR reminder while eating. He had to adjust the position of his chair before he could reach the dinner table, which required significant effort on the part of the nurse and him. As a PR reminder was triggered during dinner, P3 ignored the reminder and continued to eat. After completing dinner, P3 performed the PR without the help of a reminder. Thus, these mindful approaches allowed them to maintain their PR routines while minimizing the potential distraction, or discomfort in public or shared spaces.

Thus, all participants in our Phase 1 deployment emphasized on different contextual factors that impacted the effectiveness of the reminder modalities.

4.4.3 More Features to Enhance the Efficiency of the Reminder Notifications. We found that participants had to ignore the notifications and could not perform a PR immediately due to several contextual factors (perhaps for one of the reasons listed above). Thus, they wanted some additional reminder functionalities since they might be able to perform a PR in the near future. For instance, according to P2, reminder notifications should not stop triggering until the due PR is performed. P2 suggested that if they ignore or do not notice a PR reminder, the reminder should continue triggering until the due PR has been performed:

> *to make it effective, you would have to make it where it doesn't stop vibrating or flashing, or making the horn [audio] until you actually do it [PR]. So that, it's not just a reminder, it's almost like an alarm that you would have to turn off. And the only way to turn it off is to do the pressure relief...then it's gonna drive everybody nuts enough that you would have to just be like, hang on, I have to do this or it'll keep going off. (P2)*

Similarly, P1 suggested that there should be a snooze option so that she can snooze the reminders while she is engaged in other activities, and get the reminder again. P1 further suggested that a small touch button would be helpful for her to snooze the reminder since she does not have the hand grip to use a toggle in order to snooze the reminders. She added that the snooze button should be located conveniently on the armrest, so that she can easily touch the button:

> *.... a little button toggle would be too hard for somebody like me that I don't have a grip, a button I think would be best for like this one, maybe smaller, or something like that. It would be good. Like on the inside [of the chair's armrest], where you could, even if you don't have a lot of pressure, you can use momentum to hit it. (P1)*

Thus, our participants from Phase 1 deployment shared important features that would make the PR reminders of Tilt Tracker more efficient.

4.4.4 Uncertainty of the Tilt Angle. In many cases, Phase 1 participants attempted to perform a PR immediately following the reminders; however, participants were frequently unsure if they were reachingthe appropriate tilt angle when initiating the tilting process by using the wheelchair tilt function (typically a button or switch integrated with the joystick). Thus, to ensure they have reached the correct tilting angle, they would ask their caregivers or anyone around them.

4.4.5 Uncertainty of the Tilt Duration. Participants also struggled to track how long they had been performing the PR. The clinically recommended duration for a PR two minutes. One reason tracking the time is difficult is that most of our participants have neck injuries which prevent them from moving their heads and looking at the wall clock or wheelchair screen to track the time. As a result, they must either guess, or rely on caregivers or clinicians to track their tilt duration.

4.5 Participants' Expectations for Receiving PR Performance Data Varies

Our analysis shows that, participants have a wide range of ideas and expectations to receive their PR data to improve their PR awareness. Individuals had varying views regarding **amount**, **frequency**, and the **mode** of the data delivery.

Amount of Data Delivery: P2 expressed his interest to see the details of his PR performance to be more aware of the behavior:

> *I think it'd be cool to see like, here's when you did your [PR] here's when you were alarmed. Here's when you responded to it by weight shifting [pressure relief]. Here's where you didn't. So you get a score of out of 50 reminders. You only did 30. Right. . . . so allow you to see that, hey, I could do better than this. Right? And be more aware of it. (P2)*

On the other hand, P1, who was going through some complications and had a recent surgery, explained that she was not regular in performing the PRs, so she is not interested to get the data:

> *I've done it so badly. No, I don't want to see (P1)*

Even when we asked her if she wants to see the data in future, she expressed her reluctance in receiving any PR data and explained that it will not be helpful for her:

> *Personally, I don't think it matters. I pretty well know, when I'm not doing it... And when I'm doing it, right. I don't think it [PR data] would be helpful for me. (P1)*

Frequency of Data Delivery: Participants also vary in how frequently and through what modality they would like their PR performance data delivered to them. For instance, P2 wants his PR performance data to be delivered once a week by email:

> *I would say at the end of each week, if you got an email that showed you each week, your performance, just really easy. So it didn't take up a lot of time, but you can see it. I think that would be really effective.* (P2)

However, P3 wants his PR data delivered to their phone weekly. In contrast, P4 would like to get his PR data once every day on his PWC screen:

> *I would like to see it probably transmitted to the console on the chair itself* (P4)

Thus, participants' interest in knowing about their PR performance varied widely. In particular, the amount of detail they wanted to see, and their preferences in data delivery mechanisms differed according to their tech enthusiasm, and personal choices.

4.6 Design Iteration

Informed by the critical findings from the Phase 1 deployment (uncertainty of the tilt angle and duration, positioning of the LED light and loudness of audio reminder), we iterated the Tilt Tracker design, and integrated the following three features:

(1) *Angle notification:* When the user initiates tilting, an angle notification will inform them when they have reached the minimum angle to count as a PR, which clinicians suggested should be at least 20°. When this threshold is crossed, a notification will be triggered. If the modality is audio the notification is a confirmatory tone, if it is LED it is a specific color LED light (e.g., yellow), and if it is vibration then a distinct pattern can signify that the angle has been reached.

(2) *Duration notification:* The addition is a notification when two minutes has elapsed. Similar to the angle notification, when the user is in the tilted position for two minutes, a notification will be triggered. If the modality is audio, the notification is another distinct confirmatory tone, if it is a LED light it is another distinct color (e.g., green), and if it is a vibration, then a distinct vibration pattern will indicate that two minutes has elapsed.
(3) *Repositioning and Refining the Reminder Modalities*: We repositioned the LED light away from the armrest area toward the upper corner of the joystick area, so that users with neck injury and collars might be able to see it easier. Additionally, we changed the pitch of the audio reminder to make it distinct from the other hospital alarms and increased the volume to its maximum to make it more audible in noisy environments.

To gain a deeper understanding of the contextual factors influencing reminder effectiveness, we intentionally excluded any option for users to self-select reminder modalities in this design iteration. By doing so, we aimed to observe users' interactions and responses in Phase 2 deployment with predefined reminder types, allowing us to better analyze which modalities may be most effective under varying conditions and contexts.

4.7 Deployment and Evaluation: Phase 2

We conducted our Phase 2 deployment and evaluation using the new iteration of Tilt Tracker with the same observation and interview protocols with the other five participants as in Phase 1. We provide our Phase 2 deployment finding in the next section.

Table 2. Demographics, pre-injury occupation and details of the Tilt Tracker device deployment. That includes the duration of the system deployment, total observation hour, and if there were any health related issues of the participants during the deployment. AD*= Autonomic dysreflexia, a life-threatening syndrome involving an abnormal, overreaction of nervous system, most often happens after a spinal cord injury.

Participant Index	Age	Gender	Pre-injury Occupation	System deployment duration (days)	Total observation hour	Any health related challenges during deployment period
Phase 1						
P1	75	F	Retired	5	5	High blood pressure, a minor surgery
P2	45	M	Regional manager (mortgage company)	13	4	Multiple AD* episodes, Neck injury got worse
P3	66	M	Retired	7	4.5	NA
P4	71	M	IT Engineer, ex-military	13	3.5	Got COVID
Phase 2						
P5	61	F	Retired	12	4	Neck injury got worse
P6	25	M	IT technician	19	3.5	Neck injury got worse
P7	62	M	Truck driver	12	3	NA
P8	65	F	Retired	10	3.5	NA
P9	67	M	Construction worker	6	4.5	NA

5 FINDINGS FROM PHASE 2 TILT TRACKER DEPLOYMENT

Our analysis from Phase 2 deployment shows that participants acknowledged the importance and effectiveness of the reminder notifications of Tilt Tracker to improve their PR behaviors. However, sometimes contextual factors meant they could not respond to the reminders immediately. Thus, participants provided several suggestions to improve the features of the reminders, and enhance their future PR behavior. We expand on each of these findings below.

5.1 Participants Acknowledged the Effectiveness of the Reminder Notifications

Triangulating data from the all the observations and interviews from Phase 2, we found participants agreed that the PR reminder notifications can be a useful tool to routinize their PRs. Participants also shared that they noticed the reminders, and subsequently performed a PR immediately or became mindful about performing a PR. As P8 described:

> *I think it would be very beneficial to me to have this reminder because in any situation, I would have the reminder to help me to go back to help to not get pressures sores* (P8)

5.2 Participants Identified Pros and Cons of Different Reminder Modalities

Our findings also shed light on participants' preferences for different reminder modalities. We describe them below.

5.2.1 Audio is the Best Reminder Modality. Phase 2 participants unanimously agreed that (P5, P6, P7, P8, P9), audio is the most effective reminder modality in every context. When watching television or using a telephone, P8 indicated that in the middle of a conversation, the audio notifications would effectively remind him about PRs:

> *The sound... I really liked the sound, it just makes it easier to remind me if conversations are going on.* (P8)

In addition, P9 noted that he was able to hear the audio reminder while taking a nap on the PWC, which he saw as a positive. P7 added that he prefers audio notification because everybody around him can hear it and remind him about PR.

Similar to Phase 1 participants, P5 explained that one issue with the LED was that she cannot see it because she cannot move her neck and look down due to her neck injury. P5 added that the vibration makes too loud and startling of a sound. Thus, she preferred audio for her as a PR reminders:

> *The sound. I don't see the light. And the vibration is startling.* (P5)

Thus, the audio reminder was the most favorite PR reminder for all the participants in Phase 2 deployment.

5.2.2 LED Light Needs to be Combined with Other Modalities to be More Effective. Phase 2 participants also agreed that LED light can be an effective way to remind them about the PRs, particularly in a noisy place. However, similar to Phase 1 participants, phase 2 participants noted that reminders delivered only via an LED light on the armrest are likely to be overlooked, as users may not frequently look downward (P6, P8), and individuals wearing a neck brace, may have restricted neck mobility to observe visual cues positioned at arm-level (P5, P8). Thus, participants recommended combining the LED light with audio and/or vibration modalities to enhance its effectiveness.

P6 also suggested a combination of a primary (e.g., an audio or vibration) reminder followed by a constant flashing light to be triggered if they fail to perform a PR, in order to remind them to perform it as soon as possible after completing their current task:

> *...having that light constantly flash for like a while, [...] because then that would be like, just a constant reminder. Oh, you were supposed to do a pressure relief.* (P6)

Thus, participants from the Phase 2 deployment provided suggestion to make the LED light more effective PR reminder.

5.2.3 Vibration is Mostly Effective Except for Loudness Disrupting Relaxation. Although Phase 2 participants mentioned that vibration on the headrest is mostly an effective PR reminder, some participants (P5, P6, P8), who sustained a neck injury, and mostly keep their heads against the headrest (similar to P1 in phase 1 deployment) found it much louder. In contrast, a loud volume of vibration is beneficial to participants (P7, P9), who move their neck frequently and do not always keep their heads in contact with the headrest, as it is less likely that they will miss the sound even if they are not able to feel it. Thus, they are mostly *hearing* the vibration rather than *feeling* it. In addition, participants (P6, P8) also reported that the vibration was a jarring way to be disturbed when they attempted to nap or relax in the chair.

5.3 Contextual Factors led Participants to Ignore the Reminders or Reposition the PWC

Despite generally appreciating the reminders and different modalities, there were specific contextual issues that led participants to sometimes ignore a notification from Tilt Tracker, or otherwise to reposition their PWC before performing their PR. Due to those contextual factors, participants often could not perform PRs immediately after receiving the reminders. In Table 3, we show total due PRs and accomplished PRs of each participant, including PRs performed within two minutes and beyond two minutes of receiving the reminders.

5.3.1 The Fear of Tilting into Something. We found a common concern among all participants (P5 to P9) regarding the possibility that they might collide with a person or object behind them during the tilting process, similar to participants from Phase 1 deployment. In particular, they were scared of tilting in unknown places or while moving as they might bump into something or there may not be enough space. Thus, we found participants ignoring PR reminders in spaces (e.g.,therapy facility, corridors) where they were not confident about the space available for tilting. Similarly, we observed that participants frequently ignored reminders when they were moving in corridors or awaiting an elevator. As P5 shared:

> *I would get somewhere convenient and then recline. I am not gonna stop in the lift.* (P5)

Table 3. This table shows the number of PRs due and the accomplished PRs for participants from Phase 1 and Phase 2 deployment. In addition, we show the number of PRs performed within two minutes of receiving the reminder, and the number of PRs not performed within two minutes.

Participant Index	Total PRs due	Total accomplished PRs	PRs performed <= two minutes of reminder	PRs performed > two minutes of reminder
P1	38	16	6	10
P2	47	11	2	9
P3	43	29	8	21
P4	163	112	49	63
P5	53	30	9	21
P6	300	169	75	94
P7	44	34	23	9
P8	61	42	25	17
P9	199	18	10	8

They postponed the PR activity until they reached their room or open gym space. Additionally, we observed that even in the absence of a reminder notification, participants P5, P7, and P8 often performs a PR before leaving their rooms, similar to Phase 1 participants. They (P5, P7, P8) described this behavior in their interviews, attributing it to their concern about striking objects when tilting, given their inability to see behind them while tilting.

Participants prefer to perform the PRs only in a spot where they are confident, particularly in a specific location within their rooms, where they feel secure as they perceived this area to be sufficiently spacious to prevent collisions. Even when reminder notifications were triggered within their rooms, participants consistently relocated to that designated spot to initiate the tilting activity.

Notably, we found participants moving to that spot amid other activities, including having meals or conversing. We found that if participants had to tilt while talking with someone or when they thought someone might enter the room, they adjusted their chair position in order to facilitate better social interactions. For instance, while performing his PRs, P6 prefers his chair position facing toward the door and tilt, so that he can comfortably talk to anyone who comes into his room without moving his neck:

> *I like being over here [performing PR in the room facing the door], because I can, talk to people here more comfortably [while tilted].* (P6)

5.3.2 Reminders are Commonly Ignored during Therapy Sessions or Other Activities. We found that participants often ignore PR reminders when performing different activities, such as therapy, catheterization, or eating. For instance, participants are often tethered to therapy instruments while seated in their wheelchairs during occupational therapy sessions, thereby limiting their ability to perform PRs. Thus, they preferred to disregard PR reminders while actively participating in therapy sessions due to the additional effort and time required to disengage from these machines. As P9 explained:

> *...sometimes when you are doing therapy, you do not get the opportunity to take it [PR] every 20 minutes. They [therapists] just keep working with you, so most of the time I would not do it [PR during therapy session] [...] you will be involved in something where you have to go machine or something. And it takes so long to get hooked up and unhooked and re hooked. That you do not stop and do the pressure reliefs.* (P9)

5.3.3 Two-minute Duration Notifications can be Disturbing at Times. We found that participants sometimes prefer to remain tilted in their PWC for extended periods and the two-minute duration notification disrupts their relaxation. For instance, while performing PRs alone in their rooms, they remain tilted and watch TV, use their phones, or rest. WE observed that most participants preferred to relax in the tilted position for extended periods after completing daily activities such as therapy, physician visits, and patient education. Thus, while relaxing during the PR, they do not follow the notification of a two-minute duration and the notification becomes disturbing. As P6 shared his experience:

> *... when I'm doing the pressure relief, it's kind of a relaxing thing for me. And, so I kind of zone out a little bit. I just want to lay down here and just, you know, relax, but then when the thing [two-minute duration notification] comes in, it kind of ruins [the relaxation].* (P6)

P9 also explained that she often keeps the chair tilted for a nap. Thus, she will have to move to bed each time for a nap If she constantly receives a two-minute notification while tilted:

> *I've been coming in here [on the PWC] and tilting and sleeping for a while. If I can't remain reclined, if I only get a recline for two minutes, every 20 minutes, I'll probably get moved to the bed.* (P9)

While this duration notification effectively provided a sense of accomplishment, participants found it disruptive or unhelpful when relaxing.

5.4 Data Amount, Frequency and Mode of Delivery for Receiving PR Performance Data Varies

Our analysis shows that, participants from Phase 2 deployment also have a wide range of ideas and expectations on the **amount**, **frequency** and **mode** of PR data delivery, similar to Phase 1 participants. For instance, P6, who worked as an IT technician prior to his injury and enjoys technology, would like to see detailed statistics of his PR data, including the number of his performed PRs versus his due PRs, percentages of his PR goal achievement, and detailed graphs showing his PR performance, such as delays to respond to PR reminders, average delays, and the length of time he was tilted for each PR. In contrast, P7 does not wish to receive the details of his PR performance. He is only interested in just-in time PR reminders to be more routinized:

> *I do not have my phone with me a lot. I do not wear a watch. Or I am not a high tech. If it [Tilt Tracker] reminds me, that's all I want.* (P7)

Regarding frequency and modality of data delivery, P6, P8 and P9 want their PR data delivered to their phone weekly, and most participants desired that the data be delivered in a convenient manner, so that it would be easy to glance at and did not require additional effort on their part. Thus, participants' interest in the amount of detail they wanted to see, and their preferences in data delivery frequency and mode differed according to their tech enthusiasm, and personal choices.

6 DISCUSSION

Our work was an effort to design, develop and evaluate the feasibility of a novel self-tracking system for people with a severe motor disability. We focused on the intersection of ubiquitous computing and accessibility research to impact the lives of a underrepresented population—people with a severe motor disability—with a tailored PWC-mounted self-tracking solution integrating their needs and constraints. We also implemented and evaluated our system's feasibility with individuals with a recent SCI in a rehabilitation hospital. In this section, We discuss and synthesize the key findings from our design and deployment of this self-tracking system, and provide future design implications for the design of PR systems and more broadly for the design of systems that target PWC users based on what we have learned from our deployment.

6.1 Enhancing PR Adherence: Contexts of "Rehabilitation" vs "Post-Rehabilitation" Setting

Our findings highlight that the reminders and notification features of the Tilt Tracker device efficiently assisted the participants in the rehabilitation hospital context to follow PR routines and being more mindful about PRs, which was the preliminary objective of the design of the system. These findings highlight the utility of reminders for the unique self-care activities for people with severe motor impairment [53] or people with chronic conditions [8]. Indeed, many of our findings, such as preferences for an audio reminder, or proprioception with respect to the PWC and its surroundings are appropriate for the rehabilitation context, when individuals begin to adopt new behaviors and helping them with these new behaviors is the main objective of their surrounding people (e.g., caregivers, or clinicians). For instance, The audio notifications were prominent, and audible to anyone nearby, which are acceptable to the clinicians and caregivers as those notifications are a part of the rehabilitation process to help the patient adopt their new self-care routines; as a result, regardless of the loudness of the audio notification, it is less likely that it would disturb or distract surrounding people. Similarly, performing a PR in a rehabilitation hospital would be less awkward or hesitant for individuals with a PWC than performing a PR post-rehabilitation, on the streets, on public transportation, or amongst people who are completely unaware of the PR process and the need to perform PRs [53].

Thus, participants' preference for audio over the other two modalities of reminder (e.g., vibration and light) guides us to rethink the contextual considerations for design decisions for the post-rehabilitation context. In addition, rehabilitation is the first stage of the post-SCI life, and prior research suggests that post-rehabilitation is unpredictable and more uncertain [22, 45]. Thus, even though our deployment and evaluation took into account contextual factors successfully, it is possible that a deployment that occurs in post-rehabilitation could bring forth additional contextual factors. That indicates that the system should be separately evaluated “in the wild.”

There are some clear opportunities to also better leverage Tilt Tracker in the context of the in-patient setting. One such opportunity might be to leverage data collected through Tilt Tracker to improve patient education on PRs. Recent work has explored opportunities to leverage technology in the hospital to improve aspects of patient education, focusing primarily on smart spaces and technology integrated into the hospital [20, 21]. Adding PR data into the patient education or physical therapy process could help educators and therapists better tailor their efforts for the needs of each specific patient.

6.2 Design Implications of PWC Self-Tracking System

Our evaluation of Tilt Tracker also shows that it helped them independently perform an important and frequent self-care activity, as all participants reported. Although, our participants found value in Tilt Tracker, there are also opportunities to advance the design of the system to make the notifications more effective in that critical setting. In addition, the automated data collection process, and interaction with reminders and notifications led us to capture a range of social, physiological, and intrinsic challenges of PR behaviors that inform the future design of more effective self-tracking technologies for this population. Similar contextual factors may be present in the other new self-care activities (e.g., bladder and bowel management) that people with an SCI need to adopt, and other activities of daily living (ADL) that people with PWC need to perform [41], despite the fact that these self-care activities do not occur as frequently as PR.

Thus, we identified more rigorous design implications that will help future researchers and designers to implement such chairable self-tracking systems:

(1) **Pausing reminder notification while on the move:** Participants tend to skip PRs when reminders are triggered during wheeling, so perhaps a future system should explore the potential to be more context-aware. A possible approach is to use the data from the attached IMU to determine whether the individual in the wheelchair is moving, and then hold the reminder until the individual has stopped moving for a period of time.
(2) **Options for persistent notifications/hybrid notification modalities or snooze option:** Our findings indicate that self-care technology could facilitate more flexibility in following the reminders; for example, a blinking light is less invasive, so it could continue to blink until the activity has been completed. Another possibility is to allow snoozing reminders in situations where they know they cannot perform the activity now but may be able to soon. Notably, depending on the frequency and the complexity level of the activity, the secondary reminders can be programmed and integrated within the users’ reachable spots on the PWC [43].
(3) **Automatic sensing for reminder intensity:** We found a common concern that the intensity of the reminders (e.g., audio, vibration) should not be static, instead vary depending on the situation. For instance, crowded and noisy places should have a higher audio intensity for the reminder, while quiet places should have a lower one. Integrating a sound detector—for privacy reasons, one without an audio output—can indicate to the system if the surrounding environment is noisy, thus it can adjust the intensity level of the audio reminder. Similarly, by implementing touch sensors on the headrest, the vibration intensity can be reduced if the user’s head is in contact with the headrest.
(4) **Automatic selection or combination of reminder modalities:** Similar to the intensity, the chairable self-tracking system could be programmed to switch between reminder modalities or combinations of modalities automatically depending on the user’s choices, contexts and preferences. For instance, starting with an LED notification when the next due PR is getting close, then adding in something more invasive (e.g. audio) if they did not respond to the LED. Similarly, an ambient sensor or GPS tracker can be used

to determine the user's location so that the system can determine which type of reminders should be triggered.

(5) **Providing feedback to users on their tracked PR data:** Another crucial implication for such self-tracking system is providing customized feedback on users' tracked PR data. As the amount of data delivery, frequency and mode of delivery vary according to the individuals' personal choice, we recommend to integrate several options in the system, so that users can make the selection of the data delivery mode according to their preferences.

6.3 Reflecting and Making Sense of PR data Through Collaboration with Clinicians

Although the Tilt Tracker device could successfully collect participants' data through deployment in the rehabilitation hospital, and participants expressed their interest in receiving various amounts of data in different frequency and delivery methods to reflect on the data, it is crucial to examine how clinicians can utilize this data to assist these newly injured individuals in learning from their PR data and assessing their progress. Additionally, individuals might be able to participate actively in this data exploration process, and the system should provide a variety of options for data delivery and selection. Indeed, reflecting and making sense of collected personal data is crucial in PI literature [42]. Particularly, research identified that individuals with motor disabilities want to visualize and reflect on their personal information in visually appealing formats to reinforce the essential takeaways of the collected data (perceptible information) [54]. Thus, Tilt Tracker, as a chairable self-tracking technology, should provide users with the ability to access and reflect on their collected personal data.

Additionally, researchers have previously examined challenges associated with patients and providers' collaborative sensemaking of clinical and contextual data using multiple data sources. For instance, Raj et al. [63, 64] examined how patient-generated data (PGD) was interpreted in collaborative settings and found that patients and providers have differing data interpretation criteria, perceive risk differently, differ on the type of problem to focus on, and patients are not aware of the evaluation criteria used by providers when determining instances. Thus, differences in perception can negatively impact collaboration, as patients may perceive them as mistakes on their part, impacting their confidence and self-efficacy in handling their data and communicating with providers.

PR is an entirely new health activity that individuals begin to learn soon after sustaining an injury and using the PWC. Thus, future research should explore how clinicians and Tilt Tracker users interpret PR data collaboratively and how this collaborative data exploration could help improve PR adherence.

7 CONCLUSION

Tilt Tracker is a first-of-a kind self-tracking system integrated on a PWC with a goal of improving PR adherence of individuals who recently sustained a severe SCI. Our iterative, multi-stakeholder design process helped to ensure that it could successfully aid this vulnerable population in adopting new health activities independently, even during the rehabilitation period. This study is a first step towards designing more sophisticated chairable self-tracking systems for other PWC-related activities that individuals need to perform both in their rehabilitation and post-rehabilitation life.

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