Development of a Scalable Monitoring System for Wheelchair Tilt-in-Space Usage

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***Abstract*—Despite advances in rehabilitation research and assistive technology, pressure ulcer rates remain high among people affected by spinal cord injury. The Rehabilitation Engineering and Assistive Technology Society of North America recommends using power seat functions, such as tilt-in-space (tilt), to reduce seating interface pressure and restore blood flow to ischemic tissues. However, recent studies suggest that pressure-relieving tilts are not being adequately used in daily life. Additional data collection is needed to better understand tilt trends in daily life; however, conventional data logging procedures that involve the physical initialization, retrieval, and management of the data loggers may not be practical in large-scale settings. Thus, we developed a longitudinal monitoring framework with a focus on scalability through connectivity and affordability. Connectivity was achieved through wireless technologies, allowing the data to be both recorded and retrieved remotely, along with Web technologies, allowing the server-processed results to be viewed in real time from any internet-accessible browser. Affordability was achieved through the use of free software and relatively inexpensive components, including the Raspberry Pi and MMA7455L accelerometer. Preliminary validation was performed by comparing the tilt distributions of our automated online processing system with a manual offsite processing method. Two protocols were tested, and statistical analysis revealed a correlation coefficient of 1.00 in both cases. Thus, our system may be a viable means of both broadening and deepening the scope of longitudinal monitoring by reaching more participants and analyzing more data over longer periods.**

I. INTRODUCTION

Spinal cord injury (SCI) is a life-altering event that affects approximately 265,000 people nationally and 12,000 new people annually in the United States [1]. Beyond the primary physical and psychosocial trauma, SCI induces various pathophysiological changes that result in secondary complications, often requiring rehospitalization [2], [3]. Of these complications, pressure ulcers are among the most common. In the United States, treatment costs approach $20,400 per hospitalization and $11 billion per year [1]; and the annual incidence, lifetime incidence, and recurrence rate are estimated at up to 30 percent, 85 percent, and 70 percent, respectively [4]. Despite advancements in rehabilitation research and assistive technology, pressure ulcer-related SCI hospitalizations in the United States increased at a higher rate (75 percent) than total SCI hospitalizations (15 percent) between 1993 and 2006 [5]. These pressure ulcer morbidity rates can decrease long-term employability, increase cost of care, and even lead to premature mortality.

Pressure ulcer prevention remains a challenge, largely because the etiology of pressure ulcers is not fully understood [6]–[8]. Extrinsically, the altered levels of pressure, shear, moisture, temperature, hygiene, and nutrition are believed to contribute to ulceration [9], [10]. Intrinsically, SCI disrupts sensory pathways to the brain, interrupting the signals of discomfort and pain that normally trigger weight-shifting. Consequently, prolonged pressure occurs and is widely believed to prompt the development of pressure ulcers [3]. Various causation theories that involve the disruption of capillary, interstitial, and cellular mechanisms have been proposed, among which tissue ischemia appears to be the final common pathway toward the development of pressure ulcers [3], [11]. Compressive and shearing forces deform the soft tissues, inducing ischemia due to vascular occlusion and the disruption of internal cellular mechanisms, eventually leading to cell necrosis and tissue breakdown. Thus, the reduction of seating interface pressure is advocated to allow blood flow restoration to ischemic, weight-bearing tissues via reactive hyperemia [3], [12], [13]. The Consortium for Spinal Cord Medicine recommends weight-shifting at least twice per hour [14], and Coggrave and Rose recommend unloading for roughly 2 min to allow for adequate tissue reoxygenation [15]. Clinical interventions for pressure relief include wheelchair pushups, lateral leaning, forward flexion, active and reactive support surfaces, and power wheelchair seat functions, such as tilt-in-space (tilt) [3], [6], [13]. For power wheelchair users with SCI, the integrated tilt function is a practical weight-shifting technique to enhance skin perfusion over the ischial tuberosity, thereby reducing the risk of sitting-induced pressure ulcers [7], [16].

In recent years, there has been increasing interest in monitoring the pressure-relieving activities of wheelchair users in daily life with the goal of improving conventional qualitative

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assessments via quantitative analysis [17], [18]. While the participants were found to be performing pressure-relieving maneuvers throughout the majority of the day, rarely were the tilt angles larger than 20° [17]. In some cases, participants sat for extended periods of up to two and a half hours without repositioning. Data logger results were also compared with participant self-reports, but there was no statistical correlation between the measured observations and personal expectations [17]. In another study, surveyed participants self-reported the usage of large angles that were not reflected in logged recordings [18]. These findings suggest the possibility that users may have misconceptions about their own usage of wheelchair tilt. Longitudinal monitoring will allow researchers and clinicians to learn the true pressure-reliving habits of power wheelchair users in daily life.

To build an accurate picture of tilt usage in the SCI population, the goal is to monitor as many power wheelchair users for as long as possible. In the previous studies [17]–[19], the authors reported a common limitation that the participant counts and study durations were low. To collect their tilt data, these studies used custom loggers, such as the Wheelchair Activity Monitoring Instrument (WhAMI) [18], [19] and Seating Function Data Logger (SFDL) [17]. With both devices, the researchers and wheelchair users would schedule visits to download the logged data and either remove the data loggers or perform maintenance on them (e.g., replace the batteries) [17], [19]. The retrieved data were manually processed and analyzed in external computation programs. However, as the number of monitored wheelchair users grows larger, this data collection and retrieval routine may become progressively unmanageable due to the increased overhead in manpower and time. Furthermore, as with all observational studies, there are concerns of observer-expectancy bias in which participants may alter their natural behaviors because they are being recorded [20], [21]. Thus, reducing how often the participants are reminded of the monitoring process (e.g., reducing the frequency of data retrieval) may also help in the effort to understand true behaviors in daily life. The purpose of this study was to design a scalable monitoring system that could automate the data logging process in order to increase both the feasibility and accuracy of performing long-term, large-scale tilt monitoring. Its scalability is facilitated via connectivity and affordability. Connectivity would allow the data not only to be recorded remotely, but also to be retrieved, processed, and/or viewed remotely (e.g., wirelessly). Affordability would allow the system to be reasonably deployed by places such as clinics and nursing homes.

II. METHODS

Power wheelchair tilt angles (Fig. 1) were continuously logged and automatically displayed via a Web interface using our client-server framework (Fig. 2). Meanwhile, we simulated a manual data logging test case using a commercial accelerometer and processed the results manually.

A. Instrumentation

The client-side monitoring device (Fig. 3) consisted of a Raspberry Pi (RPi; Raspberry Pi Foundation, Cambridgeshire, UK), MMA7455L accelerometer (Freescale Semiconductor, Austin, TX), and EW-7811Un wireless nano adapter (EDIMAX Technology Ltd., Taipei City, Taiwan). We chose the RPi as an inexpensive, yet robust, platform upon which to base the system. It was originally developed with the goal of reinvigorating the interest of children in the fields of science, technology, engineering, and mathematics (STEM), but projects such as the Iridis-Pi (University of Southampton, Hampshire, UK), an RPi supercomputing cluster, have demonstrated the device's flexibility. Given its myriad of features and low price point, the credit card-sized computer has stimulated a wide range of projects from users of all ages and backgrounds. The RPi utilizes a Broadcom BCM2835 system on a chip with a 700 MHz Advanced RISC Machine (ARM) processor, VideoCore IV graphics core, and 512 MB memory. It provides a non-volatile storage option via its secure-digital high capacity slot and contains various connectivity ports, including universal serial bus support for the wireless nano adapter. Crucial to the RPi's flexibility is its 26-pin expansion header, containing eight general purpose input/output (GPIO) pins and enabling convenient communication with peripheral devices—in this case, the MMA7455L tri-axis accelerometer. The MMA7455L is a low-cost, low-power, low-profile sen-

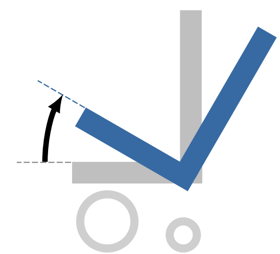

Fig. 1. Visualization of the tilt-in-space angle of a power wheelchair.

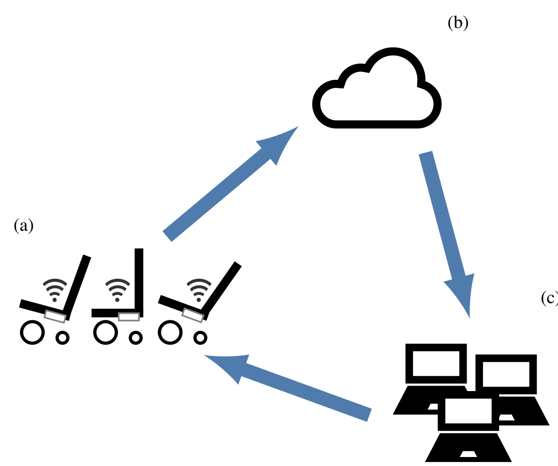

Fig. 2. A component overview of the wireless monitoring system. The tilt-in-space orientations of (a) power wheelchairs are logged by wireless monitoring devices. The data are automatically transmitted to the (b) server-side Raspberry Pi and served to the end users via a (c) Web interface.

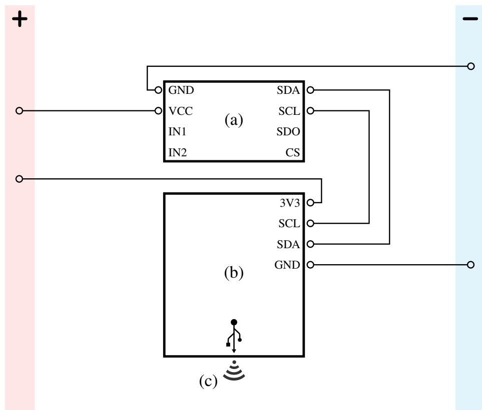

Fig. 3. A schematic of the wireless monitoring unit's components. The (a) MMA7455L sensor samples tri-axis accelerations for the (b) client-side Raspberry Pi, which automatically transmits the logged data to the remote server via its (c) wireless USB adapter.

sor featuring automatic temperature compensation, sampling speeds of up to 250 Hz, and an adjustable **g**-range of up to 16 **g**. In its prototype form, our system interfaces the sensor with the expansion header via the Pi Cobbler custom printed circuit board (Adafruit Industries, New York, NY) and a standard breadboard.

As the client-side RPi units record the tilt orientations of the power wheelchairs, the data are transmitted upstream to the server-side RPI unit where they are processed and served to the end users via a Web interface (Fig. 4). The client-side RPi units, which use the Arch Linux ARM operating system [22], communicate with the MMA7455L via the `i2c-dev` kernel module over the inter-integrated circuit (I^2C) bus, a synchronous serial protocol employing a single master device—in this case, the client-side RPi—with one or more slave devices—in this case, one MMA7455L sensor. A daemon script, written in the Python [23] programming language, uses the `smbus` module to read the three register values corresponding to the three physical axes ($\mathbf{x}$, $\mathbf{y}$, and $\mathbf{z}$), and samples are recorded at regular intervals based on a given sampling rate. Initial data are received as unsigned values ranging from 0 to 255 and are converted to signed values ranging from -128 to 127 ($\pm\mathbf{x}$, $\pm\mathbf{y}$, and $\pm\mathbf{z}$). The signed values are normalized to **g**-forces ($\mathbf{g}_x$, $\mathbf{g}_y$, $\mathbf{g}_z$) based on the selected **g**-range setting. Data are written as CSV files to a log directory that is watched by a `pyinotify` [24] daemon, and the output is periodically rotated to a new file. In the watched directory, each file creation triggers the `pyinotify.IN_CREATE` event. Upon the completion of the writing and closing of the file, the `pyinotify.IN_WRITE_CLOSE` event is triggered, and the file is automatically transferred to the remote server via the `scp` network protocol from the OpenBSD Secure Shell suite [25]. The `scp` utility facilitates secure remote data transfer by encrypting all network traffic and using public-key cryptographic authentication. Thus, the tunneled transmissions of the logged data are protected against malicious attacks, including eavesdropping and man-in-the-middle attacks.

The server-side RPi uses its own `pyinotify` daemon to watch for incoming data files. Although personally identifiable data are never transmitted, stored, or even logged in the first place, measures are in place to protect the logged sensor data. The users' sensor data are saved to their respective `$HOME` directories. Inherent filesystem permission mechanisms are afforded by the Linux kernel, restricting the visibility and access of `$HOME` directories to the respective users and administrative users. Once the data have been completely transferred and the file has been written, a data processing script is called to calculate the tilt angles from the component **g**-force vectors (Fig. 5). The relationship between the tilt angle (θ_{tilt}) and acceleration vectors (radial and tangential) is represented by the trigonometric relationship, $\theta_{tilt} = \arctan\left(\frac{radial}{tangential}\right)$. The element-wise inverse tangent calculations are calculated using the `numpy.arctan2` function on the `numpy.ndarrays` of the corresponding axial **g**-forces. The computed angles are inserted into the server database to be accessed as needed by the Django [26] application, a Python Web framework. Results are visualized using the `matplotlib` Python library and integrated into the Django views and templates. Access to each user's results is password protected via Django's built-in user authentication system.

B. Protocol

Preliminary testing of our system was performed using a Permobil C400 power wheelchair (Permobil, Lebanon, TN), capable of tilting up to 45°. Our monitoring device was powered by a power converter plugged into the C400 power supply unit. In addition to our wireless data logger, we also used a wGT3X+ accelerometer (ActiGraph, Pensacola, FL) in order to compare our method of automated online processing with a more conventional method of manual offline processing.

We tested two protocols using the 0°, 15°, 25°, and 35° tilt angles that were examined in our previous studies [7], [16]. In the first protocol, these angles were adjusted every 5 min [7]. Over the course of 40 min, a total of 15 min were spent in each of the 0° and 35° positions, and 5 min were spent in each of the 15° and 25° positions. In the second protocol, the 0° and 35° tilt postures were used at varying durations [16]. Over the course of 109 min, a total of 90 min were spent in the 0° position, and 19 min were spent in the 35° position. We attached our device and the wGT3X+ sensor to the C400 seat chassis's right and left sides, respectively. Data collection occurred in our laboratory, and the data from our logging system were sent to a privately hosted server located 1.3 miles from the laboratory.

C. Analysis

The tilt outcomes were calculated automatically as previously described and shown in Fig. 4. For the wGT3X+ sensor, the data were manually downloaded using the ActiLife 6 application (ActiGraph, Pensacola, FL) and processed using custom scripts in MATLAB R2012a (MathWorks, Natick, MA). The resulting tilt angle distributions between the two methods were compared by calculating the Pearson correlation coefficient ($\alpha < .01$) in SPSS 21 (IBM Corporation, Somers, NY).

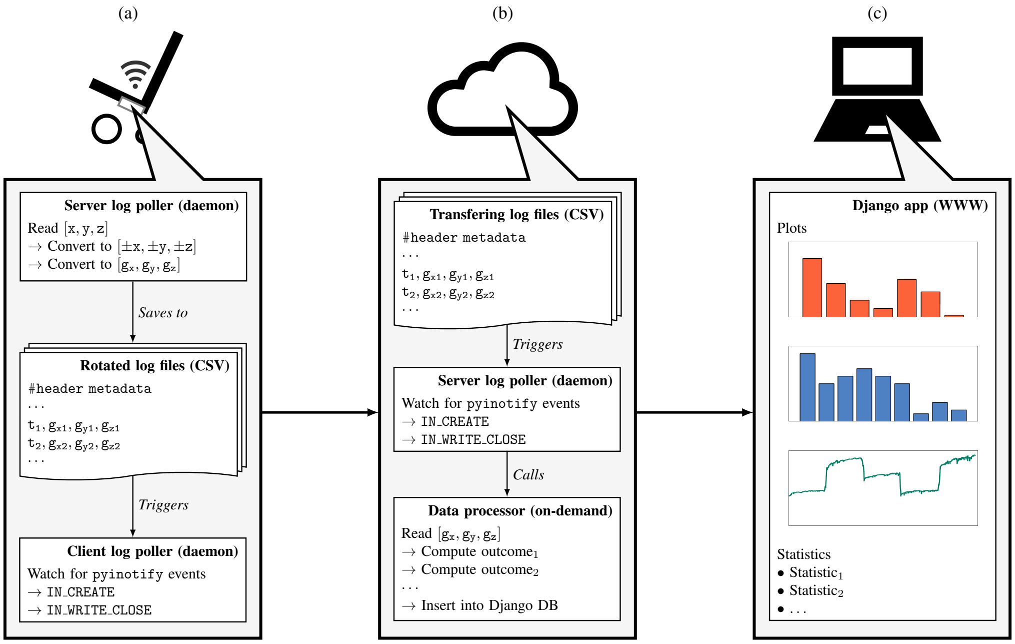

Fig. 4. A simplified process flow of the wireless monitoring system. The (a) client-side Raspberry Pi (RPi) units continuously collect and automatically transfer the logged data to the (b) server-side RPi for online data processing. The (c) Django application allows clinicians, researchers, and wheelchair users to view the results via a Web interface.

III. Results

For the first protocol, the distributions of tilt durations per angle were compared between our method of automated online processing versus the conventional method of manual offline processing (Fig. 6). Statistical testing showed a Pearson correlation coefficient of 1.00 between the two methods of data logging. For the second protocol, the distributions of tilt angles per testing period were compared between the two data logging methods (Fig. 7). Statistical testing again showed a Pearson coefficient of 1.00 between the two methods of data logging.

IV. Discussion

We developed a data logging framework that automated the repeatable tasks of the data collection process. Data were transmitted to, processed on, and served by a remote server located over a mile away from the data collection site. This automated, online approach aims to increase the feasibility and accuracy of monitoring wheelchair users in a long-term, large-scale setting.

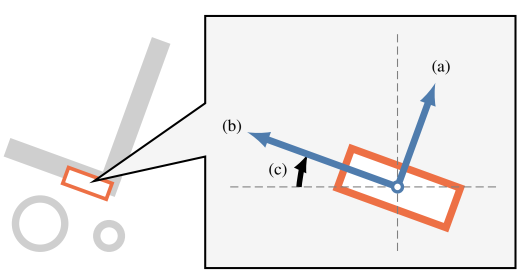

Fig. 5. The relationship between the (a) radial and (b) tangential acceleration vectors with the (c) tilt-in-space angle.

A. Increasing Feasibility of Longitudinal Monitoring

By reducing the required amount of time and manpower to manually install, maintain, and retrieve data through the monitoring process, our goal is to enable researchers to monitor more participants for longer durations. Traditionally, the remote monitoring process requires the physical initialization, retrieval, and maintenance of the data logging system. This was the process we simulated with the wGT3X+ test case. The sensor was initialized using the ActiLife 6 software, and after the data collection was completed, the data were retrieved using the ActiLife 6 software and analyzed using MATLAB scripts. In contrast, our wireless system streamlines the monitoring process by wirelessly transmitting the data to the server and automatically analyzing all data on the server using Python daemons. We compared our wireless monitoring system to the conventional data logging approach in order to verify that our automated online processing technique could produce comparable results to that of a manual offline processing procedure. Our system performed appropriately in these preliminary protocols, showing that long-distance data analysis could be feasible. Thus, our system may both broaden and deepen the scope of monitoring by reaching more participants and analyzing more data over longer periods.

B. Decreasing Observer-Expectancy Bias

To reduce the influence of the observer effect, we developed the system to operate inconspicuously for long periods of time. Whenever researchers and participants have to meet to physically download the logged data and perform device maintenance, the participants are reminded of the fact that they are being monitored. Moreover, regularly scheduled visits may disrupt their normal routines. The purpose of longitudinal

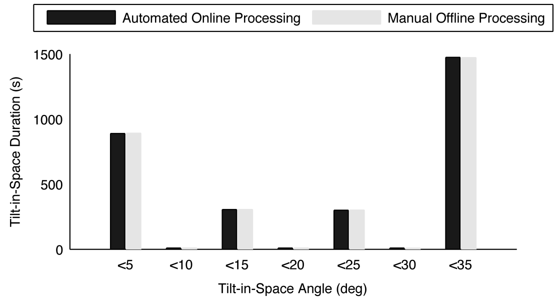

Fig. 6. Comparison of the distribution of tilt-in-space durations per angle from our method of automated online processing versus a more conventional method of manual offline processing.

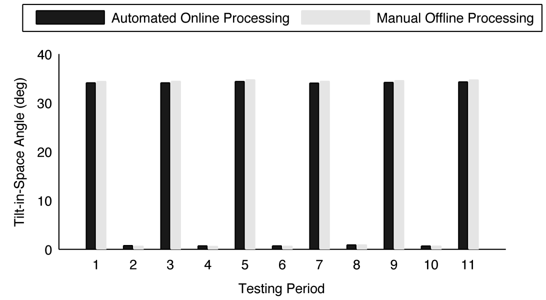

Fig. 7. Comparison of the distribution of tilt-in-space angles per testing period from our method of automated online processing versus a more conventional method of manual offline processing.

monitoring is to gain an accurate picture of natural daily behaviors, and disturbances to these natural behaviors may introduce unwanted influences on the data. Using our system, researchers would not need to physically download the data, and although occasional onsite visits may be required for proactive upkeep or reactive repairs of the electronic components, we anticipate these visits to be rare (e.g., every 6 months). The automated framework allows researchers to access the results remotely via a Web interface while limiting the observer effect.

C. Clinical Applications

In addition to learning about natural tilt behaviors, our system may be subsequently used to improve them. For example, wheelchair users could use the system's Web interface to learn if their tilt angles are large enough. The real-time, online accessibility to these data may help to improve compliance levels. Recent evidence suggests that tilt angles should be at least 35° to enhance skin perfusion over the ischial tuberosity [7], but these angles might not be used in practice. Sonenblum et al. [18] conducted a longitudinal monitoring study in which only 1 out of 16 wheelchair users tilted beyond 30° at least once daily. Their follow-up study [20] found that the participants tilted beyond 30° less than once per day on average. Yet, when asked to identify, verbally describe, and physically demonstrate various pressure-relieving maneuvers, roughly three-quarters of the participants succeeded. Nevertheless, the participants rarely used the maneuvers in daily life. One possible explanation is that the users are not fully aware of the actual duration and frequency distribution of their own tilt usage. Based on the inconsistencies between self-reported and logged usages [17], [18], this appears to be a plausible explanation. Power wheelchairs generally do not provide any indication of the current angles being used, and users are unlikely to manually measure and record each of their tilt maneuvers. Using our framework, the logging system would always be available via the Web portal, and wheelchair users could log into the Django application to receive real-time feedback or historical trends of their tilt angles based on empirically logged data. For example, one wheelchair user might believe that he or she regularly tilts beyond 35° until our Web application's angle histogram reveals that the angles never actually exceed 25°.

Furthermore, the real-time availability of our system's Web interface can help wheelchair users to learn if their tilt maneuvers last long enough. The distribution of tilt durations is important because the risk of pressure ulcers is related not only to the magnitude, but also the duration, of loading [27]. Jan et al. [16] recently reported significant differences in skin perfusion outcomes when contrasting 1-min with 3-min durations. Thus, even if two wheelchair users were to use the same average angles over the course of each day, the outcomes may differ based on the different duration distributions. Using our system, clinicians could conveniently sign into the Django application and review the users' tilt statistics without making physical house visits to retrieve the data. For example, one user might believe that he or she tilts twice per hour until our Web application's time series plots reveal that the frequency is closer to once per hour. Such scenarios may play an important role in boosting at-home adherence levels of tilt usage. From any location with internet access, the clinicians could 1) review the compliance of prescribed tilt regimens and 2) advise the wheelchair users about possible changes in routine (e.g., check why a certain user, at the same time every afternoon, seems to go for a couple hours without tilting).

D. Future Work

First, additional sensors will be added to monitor other clinical recommendations, such as wheelchair recline. Research has shown that a combination of tilt and recline provides the maximal amount of pressure relief [7], [13]. Second, we will begin catering the Web interface to the wheelchair users. Because of the accessibility and availability of our framework, it can become a powerful outreach tool to connect clinicians with the wheelchair users and promote at-home adherence of clinical guidelines. Kravitz et al. [28] demonstrated that the adoption of clinical recommendations was directly proportional to the amount of time devoted to getting that message across. Verbal and written agreements have also been shown to promote compliance with clinical recommendations [29]. When posed with direct commitments, users may feel a stronger obligation to adhere to prescribed regimens. With constant access to their usage patterns, wheelchair users may be more easily reminded of their prescribed tilt regimens and more motivated to comply. Our Web interface could present the user with milestones to meet or even incentives for completing various actions. Finally, we plan to leverage the capabilities of the cloud to provide an even more immersive experience for the wheelchair user. The Django application can be integrated with Google App Engine [30], and a mobile application can be developed in parallel for an even higher level of interaction with the wheelchair user, including status updates and notifications over the phone.

E. Limitations

Our preliminary testing of the monitoring system presented certain limitations. First, the system was tested on a single power wheelchair, so we were not able to report the system's performance between different drive motors and tilting mechanisms. Furthermore, it was an unmanned wheelchair within a controlled laboratory setting. Thus, we could not account for real-world factors, such as sensor noise from driving and activities of daily living.

V. CONCLUSION

We developed a wireless monitoring framework to automatically gather, retrieve, and analyze wheelchair tilt usage. Web technologies allow the system to be remotely accessible to all involved parties, including clinicians, researchers, and wheelchair users. In contrast to conventional data logging methods that require the physical retrieval and maintenance of data loggers, our system streamlined this process by automating the repeatable tasks. Furthermore, we used free software and relatively inexpensive components with the hope that clinics and nursing homes will be able to reasonably deploy the monitoring system for their wheelchair users. Because of these features, our system can accommodate the large-scale, longitudinal monitoring of wheelchair tilt and provide important insight into the longitudinal compliance of clinical tilt recommendations in daily life.

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