DEVELOPMENT AND EVALUATION OF A SMARTPHONE VIRTUAL SEATING COACH APPLICATION TO FACILITATE POWERED SEAT FUNCTION USAGE FOR POWERED WHEELCHAIR USERS

by

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Powered wheelchairs with powered seat functions (PSFs) are prescribed for wheelchair users who are unable to adjust their postures or manage their seating pressure independently because of motor and/ or sensory impairments. However, a novice powered-wheelchair user might not have appropriate or sufficient training on using PSFs due to the limited time in clinics or complex situations in real-life environments. The Human Engineering Research Laboratories have developed the Virtual Seating Coach (VSC) which records PSF usage and reminds users to adjust their PSFs.

This research project was to develop a smartphone virtual seating coach (SVSC) and investigate several improvements. The SVSC used low-cost accelerometers to detect the seating angles which decreased the complexity of the sensor installation. By using the smartphone for information display and integrating the electronic components into the phone holder, the SVSC significantly decreased the dimension and increased the clearance of the whole system. A usability study has been conducted from five powered wheelchair users and five rehabilitation professionals to gather their feedback and refine the SVSC.

In order to overcome the limitation of the internal storage in the system and enable the PSF usage to be reviewed by clinicians in real time, a prototype web service was constructed for

data storage and data visualization. This web service allowed the SVSC to upload the daily PSF usage data from different users and provided the longitudinal PSF data plots for review.

Ten powered wheelchair users were recruited for a three-week in-home trial to evaluate the effectiveness of SVSC. The compliance rate of performing repositioning exercise has increased around 44% after the intervention of the SVSC. The results also show that the users' attention and decision toward the reminders can be predicted by context factors collected from the smartphones' sensors (around 80% and 75% accuracy respectively). Furthermore, the negative correlation between the frequency of using PSFs and the wheelchair discomfort indicate the need for dynamic seating posture and suggested that the SVSC could implement this functionality to remind users to change their seating angle periodically to improve wheelchair comfort.

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PREFACE

This Ph.D. dissertation contains the results of research undertaken at the Department of Rehabilitation Science and Technology of the University of Pittsburgh and Human Engineering Research Laboratories of VA Pittsburgh Healthcare System. The research was conducted under the supervision of Professor Rory A. Cooper from September 2011 to November 2014. This research was completed with the support of the National Science Foundation (Grant #EEC0540865 - Quality of Life Technology Engineering Research Center), VA RR&D (Merit Review Grant # B6591R - Powered Seating Function Usage among Veterans-Compliance and Coaching), and the University of Pittsburgh. This research is also sponsored by Permobil which provides the powered wheelchair for development the new SVSC system. Without funding and supports from these sources, this project would not have been completed.

I would like to thank my advisor, Dr. Cooper, for his mentorship and confidence in me and giving me the opportunity to carry out this project. Also, I would like to thank my dissertation committees, Dr. Siewiorek, Dr. Ding, Dr. Pearlman and Annmarie Kelleher, for their invaluable support and guidance. I would like to thank Josh Brown and Brandon Daveler for their professional work on the phone cradle and the electronic design for the smartphone virtual seating coach. I would like to thank Cheng-Shiu Joshua Chung for providing suggestions on developing the smartphone virtual seating coach app. I would like to thank Hsin-Yi Tanya Liu.

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Thanks to all of my friends and family who have supported me through this process. To my wife Ying-Chen Chen. We have our first son, Ryan Wu, four months before my dissertation defense. You were taking care of our son and letting me focus on my study. Your love and support are the priceless gifts in my life.

1.0 INTRODUCTION

Powered wheelchairs with powered seat functions (PSFs) are prescribed for wheelchair users who are unable to adjust their postures or manage their seating pressure independently because of motor and/ or sensory impairments. The PSFs include tilt-in-space, backrest recline, legrests elevation and seat elevation, which allow powered wheelchair users to maintain a better position on their wheelchairs, to redistribute the pressure on the areas that have high possibility of skin breakdown, and to improve driving safety including the prevention of tipping over and stabilizing the position while driving wheelchairs. Due to motor and/ or sensory impairments, the PSFs become an important method for powered wheelchair users to change their posture dynamically and periodically. The repositioning exercise is through altering tilt and recline angles to adjust to a better alignment, redistribute the pressure on their back and buttocks and maintain a good posture in their wheelchair. However, a novice powered-wheelchair user might not have appropriate or sufficient training on using PSFs due to the limited time in clinics or complex situations in real-life environment. It would be helpful to have a tailored system on each novice powered-wheelchair user's wheelchair to encourage and facilitate them to appropriately utilize the PSFs. The Human Engineering Research Laboratories (HERL) has developed the Virtual Seating Coach (VSC) system [1] to achieve this goal. In this chapter, the importance of using PSFs is first discussed. The second part introduces the current tablet version VSC and the challenges of a tablet VSC.

1.1 THE IMPORTANCE OF USING POWERED SEAT FUNCTIONS

1.1.1 Postural realignment

PSFs can provide users with dynamic postural support. Through altering tilt and recline angles, the gravity-assisted positioning mechanism helps people with poor head or trunk control maintain seating stability and adjust to proper alignment. [2] Adjusting posture dynamically and maintaining proper postural alignment by using PSFs in powered wheelchairs is very important for managing complications such as orthostatic hypotention, autonomic dysreflexia, spasticity, edema, and so on. [3]

Even though PSFs provide many clinical benefits, inappropriate usage may result in poor seating posture in some situations. For example, when resuming an upright position after performing a repositioning exercise with a tilt and recline angle combination, the correct sequence of moving back is to recline the backrest first and then to tilt the seat back. If the sequence is done the opposite way, it will increase the chance that the user might slide forward in the wheelchair when tilting back the seat with a large recline angle, leading to poor seating posture and increasing shear force applied on the soft tissue of the weight-bearing area. Another example is elevating the legrests to decrease lower limb edema. When elevating legrests, the backrest needs to be reclined backward to release the tension in the hamstring muscles which could pull and rotate the pelvis posterior, resulting in a slouching posture. This slouching posture would cause muscular fatigue issues because of poor head and neck posture and reduce vital organ function [3]. These scenarios are avoidable, as long as users remember the proper way to adjust the seating angles. However, new powered-wheelchair users might ignore this critical detail when adjusting the PSFs, especially for the users who have limited trunk proprioception and neuromuscular control after injury and unable to recognize they are in a bad posture. [4]

1.1.2 Pressure relief

Pressure ulcers refer to localized tissue necrosis, caused from soft tissue being compressed between a bony prominence and an external surface for a long period of time [5]. The healthcare system in the United States spends around 11 billion dollars per year for the treatment of pressure ulcers [6]. In addition to the huge expenditure to the healthcare system, pressure ulcers also result in an increased risk of infections. This complication causes deconditioning of patients, which may require rehospitalization. Powered wheelchair users have a relatively high risk of getting pressure ulcers because of their immobility. To prevent the occurrence of pressure ulcers, performing repositioning exercise as many times as possible during the day with a sufficient tilting angle is necessary. However, previous studies have shown that some powered wheelchair users still get pressure ulcers, even though they reported that they did perform repositioning exercises. One possible reason is that these users did not perform their repositioning exercises with a sufficient tilting angle [7, 8]. The other possibility is that the frequency of performing exercises is not done enough [9]. These two reasons lead to insufficient skin perfusion to soft tissue, which increases the possibility of developing pressure ulcers.

For this reason, frequent and well-performed repositioning exercises allow the area of bony prominences to redistribute the pressure, thus reducing the chance of developing pressure ulcers on these areas [10]. The most effective repositioning exercise is via tilt and recline combination. Previous study which investigated different tilt and recline angles on skin perfusion by using Laser Dopper Flowmetry over the ischial tuberosities area in people with spinal cord injury [11] found that the tilt angle should be greater than 25º with recline angle at 100º at least. This position has been found to be sufficient for effective pressure reduction to increase skin perfusion. Even though the education of performing repositioing exercises is implemented well in clinics, current powered wheelchairs, however, lack the seating angle display. It would be a challenge for most powered wheelchair users to recognize if they performed an effective repositioning exercise.

1.1.3 Driving safety and stabilizing the position while driving

The PSFs can help users prevent tipping over and maintain a good position on the wheelchair while driving. Previous research into accidents of wheelchair users [12] has shown that there was a high possibility of the wheelchair tipping and falling when going uphill or downhill. Although powered wheelchairs are heavy, there is still a chance that a powered wheelchair might tip over backward when traveling uphill because of an excessive tilt angle. Likewise, users may fall forward or slide forward when going downhill due to an insufficient tilt angle. Therefore, appropriate seating angle adjustment is very important to help prevent wheelchairs from tipping over and to maintain safe positioning of users on the wheelchair while driving on a slope. Additionally, approriate adjustment of the tilt and legrests angle can not only allow the wheelchair to have ground clearance when users encounter environments with obstacles, but also can prevent users from sliding out of the wheelchair when braking [13]. A system on the wheelchair which can detect terrain changes and instruct the users to adjust the wheelchair would be a potential application to improve driving safety and position stabilization for the users while driving their wheelchairs.

1.2 THE IDEA OF VIRTUAL SEATING COACH

1.2.1 Introduction of tablet virtual seating coach

In order to facilitate powered wheelchair users in utilizing PSFs based on clinical recommendations and extend the PSFs training into users living situations, HERL has been developing and testing the VSC [1, 14, 15]. This technology includes the data logger to record the PSF usage and a central processing system to give wheelchair users real-time feedback and reminders by comparing the usage with clinical recommendations. The idea of VSC is that a series of sensors and encoders are mounted on a power wheelchair equipped with PSFs, as shown in Figure 1, to monitor seating angle changes. An electronic box attached at the backrest contains the electronic devices for connections between encoders and tablet such as USB hub, analog to digital converter, DC/DC converter, etc. A 10-inch tablet is mounted at the end of the armrest and the holder has a swing away mechanism and provides a variety of adjustability. All the electronic devices, encoders and tablet are powered by the wheelchair batteries. The VSC software receives seating angles, seat height, wheelchair occupancy, and driving status data from the encoders and sensors. The software also compares the PSF usage data with clinical recommendations and provides appropriate reminders. In the study evaluating the tablet VSC, the results have shown that VSC increased subjects' compliance rates for performing repositioning exercises [1, 16].

Figure 1. The sensors are installed on the wheelchair for the tablet virtual seating coach. [1]

1.2.2 Challenges of the tablet VSC

In the tablet VSC study, we must provide the participants with our research powered wheelchairs equipped with the VSC system rather than installing the VSC on their own wheelchairs, because of the complicated and time-consuming sensor installation. This reason resulted in the challenge of recruitment in the tablet VSC study and decreased the possibility that the VSC could become a widespread application. The large dimension of the powered wheelchairs due to the electronic devices challenged the users' home environment accommodations. All the PSF usage data was stored in the tablet, so the data storage was limited and the data was difficult to be analyzed in real time. These challenges decreased the usability and practice of the tablet VSC. The following sections discuss each challenge in detail.

1.2.2.1 Complicated and time-consuming process of sensor installation

One main challenge of the tablet VSC is the complicated and time-consuming process to install the encoders and sensors on a powered wheelchair. In order to install the encoders on the wheelchair externally, customized cases needed to be designed to allow these encoders to be mounted on the axis of PSFs to obtain the accurate measurements. This process sometimes requires permanent modifications to the wheelchair to accomodate the shape and size of the encoders. This challenge makes it difficult to apply this system on different types of wheelchairs, because different designs of customized cases corresponding to different structures of powered wheelchairs were needed. Also, it greatly decreases the possibility of applying the VSC on users' wheelchairs, because the sensor installation could void warranty. Figure 2 has shown two different research powered wheelchairs (Pride Q6400Z and Permobil C500) equipped with VSC. As shown, different encoders' cases were designed to accommodate the structure of the powered wheelchairs to measure the seating angle changes. In addition, the electronic boxes on the back of the wheelchairs also needed different designs to mount on different wheelchairs.

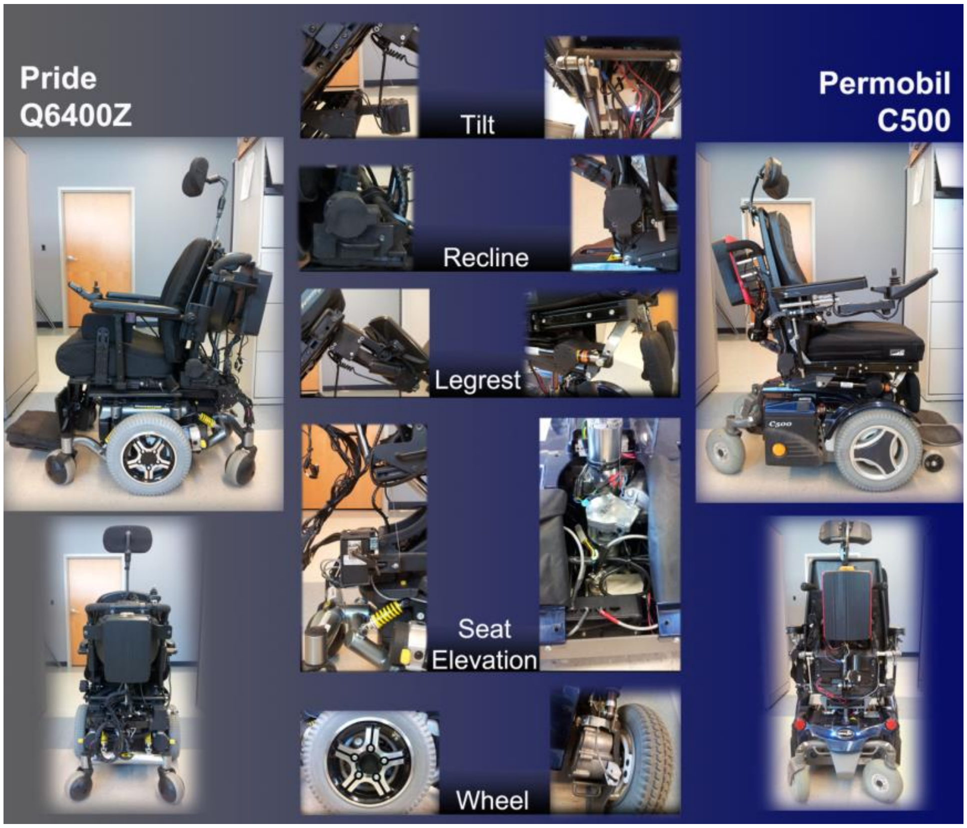


Figure 2. Different encoders' cases design to accommodate different structures of powered wheelchairs to measure the powered seat functions usage.[1]

1.2.2.2 Enlarge the dimension of the powered wheelchairs

One electronic box installed behind the backrest integrates the USB hub, A/D converter, DC/DC converter and power supply for all the sensors and sends the sensors' information into the tablet. Figure 3 shows the internal design of the electronic box in detail. It consists of a SEI hub connecting to all the encoders, a DC/DC converter for power supply, a SEI-USB adapter to send digital data of encoders to the tablet, and an Arduino for measuring the temperature and brightness. The electronic box was also designed for inserting the tablet in a way that would collect data without displaying the information to users. This design enlarges the dimension of the wheelchairs, requiring more space for turning. In the tablet VSC study, some participants had to be withdrawn, because some living environments may not allow the large dimesion wheelchairs. In addition, even though the tablet could swing away, some users reported that the dimension of tablet might sometimes interfere with their daily activity especially when doing transfers. Moreover, the tablet is designed to run the VSC program only and does not allow users to conduct other functions on the tablet, which further decreases the usability of application and willingnes of users to use this system.

Figure 3. The electronic box of the tablet VSC. [1]

1.2.2.3 Data storage limitation and offline analysis with low efficiency

In our seating function data logger (SFDL) [17] and tablet VSC applications, the size of data storage was mainly determined by the size of the devices' internal storage, so it would be challenging to use the device for a longer time and backup the data periodically. Additionally, the data must be exported from the devices for analyses, which increased the inconvenience to review the data for researchers or clinicians. If the size of the data was relatively large, it could also take longer time for analysis.

Another issue was that the SFDL and the tablet VSC purely recorded the seating angle data. One analysis program took the raw data and produced the information after making calculations and analyses. When the size of the data was large, the analysis process would take more time and the risk that the incomplete or damaged data could cause errors in this offline analysis program would be higher.

1.2.2.4 Unable to review the PSF usage by the clinicians in real time

In the tablet VSC study, we have defined some important variables to evaluate the performance of using PSFs. These variables could be potentially related to health issues or quality of life. For example, wheelchair occupancy is defined as the time that users stay in their powered wheelchair in one day. This variable is able to give the clinicians and therapists an idea whether the users use their wheelchairs and evaluate if the wheelchairs meet the users' expectation. The compliance rates of performing repositioning exercises is an important index to evaluate one's performance of doing the repositioning exercise according to clinical recommendation. A powered wheelchair user is expected to perform the repositioning exercises with a sufficient tilt angle, duration and frequency for optimal effect to reduce the possibility of development of pressure ulcers. [7, 9] A clinician usually recommends a repositioning regime for their clients. The regime includes the frequency of performing repositioning exercises, the desired seating position (seating angles), and the duration that the participant should stay in the desired position for optimal effect. For example, the clinician may recommend that a user reposition once every hour with a desired position of tilting the seat more than 30 degrees, and the participant staying in that position for more than 2 minutes. If a user performs the repositioning exercise once every hour; his/her compliance rate would be 100% according to the example. If the user sits in his/her wheelchair 4 hours and only performs two repositioning exercises every two hours, the compliance rate would be 50% (2/4 x 100%). The frequency of using PSFs records the changes of PSFs within a day which include the time and angle/position changes when a user adjusts their PSFs. Periodically changing the tilt and recline angle was reported to decrease the sitting discomfort in wheelchairs. [17-19] This variable could indicate whether the users are dynamic or static sitters, and the clinicians can encourage users to adjust their PSFs more frequently to achieve a better sitting comfort according to their performance.

However, there is no tool to analyze and present PSF data in an organized way which can be reviewed by clinicians quickly and easily. This tool could be useful for them to review their clients' PSF usage periodically and allow clinicians to communicate with their clients and customize the repositioning exercise program or encourage their clients to utilize their PSFs more frequently.

1.3 THE AIMS OF THIS RESEARCH PROJECT

The complicated and time-consuming sensor installation process is one challenge of the tablet VSC to apply to every users' wheelchairs. Also, the electronic box which enlarges the size of the wheelchair and decreases the clearance of the wheelchair decreases the users' willingness of using the VSC. To overcome these two challenges, In **Chapter Two**, the new development of VSC is reported. The new development uses low-cost accelerometers to detect seating angles and a smartphone app to display the information and remind users to use PSFs (smartphone virtual seating coach). A usability test was conducted from five powered wheelchair users and five rehabilitation professionals for the first prototype. According to the feedback from the usability test and the partnership with Permobil, some improvements of the system have been accomplished. In **Chapter Three,** the development of a prototype of web service is presented. The purpose of the web service is to solve the data storage issue and provide the real-time data visualization for clinicians. In **Chapter Four**, ten powered wheelchair users were recruited to investigate the effectiveness of the smartphone virtual seating coach. In **Chapter Five**, a study further investigated the relationship between the frequency of using PSFs and wheelchair discomfort and the results suggest the improvements for the future smartphone virtual seating coach. **Chapter Six** is a summary of this research study and directions for future studies.

2.0 DEVELOPMENT OF A SMARTPHONE VIRTUAL SEATING COACH APPLICATION

One main purpose of developing the Smartphone Virtual Seating Coach (SVSC) was to simplify the sensor installation process. We decided to use accelerometers to detect the seating angle changes and use hook and loop fasteners to attach the accelerometers to wheelchairs. [20] To decrease the dimension of the whole system, we selected smartphones as a platform to develop the SVSC app and integrated electronics (a microcontroller, a DC/DC converter, etc.) into a phone cradle. We conducted usability testing for our first prototype to gather feedback from powered wheelchair users and clinicians. According to their feedback and the partnership with Permobil, the SVSC can access the built-in actuators on Permobil wheelchairs via Bluetooth communication and the user interface was improved.

2.1 DESIGN CRITERIA

General

The SVSC system should not interfere with any wheelchair function and PSFs.

Software

1) The SVSC should be able to run in the background to monitor PSF usage continuously without interfering with any other app on the smartphone.
2) The SVSC should be activated automatically when the connection between the sensors and the smartphone has been established to prevent users from forgetting to run the SVSC.
3) Data of seat position and wheelchair status were recorded and saved with a timestamp constantly into the smartphone SD card.
4) The SVSC app should have the built-in algorithms to perform the real-time analyses and save the results in the database format.
5) Activation of the repositioning exercise and safety warning reminders should be recorded and saved into the SD card.

User Interface

1) The interface should display the seating angles to users clearly.
2) The SVSC should allow the user to change the reminders into audio or vibrate modes automatically based on how they set up the system mode.
3) The SVSC should provide a simple summary report of PSF usage and plots as the feedback to the users.

4) The SVSC should provide supplemental information, such as how to initialize the app, the introduction of PSFs and contact information if the users encounter any problems.

Repositioning Exercise Reminders

1) The SVSC should periodically (frequency) give reminders to perform repositioning exercises and instruction in the tilt and recline angles (position) and duration to stay in the position (duration).
2) The frequency, position, and duration of the reminder should be able to be modified by a clinician.
3) The user should be able to snooze or dismiss the reminder and the reminder can be automatically scheduled for the next cycle.
4) If the user ignores the reminder, the SVSC should snooze the reminder automatically.
5) If the user has performed a repositioning exercise without the reminder, the SVSC should reschedule the next reminder according to the last effective repositioning exercise.

Safety Warning Reminders

1) The SVSC should give safety warning reminders when detecting inappropriate use of PSFs (Table 1).
2) The criteria to activate the safety warning reminders should be able to be modified by the clinician.
3) If users ignore or dismiss the warning, the SVSC should repeat the reminders later.

Hardware

1) The sensors should be able to be applied on different kinds of powered wheelchairs without any problem.

2) The smartphone holder should be able to mount on different powered wheelchair and should not interfere with the users’ daily tasks.
3) The hardware should be as low-profile as possible and should not increase the dimensions of the powered wheelchair.
4) The hardware should be easily powered by wheelchair battery by plugging in the wheelchair socket and the energy consumption of the SVSC should not affect the user’s regular driving routine.
5) The hardware should be able to withstand vibration and stresses during normal wheelchair use.
6) The hardware should cause no harm to the users.

Table 1. Six warning conditions that the Virtual Seating Coach will detect; and day averages of activated frequency and participant compliance of each warning.

	Trigger Condition	Adverse Effect of the Condition
W1	Sit without the seat tilted.	The user might slide out of the wheelchair or the upper body might bend forward if they don’t have adequate trunk control ability.
W2	Recline the backrest when the seat is not tilted.	The user will tend to slide out of the wheelchair and assume a posterior pelvic tilt and slouching posture.
W3	Elevate legrests without reclining the backrest.	Hamstring muscles may be stretched over range and pull the pelvis rotated posteriorly, leading to a posterior pelvic tilt and slouching posture.
W4	Tilt the seat and recline the backrest excessively.	The user may slide backward in this extreme position.
W5	When the seat is tilted and backrest is reclined on the uphill.	The risk of flipping backward is increased because the center of mass moves backward.
W6	When the seat is not tilted on the downhill.	The user may slide forward.

2.2 THE FIRST PROTOTYPE OF THE SMARTPHONE VIRTUAL SEATING COACH

This section discusses the details about the first prototype of SVSC including hardware and software. Some of the results in this section have been published as *A Smartphone Application for Improving Powered Seat Functions Usage: A Preliminary Test*. in *Rehabilitation Engineering and Assistive Technology Society of North America Conference*. 2013. Seattle, WA: RESNA. [20]

2.2.1 Hardware

Accelerometer

Four accelerometers (DKSB1002A, DigiKey Electronics) were used in the development. A power supply of 3.3 volts was provided to the accelerometers via an Android IOIO board (Sparkfun Electronics). The accelerometers' signal output was connected to an analog input port on the Android IOIO board for analog to digital conversion. This digital data were sent to an Android smartphone via a USB cable.

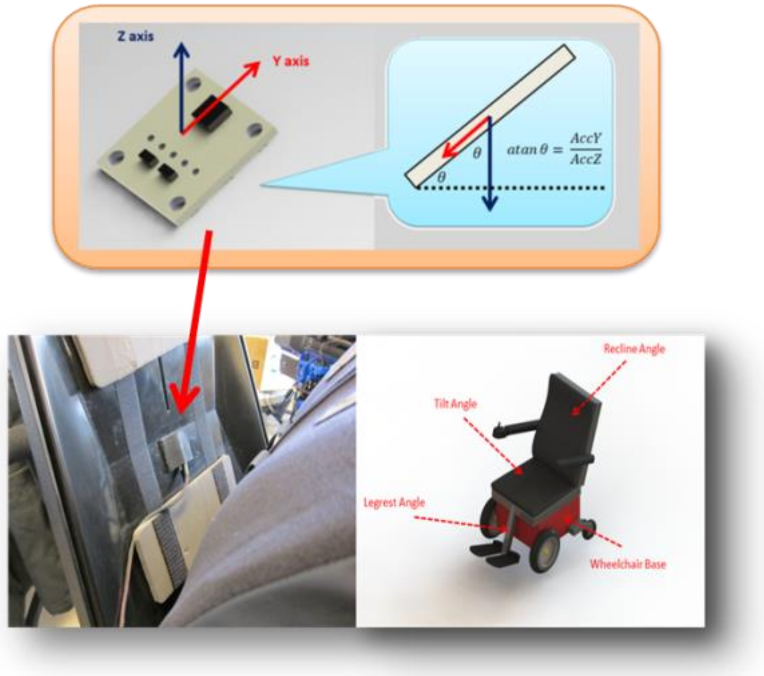


Figure 4. The concept of using accelerometers to determine the seating angle and the locations where the accelerometers were on the powered wheelchair.

Two vectors (y and z axis) were used to determine the tilt angle of the accelerometers. (Figure 4) These four accelerometers were placed on the seat pan, backrest, legrests, and the wheelchair base to detect the tilt, recline, legrests, and wheelchair base angles. In order to increase the efficiency of installation and attempt to apply our system to various types of powered wheelchairs, the accelerometers were attached to the powered wheelchair using hook and loop fasteners.

Phone Cradle Design

A phone cradle was used to hold the smartphone securely which used a hinge joint to open or close the lock by a magnetic mechanism. (Figure 5) In addition, the phone cradle integrated a micro USB connector, so users only need to slide a smartphone into the phone cradle and plug the micro USB connector into the phone.

Figure 5. The CAD of the phone cradle.

The system is directly powered by the wheelchair's battery through the charging socket. A DC/ DC converter converts the 24 volt (battery output voltage) to 12 volt to power the microcontroller. All the connectors for accelerometers connect to the analog input port on the microcontroller for analog to digital conversion. These digital data are sent to an Android smartphone via a USB cable (Figure 6).

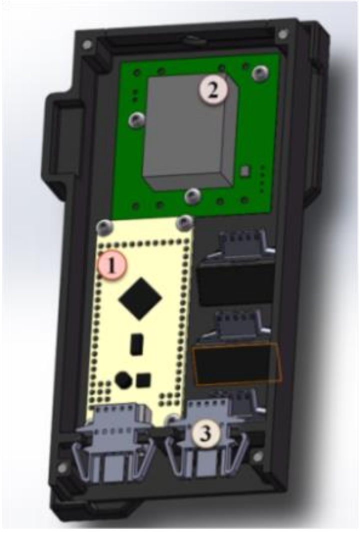


Figure 6. The internal design of the phone cradle. (1) Android IOIO board. (2) DC/DC converter. (3) The adapter connecting the accelerometers.

<u>Mounting Parts of the Phone Cradle</u>

In order to mount the phone cradle on the armrest of wheelchairs, we utilized three different mounting parts regarding different types of powered wheelchairs. A loc-line® was used to connect the phone cradle to the mounting parts (Table 2).

Table 2. Three different mounting parts regarding to different types of powered wheelchairs.

	▪ Magnetic Base The armrest of some powered wheelchairs are made of metal, which can allow the magnetic base to attach to it.
	▪ Rod mount This can be applied to most of powered wheelchairs, since we can mount this part on the joystick's pole.
	▪ Unitrack mount: Most Permobil wheelchairs have the Unitrack on their armrests.

Power Supply

The phone cradle was mounted on the armrest which is the same side with the joystick to get power supply from the charging socket of the joystick (Figure 7).

Figure 7. The red arrow indicates the power jack getting the power supply from the charging socket of the joystick on a powered wheelchair.

2.2.2 Software

The software design concept (Figure 8) was that the data collection runs as a background program, called a “service”, in the Android system. The user interface was an application that accesses the seating angle values from this background service.

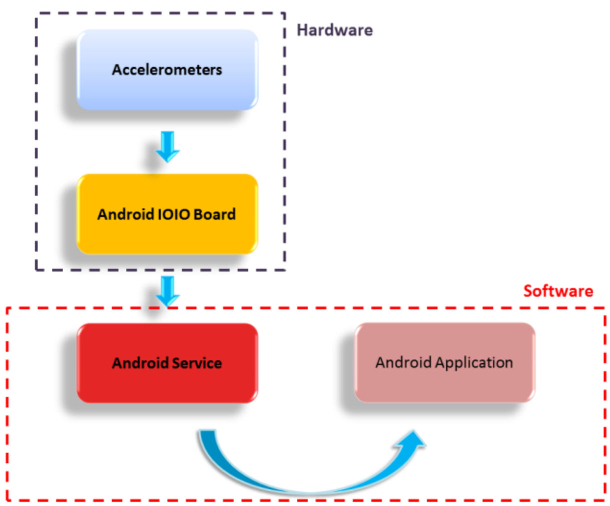


Figure 8. The flowchart shows the concept of how the accelerometer data is sent to the smartphone and how the smartphone handles the data.

The purposes of this background service are:

1) Requesting the Android IOIO board to send the accelerometer data to the phone continuously.
2) Detecting the connection between the Android IOIO board and the smartphone.
3) Monitoring PSF usage continuously without affecting other applications.
4) Broadcasting the PSF data, so other applications can access the seating angle values.

The features of the smartphone app are as follows:

1) The SVSC app runs automatically to increase the convenience for powered wheelchair users:

   The SVSC app automatically starts running once the connection between the smartphone and the microcontroller is established by either a USB cable or Bluetooth communication.

   The SVSC app has a background service that can detect the connection between the smartphone and the microcontroller periodically. Once the connection has been established, this service will start to request the data from the microcontroller. This will also trigger the SVSC app to start running, recording the data into a file and monitoring the PSF usage. Another feature is that when the connection is established, the smartphone screen will automatically turn on and show that the SVSC app is running. This can give users feedback to let them know that the SVSC app is running successfully. In addition, this could be a potential application for turning on the screen, since most smartphone power buttons are too small for people with fine motor difficulties.

2) Displaying PSF information:

The application shows the seating angle information based on the tilt angle of the accelerometers (Figure 9). Users can clearly and easily read the tilt, recline, legrests, and wheelchair base angles and have a direct angle value feedback when changing their PSFs. This feature is very critical, since most powered wheelchairs do not display the seating angle, leading to the fact that even users know that a 30 degree tilt angle can decrease the pressure on their buttocks significantly, but they have no reference when tilting their chair. This feature can ensure that users adjust their powered wheelchair appropriately. After the usability test, a new angle display interface was designed, which enlarged the text size and made the angle information much clearer.

Figure 9. The main screen of the SVSC app displays the current seating angle of PSFs.

3) The SVSC monitors and records the PSF usage in the background without affecting other smartphone functions such as calling, texting, etc:

The background service of the SVSC app keeps requesting data from the microcontroller as an independent thread in the smartphone without affecting other smartphone functions or being affected by other functions. Even when the smartphone is running other applications such as a web browser, Facebook and so on, this feature can ensure our system monitors PSF usage at all times.

4) Providing safety warning and repositioning reminders to the user:

The SVSC app reminds users with text messages or pop-up dialogs when safety reminders are triggered. In addition, the SVSC app reminds users to perform repositioning exercises within prescribed periods of time. By clicking these reminder messages, the SVSC app will lead the users to an instruction screen, where the users can follow the instructions and angle meters to adjust their PSFs properly (Figure 10).

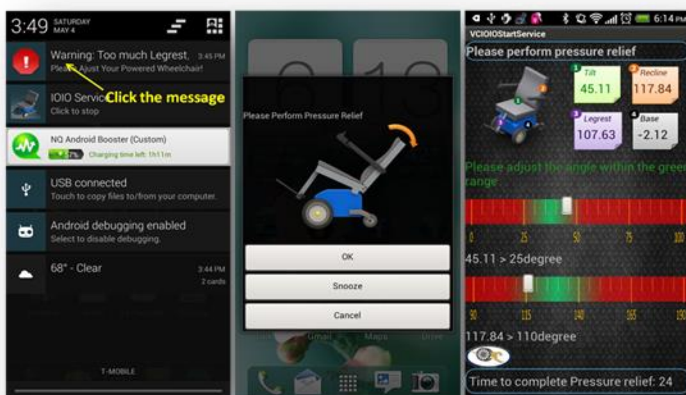


Figure 10. The reminders of powered seat function usage (left) and pressure relief (middle). The instruction menu indicates how the users can follow the instructions to adjust their powered wheelchair.

5) Recording angle data to files:

The background service activates a file recording thread to record the seating angle data with a 1 Hz sampling rate into text files. Those text files are saved onto the SD card within smartphones.

6) Recording the number of reminders to a database system:

The background service records for each reminder that users get within a day into a database system (Figure 11). This database information is saved onto an SD card within the smartphone.

Figure 11. Saving safety reminders in Sqlite form.

In addition, the SVSC can analyze the time that users stay in different angle positions in real-time and save this information onto a database system (Figure 12).

Figure 12. Saving the duration that a user stays in a certain angle range in Sqlite form.

7) Summary of PSF usage to users:

The SVSC app can provide a summary of PSF usage by analyzing the data from the database. Users can review their progress when using PSFs (Figure 13). The goal is to increase the compliance rate of performing repositioning exercises and to decrease the number of seating function usage warnings.

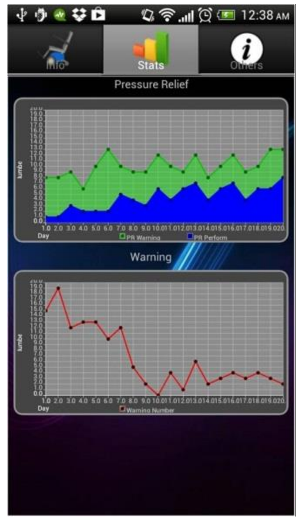


Figure 13. Chart plots give users their performance feedback. It includes the compliance of performing repositioning exercises and the number of safety reminders the users get every day.

8) General information menu:

This section gives users a brief introduction of the SVSC system, information on using PSFs, and step by step guidance on how to start the SVSC app (Figure 14).

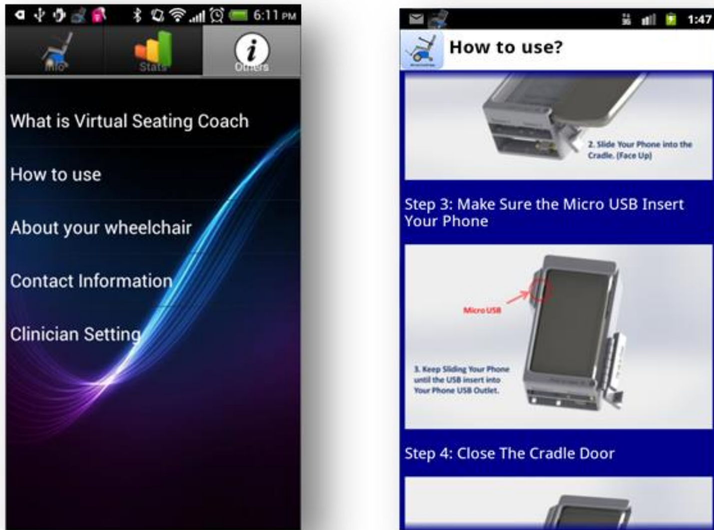


Figure 14. (Left) The general information provides some information about SVSC. (Right) The "How to Use" section provides step-by-step instructions on how to use the SVSC app.

9) Clinician section for customizing the reminders to different users:

The SVSC app contains the clinician setting section where clinicians can customize the reminder settings to different users. This is an important feature that allows the system to meet different users' needs and extend the PSF usage into users' real-life situations.

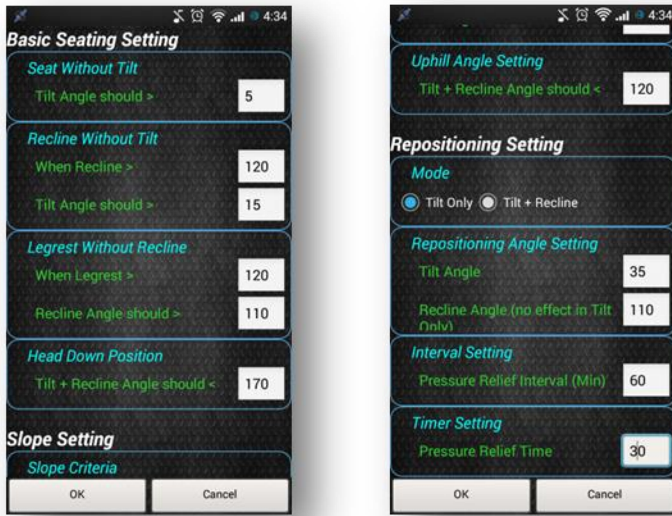


Figure 15. Different reminder settings allow clinicians to customize the coach program to individual users.

2.3 EVALUATING THE USABILITY OF A SMARTPHONE VIRTUAL SEATING COACH APPLICATION FOR POWERED WHEELCHAIR USERS

2.3.1 Introduction

Conducting a usability test on the first prototype was necessary as this gave us the chance to gather feedback from end users and refine our system. According to ISO 9241-11, the definition of usability is "the extent to which a product can be used by *specified users* to achieve *specified goals* with effectiveness, efficiency, and satisfaction in *a specified context of use*". [21] The reason for conducting usability testing was so the developers or designers had the opportunity to observe the target population that actually interacted with their products. The developers/designers needed to understand what works for the population and what does not, rather than how they think the target population was supposed to interact with the product.

Figure 16 shows the iterative design/development process. [22] This process can be categorized into three main phases: analysis, development, and post release. The analysis stage mainly focuses on gathering the product requirements from users, tasks, or market. The development team might conduct data collection by survey or focus group. For the VSC, our research group observed that powered wheelchair users, especially novice users, do not utilize the PSFs appropriately. Certain critical health related issues could occur if wheelchair users don't perform effective repositioning exercises to realign their posture in their wheelchair or redistribute the pressure on their back and buttocks. Even if users may utilize PSFs, an inappropriate adjustment might result in poor posture on the wheelchair.

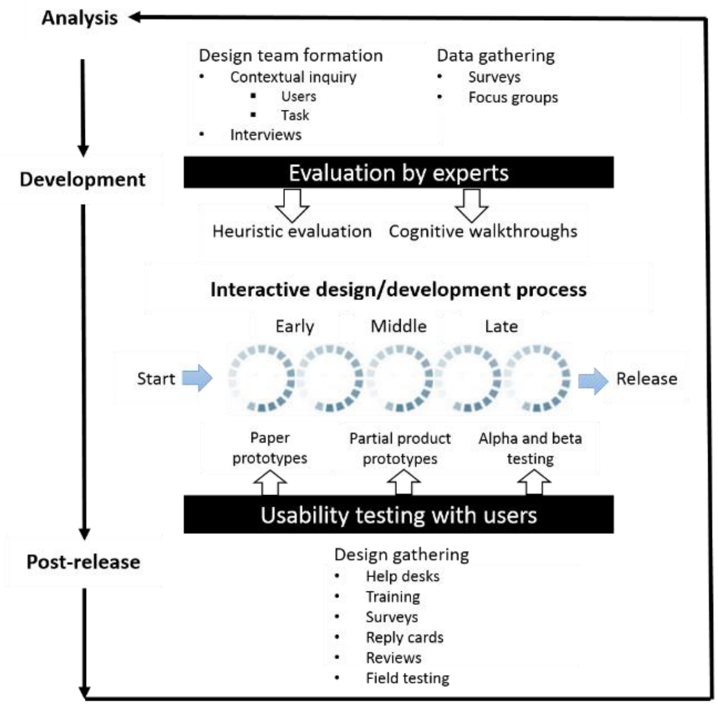


Figure 16. The iterative design/development process based on usability test. [22]

The second stage is development. In this stage, the design criteria are evaluated by experts. The experts perform some heuristic and cognitive evaluation of the design criteria, such as visibility of the system, user control and freedom, flexibility and efficiency of use, etc. The developers then come up with either the paper-based or working prototypes and conduct the usability test on the end users. The development stage is an iterative process, where the developers refine the prototypes repeatedly based on the feedback they receive before the final release of the product. In our usability test of the SVSC, the working prototype (Figure 17 for hardware and Figure 18 for software) was evaluated and reviewed by experienced powered wheelchair users and rehabilitation professionals (target users) [22] before it became commercially available to poweedr wheelchair users.

The reasons for recruiting experienced powered wheelchair users was that they understand the requirements they need for them as well as for new powered wheelchair users from this smartphone application to clearly remind them using PSFs, and if the hardware design might cause too many difficulties during daily routines. The rehabilitation professionals were recruited to provide their opinions and evaluate the usefulness of this application based on their clinical experience. The ultimate goal of this study was to test the usability of and gather feedback about the hardware and software designed for our SVSC system from powered wheelchair users and rehabilitation professionals.

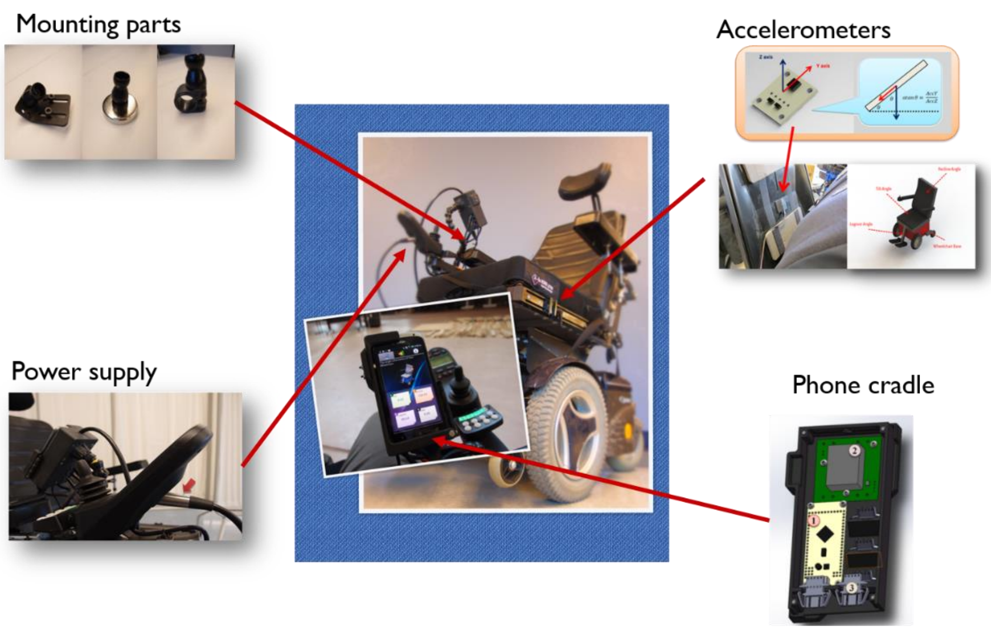


Figure 17. The hardware of the SVSC was reviewed in the usability testing.

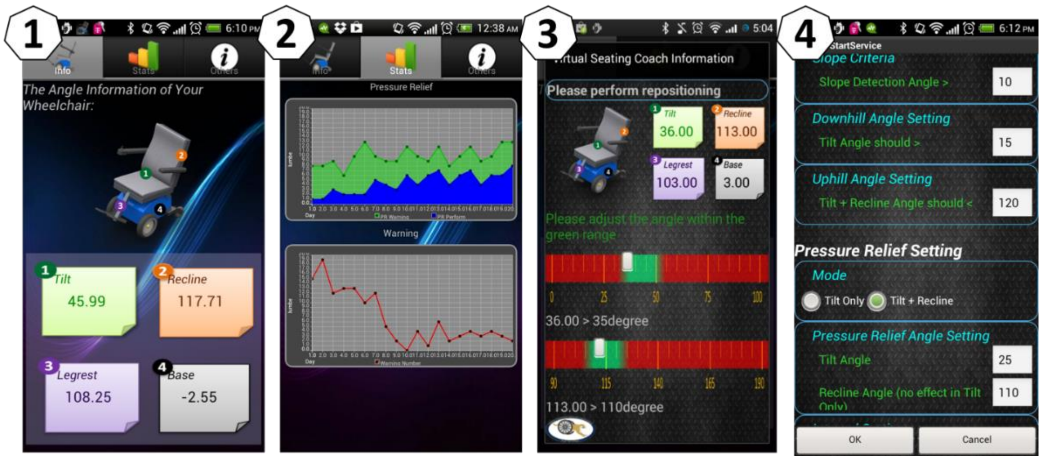


Figure 18. Screenshots of the Smartphone Virtual Seating Coach application. (1)Main Menu: Showing the angles of the powered wheelchair, including seat tilt, backrest recline, legrests elevation and wheelchair base inclination. (2)Statistics display of powered seating functions usage: Users can review their progress of using seating functions. The goal is to increase the compliance with performing repositioning and decrease the number of seating function usage warnings. (3)Instruction Menu: Instructing the users to adjust their wheelchair. The angle bars highlight the target angles in green based on the clinical recommendations. The white indicators point out the current seating angles and move as the user adjusts the seating angles. (4) Clinician Setting: Clinicians can customize reminder and warning parameters for users.

2.3.2 Method

2.3.2.1 Participants

The usability testing of the SVSC was performed on two groups of participants. One group was comprised of wheelchair users who had experience using PSFs. The other group consisted of rehabilitation professionals with experience in prescribing powered wheelchairs with powered seating functions, which included therapists, physicians, or engineers. According to a study that investigated the number of subjects needed for usability testing, 80 percent of usability problems can be detected by the first four or five subjects.[23] Therefore, five participants were recruited for each group in this study. The only criteria to recruit powered wheelchair users was to be 18 years or older and have the ability to operate a powered wheelchair equipped with powered seating functions as a primary means of mobility. All participants were required to have been using a smartphone more than one year so they understood how to operate most of the main functions of a smartphone, such as reading text messages, launching an app, etc. There were no exclusion criteria for either group of participants.

2.3.2.2 Protocol

This usability study was approved by the Institutional Review Board of the University of Pittsburgh. Informed consent was administered prior to the start of usability testing. This study centered on the assessment of the usability of the SVSC via a questionnaire and an interview with open-ended questions.

For the powered wheelchair users, the SVSC was installed on their personal powered wheelchair. The researcher gave a brief introduction of the SVSC system including the purpose of the SVSC, how the system reads the angle of PSFs via accelerometers, and an overview of the SVSC app. After an introduction of the SVSC system, participants were given two tasks: 1) receive one repositioning reminder and adjust the seating angle following the instructions delivered by SVSC and 2) receive one safety warning reminder and adjust the seating angle following the instructions delivered by SVSC. The two tasks simulate the two types of reminders generated by the SVSC app, following the usual ways Android phone generate reminders or messages to users. In order to understand the users' preferences for the display layout and effects, the repositioning and safety warning reminders were set differently. The repositioning reminder appeared on the top of the screen (Figure 19A) and showed three choices ("OK", "Snooze" and "Cancel") for users to decide if they wanted to perform the repositioning exercise. The safety warning reminders appeared as text messages (Figures 19B and 19C). To check a safety warning reminder, the users needed to scroll down the navigation bar and click the text message, which is the same way that most smartphone users check their incoming text messages. The feedback messages for all of the reminders and warnings included a short description about the reminder/warning and an angle bar indicating the recommended angle range of the powered seating functions for users to adjust. The reminders/warning will not disappear if the users do not follow the instruction to adjust their wheelchair, or follow the instruction incorrectly. After completing these two tasks, the participants were given sufficient time to use the app and to ask any questions about the SVSC system, and then were asked to complete a questionnaire with a series of usability questions and were interviewed to gather feedback about the SVSC system.

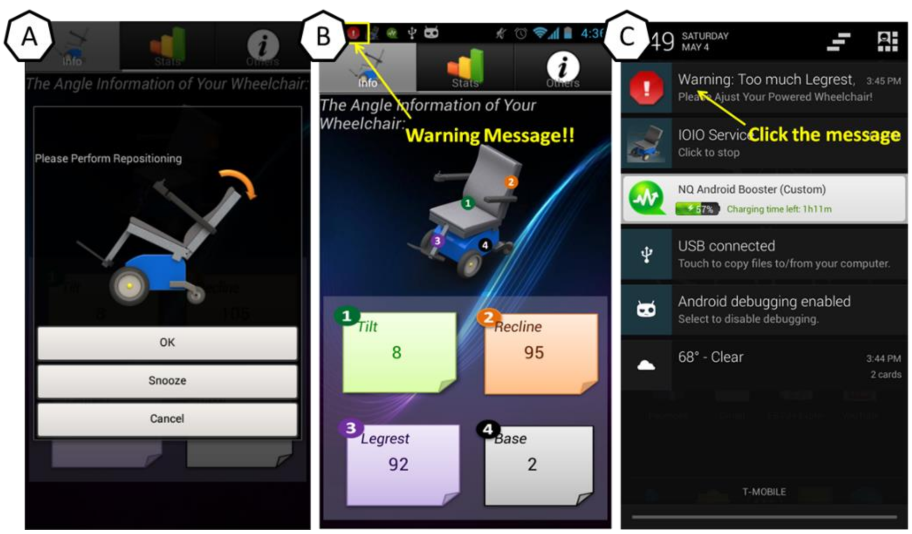


Figure 19. The screenshots of repositioning exercise and safety warning reminders. (A) Repositioning exercise reminder which pop out on the top of the screen. (B) Safety warning reminder which shows like a text message. (C) The users need to scroll down the navigation bar to click the message to read the instruction of changing PSF.

The rehabilitation professionals were asked to complete the same two tasks as the powered wheelchair user group, and were also asked to review the function of customizing the coach app, including the adjustability of settings for safety warnings and repositioning exercise reminders. Afterward, they were asked to respond to the same questionnaire and were also interviewed.

All powered wheelchair users were encouraged to participate in an in-home trial lasting up to five days. During the in-home trial, the SVSC system was on their powered wheelchair all the time so the users could experience how the SVSC worked in their daily lives. This could help determine if the SVSC would be an annoyance to the users or interfere with their daily activities. After this in-home trial, all the participants were asked to answer the same questionnaire and interviewed to determine whether they had any additional feedback.

2.3.2.3 Questionnaire and Interview

A paper-based questionnaire (Appendix C) to gather the participants' feedback on the SVSC system was used. The questionnaires included two parts. The first part of the questionnaire requested demographic information. The second part included 24 questions about general impressions of the SVSC system. Five common usability [22, 24] components were included in the questionnaires: the visibility of the SVSC app; ease of use of the app; error prevention; and usefulness and satisfaction in terms of hardware and software. [25, 26] Users rated their preference for these usability components on a five point likert scale. Other questions asked which features of the SVSC system the participants liked most, whether the participants would use or recommend it to their friends to use if the system becomes commercial, and their concerns about the whole system. The interview followed up on the questions in the questionnaire was to provide an open forum for discussing concerns or to provide suggestions with respect to the hardware and software of SVSC system.

2.3.2.4 Data Analysis

Factor analysis using principal component analysis (PCA) was used for analyzing the constructs of usability questions in our questionnaire to test construct validity. Descriptive analysis was performed on each question to compare the differences among the two visits of the powered wheelchair user group (PW visit 1 and PW visit 2) and rehabilitation professionals (Rehab Pro). A PC algorithm was performed to infer causal links with acyclic directed graph among different usability questions in the questionnaire from powered wheelchair users based on correlation tests. The Spearman's rho was used to perform the correlation test. [27] The reason for using the PC algorithm to discover the casual relationship between each usability question was to investigate the factors which might determine whether the participants would use this SVSC application or recommend this to their friends if this application becomes available.

2.3.3 Results of Data Analysis

<u>Construct validation of questionnaire</u>

The scree plot of the PCA (Figure 20) shows the presence of five factors with Eigen values > 1, representing 90% of total variance in the index. Furthermore, after analyzing each question in each factor, most of the questions can be categorized in the five factors, which are visibility, ease of use, error prevention, usefulness and satisfaction. As a result, our questionnaire has the ability to gather the usability information from our participants in this study.

Figure 20. Scree plot of factor analysis from the principal components in the questionnaire.

Visibility

Figure 21 shows the results about visibility from the powered wheelchair users and rehabilitation professionals. Generally, the powered wheelchair users and rehabilitation professionals in our study felt that the information was clearly delivered by the SVSC interface. The app provided statistical information for the compliance for performing the repositioning exercise and the number of safety warning reminders to the users. However, the statistics display of PSFs usage (clear stats chart display) and safety warning reminders (clear safety warning reminder for seat functions) were two items with lower scores for powered wheelchair users after the in-home trial. Our SVSC app used charts to present statistical changes, but the small smartphone display seemed to be not able to deliver the information clearly. The second issue of visibility was the safety warning reminders, which appeared as text messages. Some participants reported that the text message was too easy to ignore and they usually did not check the text messages. Besides, the navigation bar sometimes contained several icons of other different smartphone apps, leading to the fact that it would be harder to notice the reminders from the SVSC. For these reasons, having the reminders pop up on the screen would be a better way to remind powered wheelchair users to adjust seating angles. Another visibility issue brought from the interview was that most rehabilitation professionals had concerns about the font size in our SVSC app. It would be better if the app could have different font size options, or the app could generate a voice delivering the feedback message and instructions to adjust the seating angles for people with poor visual perception.

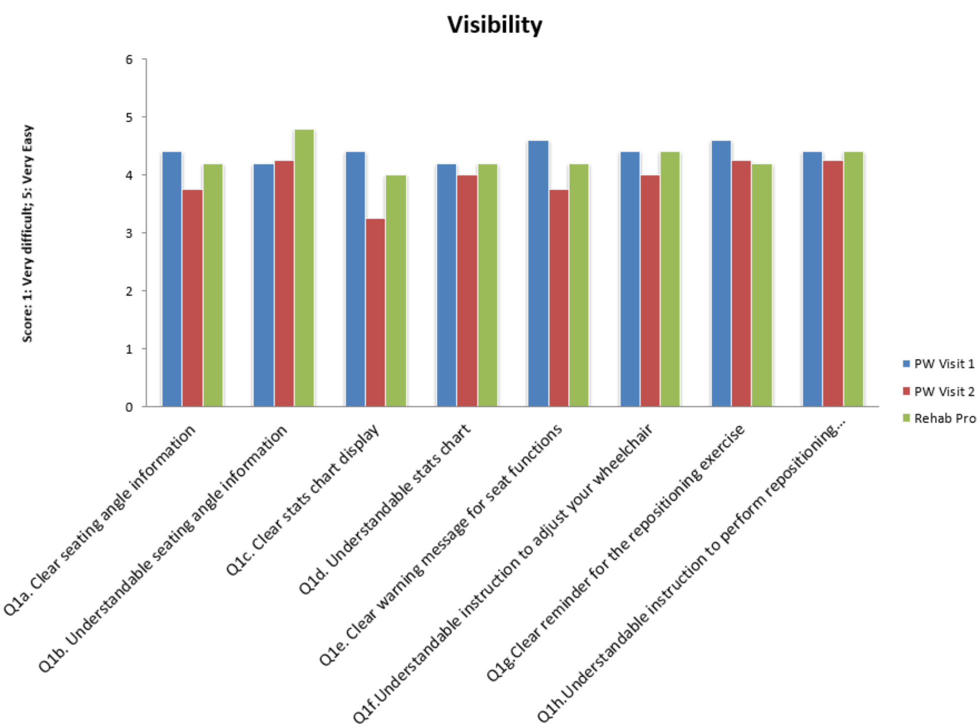


Figure 21. The visibility results from the powered wheelchair (PW) users and rehabilitation professionals (Rehab Pro). PW visit1 and PW visit 2: two visits of the powered wheelchair user group, Rehab Pro: rehabilitation professionals group. Q1a: The sub question "a" in question 1 in the questionnaire.

Ease of Use and Error Prevention

Figure 22 shows the results of ease of use and error prevention. The "easy to navigate the application" item received the lowest scores in both powered wheelchair users and rehabilitation professionals. In this study, the users had to go through different steps for the repositioning and safety warning reminders to access the instructions for adjusting seating angles. For the safety warning reminders, the alerts appeared as text messages. To check the reminders and enter the instruction screen, the users needed to click the text messages from the navigation bar. For the repositioning reminders, the alerts came up on the screen, and the users could choose if they wanted to perform the repositioning exercise. The results show that most participants liked the reminders coming up on the screen directly; however, the safety warning reminders required too many steps to access the instructions. The rehabilitation professionals were also concerned that if the users had impaired fine motor function, clicking the text messages might be challenging for them.

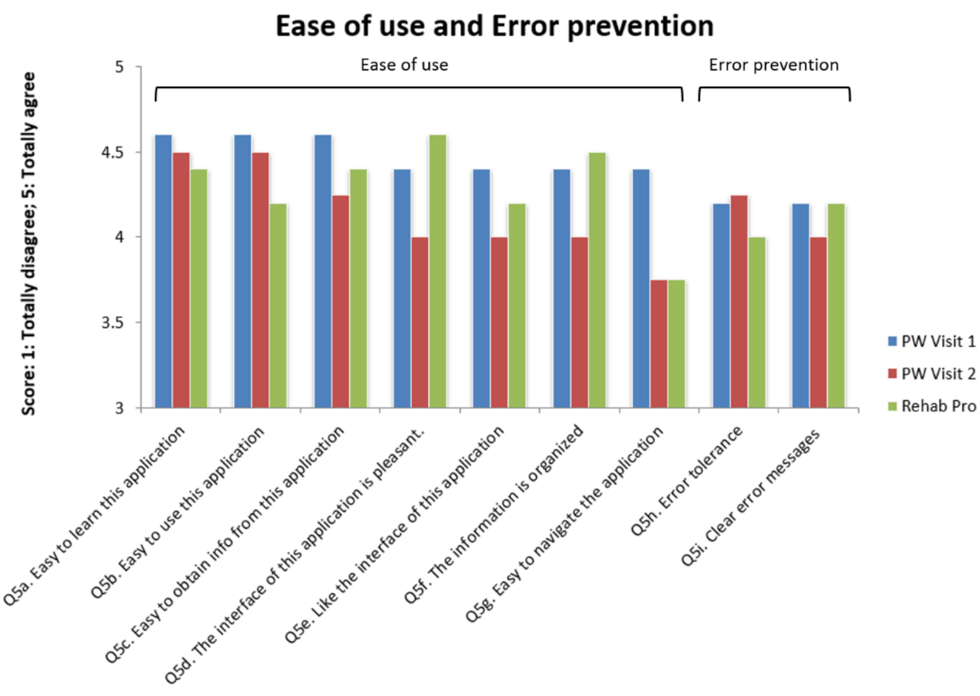


Figure 22. The results of ease of use and error prevention. PW visit1 and PW visit 2: two visits of the powered wheelchair user group, Rehab Pro: rehabilitation professionals group. Q5a: The sub question "a" in question 5 in the questionnaire.

For error prevention, we designed the SVSC app such that it can automatically execute once the USB connection is made with the microcontroller. Also, the system is powered directly from the charging socket of the powered wheelchair. If the USB is not connected or the power jack is loose, the app will generate a message to the users indicating that there is a problem with the power connection and remind the users to check the power connection if they are using the SVSC system. In our study, most of the users liked this design, which helped them to check whether the SVSC was running normally.

Usefulness and Satisfaction

Figure 23 shows the results of usefulness and satisfaction. The usefulness of the SVSC increased after the in-home trials for powered wheelchair users. However, the results indicate the intention of using the application decreased after the in-home trial, but the powered wheelchair users tended to recommend the SVSC to other users. One main reason they reported was that they already understood most of the safety reminders and had their own schedule to perform repositioning exercises because they had already used powered wheelchairs for a long time (average powered wheelchair usage: 3.8 years). Moreover, the smartphone cradle and the wires of accelerometers' sensors on the wheelchair decreased the clearance of the wheelchair, even though we had designed the SVSC system to be compact. On the other hand, all the rehabilitation professionals in this study would recommend the SVSC to their clients. However, the scores of the "sufficient functions and capabilities" item were relatively low compared to the other items. They suggested that the system needs to include a desktop software element or web-based dashboard to present a summary of powered seating function usage of different users to review users' usage reports quickly and tweak the SVSC settings to provide tailored recommendations. Table 3 and Table 4 show which feature of SVSC that the participants liked the most and their concerns about the hardware and software from the questionnaire.

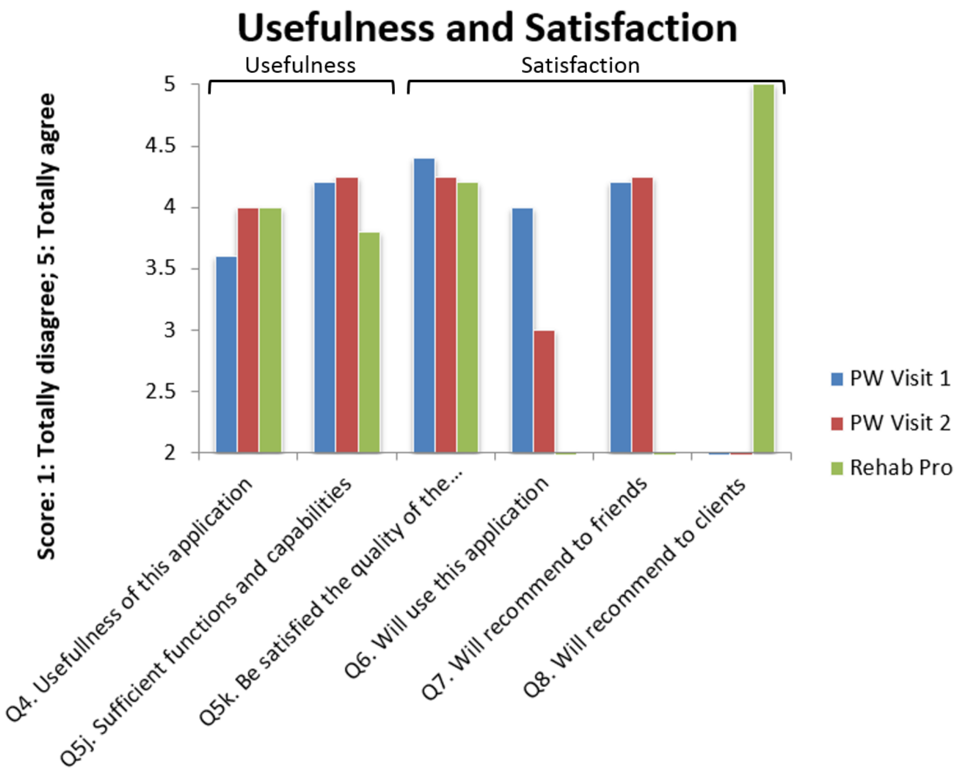


Figure 23. The results of usefulness and satisfaction. PW visit1 and PW visit 2: two visits of the powered wheelchair user group, Rehab Pro: rehabilitation professionals group.

Table 3. The SVSC features that the participants liked (Question 2). [a] The coaching instruction is shown in Figure 19-3. [b] The repositioning exercise reminder is shown in Figure 19-2. [c] One rehabilitation liked the color of the whole smartphone app.

	PW Visit 1	PW Visit 2	Rehab Pro
▪ The seating angle information showed on the application	1	2	4
▪ Brief summary about the repositioning performance and the number of safety warnings	1	1	2
▪ The coaching instruction for repositioning and safety warning [a]	1	1	1
▪ The automatic repositioning exercise reminder [b]	5	3	3
▪ Customized setting for clients (If you are a clinician)	0	0	5
▪ Other	0	0	1[c]

Table 4. The issues which are concerned by the participants (Question 3). [a] One rehabilitation professional suggest the whole system should have a dashboard for them to review the PSFs usage of wheelchair users.

	PW Visit 1	PW Visit 2	Rehab Pro
▪ The small display of a smartphone might not show the information clearly	0	0	3
▪ The location for the smartphone cradle might interfere with transfers or other daily activities	5	4	2
▪ The wires connecting the accelerometers might interfere with transfers or other daily activities	4	3	1
▪ The accelerometers might be damaged for long time usage	1	0	1
▪ Other	0	0	1[a]

The SVSC implements various coaching algorithms to remind users to use their PSFs appropriately. These coaching reminders are important clinical recommendations to prevent ineffective usage behaviors which may decrease sitting stability, result in tipping incidents, or induce complications due to prolonged static sitting. In our current design, the safety warning reminders kept reminding the users until they adjusted their seating angles appropriately. However, these coaching reminders might not be ideal in some situations. For example, when users are in their wheelchair, the system would remind them to have some minimal tilt angle to increase sitting stability. However, this warning reminder becomes inappropriate when the user wants to get close to a dining table where the height can only accommodate the sitting position without being tilted. Another dilemma is legrest usage. When users elevate their legrests to a relatively large angle, it is recommended that they need to recline their backrest backward to prevent the over stretched hamstring muscles from rotating their pelvis posteriorly, causing a slouched posture in the wheelchair. This reminder, however, might not be suitable when they need legrests clearance to drive through places with obstacles where a mild tilt angle is not enough. To avoid continuously reminding users under these situations, the safety warning reminders need to have the option which allows the users to choose whether or not they should follow the recommendation to adjust their wheelchair based on their current situation. Another way to deal with this issue is using context awareness technology to determine the appropriateness of sending reminders to users. [14] This will be one of our future goals.

Causal Relationship from the Questionnaire

The causal relationship revealed by the PC algorithm shows that understandable instructions to adjust the powered seating functions corresponding to the safety warnings (r_s = 0.614, p = .02) and repositioning exercises reminders (r_s = 0.624, p = .017) were two possible causes for powered wheelchair users to recommend the application to other users. Especially for the instruction to perform repositioning exercise, based on our results, the participants would definitely recommend this app to other users if the users felt the instruction provided by our app was very clear. In our current design, the SVSC provides a description and an angle meter with target angle, so the users can follow the description to adjust their seating angle. While interviewing the powered wheelchair users, we discovered that when they received the reminders, they expected the information in the reminders to tell them clearly which specific PSF(s) they need to adjust, how they have to adjust them, and the reason that the PSFs need to be adjusted. Some users even suggested that the instructions can be more intuitive such as having the figure indicating the button for the PSF on the controller or having animations of the specific

PSF. The experienced powered wheelchair users in our study also emphasized that clear PSFs adjustment is very important for new powered wheelchair users, because they sometimes feel confused among the functions of different seating angle change especially the tilt and recline angle. In addition, clear and understandable instructions to adjust the PSFs could be important when the powered wheelchair users receive the reminder while they are doing tasks. It would minimize the interruption to their current tasks, if they can change their PSFs quickly and intuitively. Clear and understandable instructions can also reduce cognitive burden for new powered wheelchair users to understand the meaning of reminders while they are learning using PSFs. From the causal discovery in this study, it verified this point through the result that understandable and clear instructions for adjusting PSFs would be the reason that experienced powered wheelchair users would recommend the SVSC to other powered wheelchair users.

Limitations

Conducting the usability testing after creating a working prototype might limit some creative ideas from users about the application. [28] Another limitation is that new powered wheelchair users were not recruited in this usability test. The reason we recruited experienced powered wheelchair users and rehabilitation professionals is they realize the importance of these reminders during the learning period of using PSFs, so they would focus on the usability of the application. However, it is necessary to include new powered wheelchair users, because they are one of the important target populations for this application. Our small sample size might be an issue for the data representation of the target population. However, the idea of the usability study is to gather feedback from the end users and refine the development.

Some other issues which are not included in this usability test were brought to our attention by study participants. First, all powered wheelchair users in this study had already used smartphones for more than 4 years, and were able to use regular smartphones without any problems. However, there is currently no alternative controller on the market designed for people with impaired fine motor functions. This would be a potential challenge in using the SVSC app for the population with impaired fine motor functions. This is also an issue in the assistive technology field since smartphones have become the basis of the current cell phone market. In addition, using accelerometer to measure angle was unstable ($\pm 3^{\circ}$) while the wheelchair was moving, and the wires that connected the microcontroller to the accelerometers decreased the clearance of their wheelchairs. The ideal design for the SVSC in the future would be to place the built-in sensors inside the actuators of PSFs and use wireless data transmission such as Bluetooth to eliminate wires.

2.3.4 Conclusion

The results from the usability testing provided information necessary to refine the SVSC system. Future development should provide more intuitive instructions to adjust PSFs in the SVSC app, come up with more clearance for sensor installation, and have an interface for rehabilitation professionals to review and tune the SVSC app.

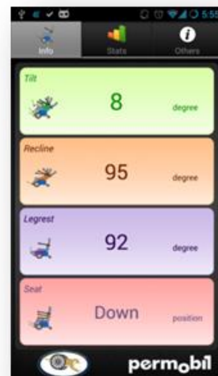
2.4 IMPROVEMENT OF THE SMARTPHONE VIRTUAL SEATING AFTER USABILITY STUDY

According to the results and feedback from the usability study, improvements were made to both the user interface and the hardware of the SVSC. Amendments made to the user interface included: a new main screen for displaying seating angles, large font size, clear instructions with animation for PSF adjustment, etc. HERL has already filed the patent for the virtual seating coach project as “POWERED SEATING FUNCTION MONITORING AND COACHING SYSTEM” (Patent application number: 14/609,747) that has been licensed by Permobil, USA. The partnership with Permobil permitted the SVSC to access the seating angle data directly from Permobil wheelchairs via Bluetooth communication, which eliminated the process of external sensor installation and custom electronics. Permobil also used the RAM X-Grip® Mount for mounting a smartphone on wheelchairs, which accommodates different sizes of smartphones. However, Permobil wheelchairs do not have sensors on the wheelchair base to detect whether their wheelchair is on a slope. As a result, an added feature to detect the slope incorporates using the smartphone embedded accelerometer to resolve the issue of finding the slope.

2.4.1 Improvement of user interface

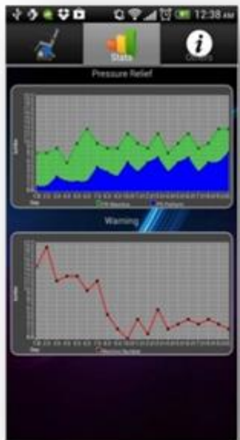
1) In the new interface, icons are used to indicate different PSFs. Another improvement is the increased font size of the seating angle.

Table 5. The comparison of the main screen between the previous and current version.

Previous Version	Current Version
	

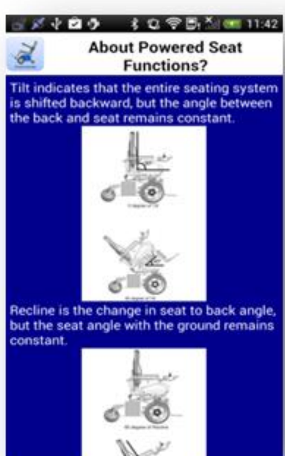
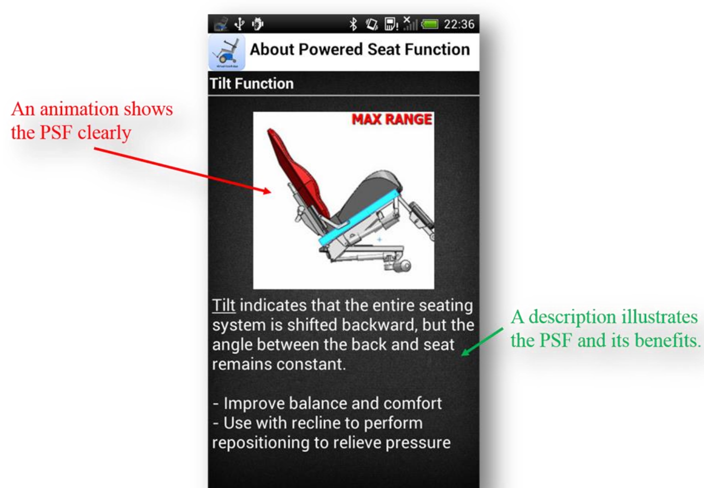
2) Another addition is a brief summary report located in the statistics section, so users can easily get the information about their PSF usage. The previous version of the application only provides chart plots. Also, the information encourages users to stay within medium to maximum tilt and recline angles to decrease the pressure on their back and buttocks.

Table 6. New summary report has a brief text report and the plot of compliance rate only displays the past 7 day data to prevent too complicated plot reading.

Previous Version	Current Version
	

3) The new PSF information section includes animation to explain different PSFs and also includes descriptions of how certain PSFs are used and their benefits.

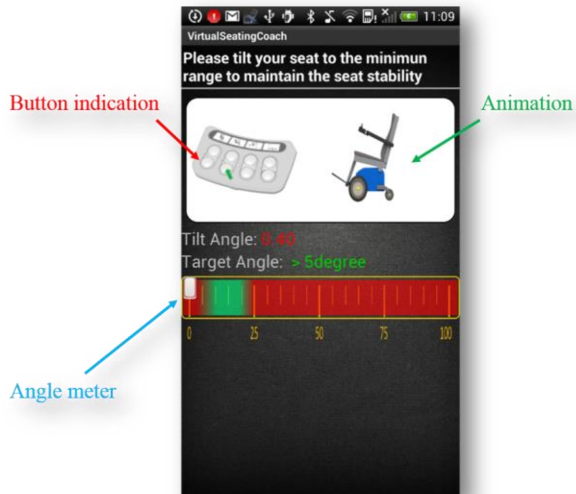
Table 7. New PSF information section uses the animation to illustrate different PSFs.

Previous Version	Current Version
	

4) The new reminder screen includes: (a) a brief description of the reminder, (b) a button figure indicating how to adjust the PSF, (c) a wheelchair animation displaying how the wheelchair will change and, (d) an angle meter, giving users the target angle to adjust.

Table 8. New reminder screen includes a button figure indicating the PSF needed to adjust, an animation showing how the wheelchair will change, and a brief description illustrating the adjustment.

Previous Version	Current Version



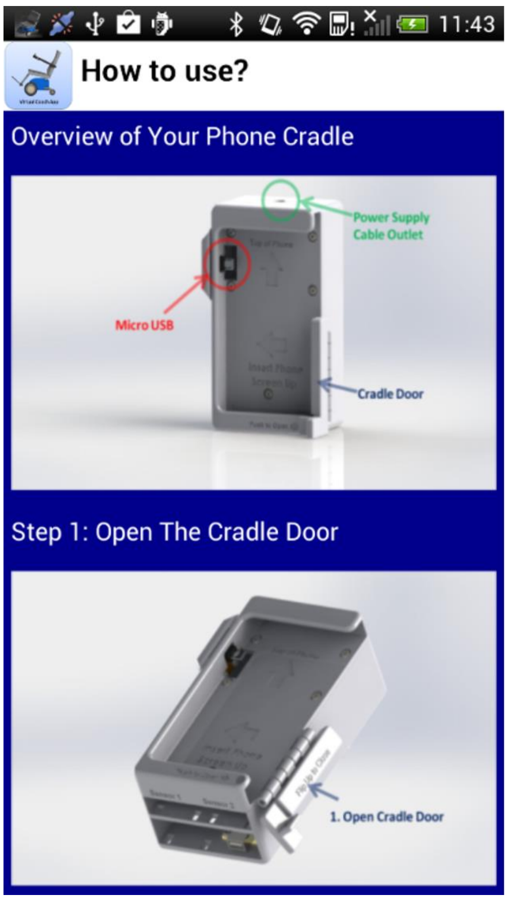
5) The new clinician setting section includes figures and brief descriptions to explain the reminders.

Table 9. The new clinician setting section includes pictures to illustrate each reminder.

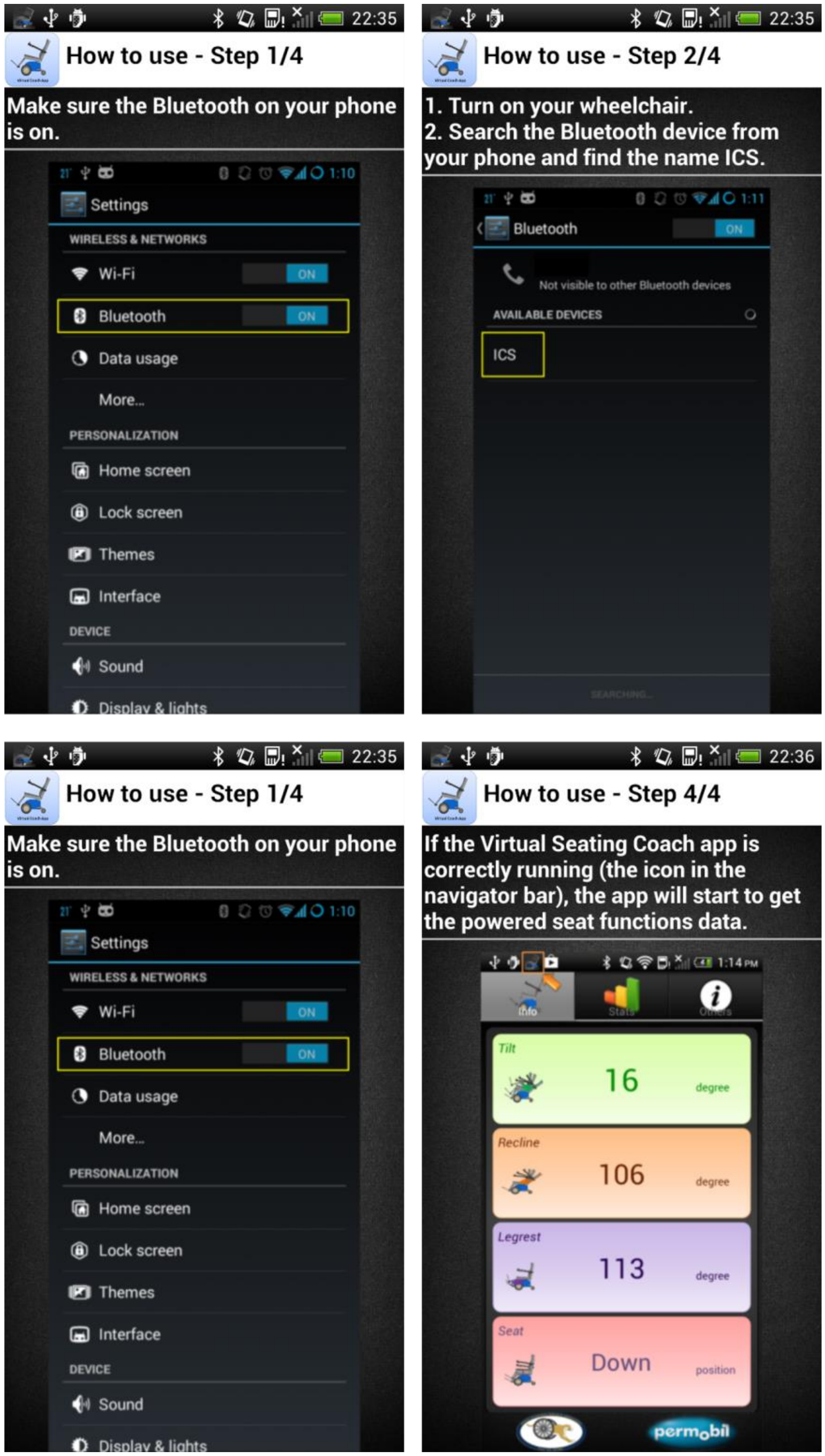
Previous Version	Current Version
	

6) The new "how to use" section gives a step by step instruction to set up the Bluetooth communication with the powered wheelchair.

Table 10. The new "how to use" section instructs the users on how to connect the smartphone with the wheelchair via Bluetooth.

Previous Version
 

Current Version



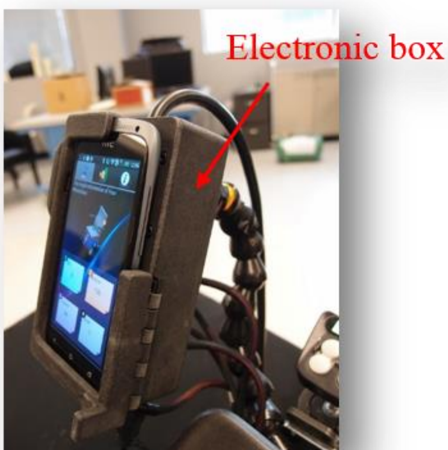
2.4.2 Improvement of hardware

1) Remove all external sensors:

   The SVSC app now accesses the seating angle data directly from the Permobil wheelchairs through Bluetooth communication.

2) RAM X-Grip® Mount (http://www.permobilus.com/new/xgrip-phoneholder.png):

Table 11. The SVSC accesses the sensors on the Permobil wheelchairs via Bluetooth. The electronic box is no longer needed.

Previous Version	Current Version
	

2.4.3 Slope detection by the smartphone embedded accelerometer

Since Permobil wheelchairs do not have sensors on the wheelchair base to detect whether the wheelchair is on a slope, we added a new feature to detect the slope by using the smartphone embedded accelerometer. When a user is approaching a slope (still on the ground surface) and starts the slope detection function, the app will capture the current wheelchair status as a level surface. When the wheelchair drives on a slope, it will detect the degree of the slope. (Figure 24) If the PSFs are improper positioned, the app will remind the user to adjust them.

Figure 24. When the slope detection function is initialized, it will detect if the wheelchair is on a slope and display the information on the screen.

2.4.4 FDA approval for the smartphone virtual seating coach

The patent for the virtual seating coach has been filed and the device has been licensed to Permobil with the software protected by copyright. Depending on their product positioning, the SVSC may not require FDA approval if the SVSC is an accessory to powered wheelchairs rather than a component of the powered wheelchair. Even though the SVSC requires a Bluetooth device on the wheelchair to perform data transmission, the Bluetooth device is part of the component of the wheelchair rather than one of the SVSC's components. In the FDA's new released update to the classification of mobile medical apps (MMAs) [29], one criteria in the list of MMAs that are not medical devices states that "Mobile apps that are intended for general patient education and facilitate patient access to commonly used reference information. These apps can be patient-specific (i.e., filters information to patient-specific characteristics), but are intended for increased patient awareness, education, and empowerment, and ultimately support patient-centered health care." [29] According to this criteria, the SVSC may not require FDA approval. However, under the same criteria, it also mentions that "These are not devices because they are intended generally for patient education, and are not intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease by aiding clinical decision-making." In the latest flyer of virtual seating coach on the Permobil website, it states that "Clinicians typically recommend a repositioning program using power seat functions to help their clients avoid painful pressure issues and skin breakdown." If the benefit of using the SVSC is avoiding painful pressure issues and skin breakdown, the SVSC might require FDA approval. However, if the benefit of using the SVSC is claimed as bringing the training of PSF usage from clinics to users' home environment, this might influence the FDA's decision-making.

3.0 DEVELOPMENT OF A WEBSITE FOR CLINICIANS TO REVIEW POWERED SEAT FUNCTION USAGE

3.1 INTRODUCTION

In order to overcome the limitation of the internal storage and enable the SVSC to track usage data for months or years, using the concept of cloud computing [30, 31] could be a potential solution. The approach to applying cloud computing on the SVSC system was using smartphones to upload and download information from a cloud space or a web server. The advantages of using cloud computing are: (1) current infrastructure of cloud computing allows to expand the storage space easily and perform backup simultaneously; (2) it allows different machines from different locations to access the data in the server at the same time; (3) it is easy to create web applications to perform data analyses and visualization. In the tablet VSC study, the researchers needed to visit the participants to export the data from the tablet for analyses. A program developed to analyze the PSF data also helped to calculate the clinically important variables such as the wheelchair occupancy, compliance rate for performing repositioning exercise, etc. However, One disadvantage for this offline analysis is that clinicians and users have to physically meet together to access the data within the tablet. Another disadvantage is that once the amount of data becomes large, this offline analysis would take an extensive time to complete the calculation and it is difficult to prevent the incomplete or damaged data files from causing the failure during the analysis. Moreover, the clinicians would need to spend a significant amount of time to review enormous amount of information at once. Therefore, cloud computing could be a better solution for the SVSC application. The SVSC app can upload the PSF usage data into a server for data storage and backup. Furthermore a web service can be used to extract the data from the server and perform the data visualization on a webpage for clinicians. This web service would enable the clinicians to adjust the coaching parameters in the SVSC app remotely.

One possible solution to increase the efficiency of analyzing the PSF usage data is to create the algorithms to perform the real-time analysis within the SVSC app rather than an offline program to analyze the raw data periodically. The results could be stored in a relational database management system (RDBMS). [32] In the RDBMS, the data were stored and presented in a tabular format, so the data can be easily accessed. The RDBMS provides the mechanism to prevent database collision, so the database can retain completeness even when the app crashes or failures occurred when accessing data. The results in this chapter have been published as *A Prototype wbesite for providing powered seat functions usage collected from Smartphone virtual seating coach,* ***Proceedings of the Rehabilitation Engineering and Assistive Technology Society of North America Conference****, Denver CO, June 10-14, 2015*.

3.2 METHODS

Amazon Elastic Compute Cloud (EC2) is the web service where the prototype website was constructed. The operating system on the web service is Ubuntu Server 14.04 and a LAMP (Linux-Apache-MySQL-PHP) server package has been installed in the Ubuntu Server. Chart.js [33] is the jQuery library that was used to present all plots on the website. The data transmission between EC2 and SVSC app is through SSH File Transfer Protocol (sFTP). The SVSC is an app developed on the Android platform which utilizes the SQLite as the RDBMS to store data. The app stores different variables into different tables in the database system. In order to allow clinicians to customize the coaching parameters of SVSC remotely, the SVSC creates the original coaching parameters as a JSON file and the SVSC uploads this file to the server when the app first executes. On the server side, the clinicians may adjust the JSON file with the coaching information. The SVSC checks the JSON file on the server each day and the coaching parameter will refresh if the JSON file on the server is different with the file in the SVSC app.

The variables selected to present with the website portal include (1) wheelchair occupancy, (2) compliance rates for performing repositioning exercises, (3) number of safety warnings, (4) frequency of using different powered seat functions, and (5) scores of Tool for Assessing Wheelchair discomfort (TAWC) questionnaire.

Wheelchair occupancy

Wheelchair occupancy was defined as the time that users stay in their powered wheelchair in one day. The wheelchair occupancy of a day also governed the compliance rates for performing repositioning exercises and frequency of using PSFs. Therefore, variables of PSF usage were normalized by the wheelchair occupancy of the day. In order to estimate the wheelchair occupancy in the SVSC app, the app records every time the users turn on and off their wheelchairs and uses the first time of turning the wheelchairs and last time of turning off the wheelchairs in a day to estimate the wheelchair occupancy.

Compliance rates for performing repositioning exercise

Effective and frequent repositioning exercises are able to relieve pressure and restore the skin perfusion, leading to decreasing likelihood of the occurrence of pressure ulcers. [7, 9] A clinician usually recommends a repositioning regime for their clients. The regime includes the frequency of repositioning, the desired seating position (seating angles), and the duration that the participant should stay in the desired position for optimal effect. For example, the clinician may recommend that a user reposition once every hour with a desired position of tilting the seat more than 30 degrees, and the participant staying in that position for more than 2 minutes. If a user repositions once every hour; his/her compliance rate would be 100% according to the example. If the user sits in his/her wheelchair 4 hours and only performs two repositioning exercises every two hours, the compliance rate would be 50% (2/4 x 100%). The SVSC records every time the users perform the repositioning exercise.

New	_ID	Time	Manner	Time_To_Next_Cycle	DATE
Edit	2	12:26:53	Spontaneous	3568	2014-06-06
Edit	3	14:25:51	Spontaneous	3384	2014-06-11
Edit	4	15:26:45	Reminder	0	2014-06-11
Edit	5	13:05:00	Spontaneous	3508	2014-06-13
Edit	6	14:34:09	Button	248	2014-06-16
Edit	7	14:34:40	Spontaneous	3569	2014-06-16
Edit	8	14:35:26	Spontaneous	3567	2014-06-16
Edit	9	14:39:43	Spontaneous	3564	2014-06-16
Edit	10	16:50:09	Reminder	0	2014-06-16
Edit	11	10:45:08	Reminder	0	2014-06-17

Figure 25. The SVSC app records each time the users perform the repositioning exercise spontaneously, by the reminder.

Safety reminder

The SVSC app detects six safety reminders when using a powered wheelchair. Table 1 describes the six safety reminders and the adverse effect of each condition. These safety reminders are to prevent users from sliding out of the wheelchair or using poor sitting posture.

Frequency of using different powered seat functions

The SVSC collects tilt, recline, legrests angle and seat elevation (if applicable) changes within a day. The data also includes the time and angle/position changes when a user adjusts their PSFs. In order to detect the PSF changes, one algorithm is built in the SVSC app. Once the algorithm detects the seating angle change, it first records the initial seating angle (from angle) and the algorithm will wait for the seating angle becoming stable which is marked as final angle (to angle). The SVSC app records the date, time, which seat function, from angle, to angle, and the difference of angle.

New	_ID	Time	Seat_Function	From_Angle	To_Angle	Diff_Angle	DATE
Edit	127	14:56:53	Legrest	97	127	30	2014-06-16
Edit	128	14:57:46	Legrest	127	106	-21	2014-06-16
Edit	129	16:48:39	Tilt	10	3	-7	2014-06-16
Edit	130	16:49:43	Tilt	3	38	35	2014-06-16
Edit	131	16:49:44	Recline	102	107	5	2014-06-16
Edit	132	16:50:45	Tilt	38	4	-34	2014-06-16
Edit	133	16:50:46	Recline	107	103	-4	2014-06-16
Edit	134	16:59:22	Tilt	4	9	5	2014-06-16
Edit	135	17:04:06	Tilt	9	4	-5	2014-06-16
Edit	136	17:12:08	Tilt	4	9	5	2014-06-16

Figure 26. The SVSC app records the seating angle change in the SQLite database.

Tool for Assessing Wheelchair disComfort (TAWC)

The TAWC consists of three sections. [34, 35] Section I is general information about factors that directly affect discomfort in one's wheelchair. Section II contains eight statements related to discomfort and five statements related to comfort. These 13 statements were rated on a seven-point Likert scale where 1 is “strongly disagree” and 7 is “strongly agree”. In Section III, seven body areas (back, neck, buttocks, legs, arms, feet, and hands) are rated for a degree of discomfort intensity on a scale of 0 (no discomfort) to 10 (severe discomfort). The TAWC was built in the SVSC app which allows the users to give feedback about their comfort levels seated in their wheelchair. The SVSC app only asks section II and III of TAWC to users. (Figure 27)

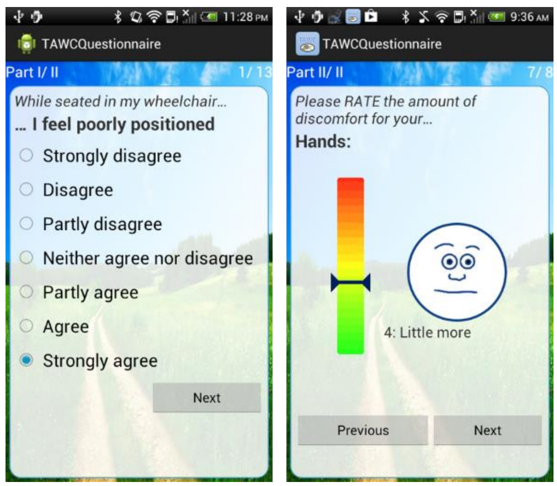


Figure 27. The screenshot of TAWC.

3.3 RESULTS AND DISCUSSION

The cloud security is the main consideration of choosing a web service, especially the service hosting users’ health information. Amazon web service provides several built-in security features, such as secure access, which allows secure HTTP access (HTTPS), built-in firewalls, and multi-factor authentication for administrations managing the server. The web service also provides encrypted data storage. Even though there is no personal information stored in this prototype web service, encryption is the most important in data storage and data transmission. Encryption ensures that the data is unable to be accessed by anyone during the data transmission and within the server. Amazon web service also allows use of sFTP as a method of data transmission. The cloud security infrastructure and sFTP were approved by the institution review board at the University of Pittsburgh.

Figure 28 shows the webpage which presents the wheelchair occupancy, compliance rate and the distribution of the safety reminders. The webpage allows the clinicians to choose the time period that he/she wants to review for their clients. The wheelchair occupancy allows the clinicians to know the length of time that the users stay in their wheelchairs. If a clinician finds that their client does not use their wheelchair frequently, they can communicate with their clients to see which factors cause them not to use their wheelchair. For example, the wheelchair does not meet their requirements, their home environment is not wheelchair friendly or other reasons. High compliance rates of performing repositioning exercises is encouraged for every powered wheelchair user, since it decreases the likelihood of developing pressure ulcers. Currently, there is no study to demonstrate the relationship between compliance of performing repositioning exercises and the probability of developing pressure ulcers. Therefore, if the SVSC becomes a wide-spread application for powered wheelchair users, this longitudinal data of compliance rate may be able to discover some valuable results. The third piece of information displayed on the webpage is the number of safety reminders, which allows the clinicians to know whether their clients might adjust their PSFs in the appropriate manner. These inappropriate adjustments might yield higher risk that users might slide out of their wheelchair or end up in a poor sitting posture in their wheelchair.

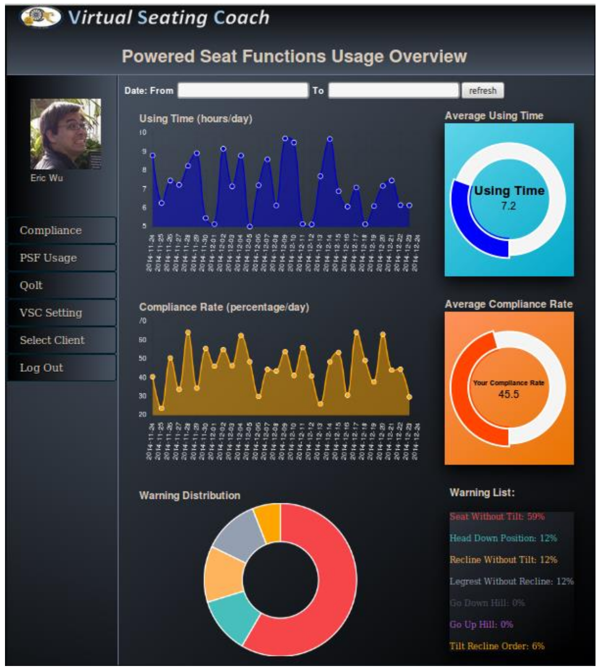


Figure 28. The webpage displays the daily wheelchair occupancy, compliance of performing repositioning exercise, and the safety warning.

Figure 29 (left) shows how the webpage presents the frequency of using PSFs. Wheelchair seating discomfort is a very common problem for wheelchair users. [18, 36-38] Because of motor and/or sensory impairments, powered wheelchair users may not be able to adjust their sitting posture as frequently as needed. Insufficient postural changes in their chair may be one reason causing wheelchair discomfort. For this reason, recording the frequency of using PSFs and the TAWC score (Figure 29 (right)) could provide the information to investigate the relationship between PSFs usage and wheelchair discomfort. In addition, answering TAWC in the app allows the users to let their clinicians know their condition in their wheelchair on a daily basis, which enables the clinician the opportunity to look into the issues that the user might have and provide solutions.

Figure 29. (Left) The webpages shows the frequency of using different PSFs each day. The bottom shows the number of PSFs changes in different angle ranges (small: < 10°, medium < 20° and large > 20°). (Right) The webpage shows the daily TAWC score. It also displays the average score of each item in section II and section III of TAWC.

Figure 30 shows the webpage which allows the clinicians to adjust the coaching parameters for different clients. With this functionality, the clinicians can communicate with their clients and tweak the coaching parameters for them.

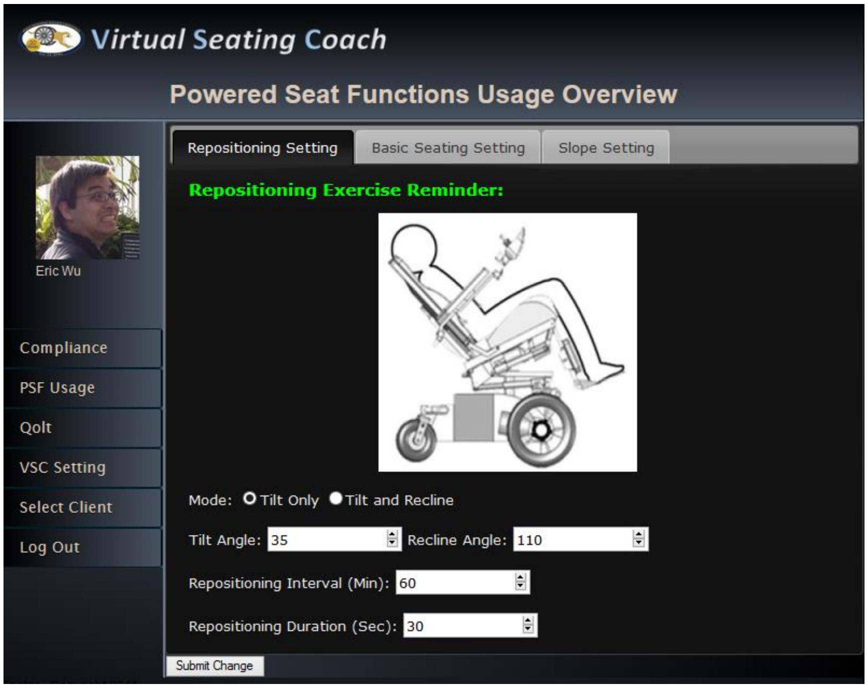


Figure 30. The webpage allows the clinicians to adjust the coaching parameters for their clients.

4.0 THE EFFECTIVENESS STUDY OF THE SMARTPHONE VIRTUAL SEATING COACH

4.1 INTRODUCTION

In our tablet VSC, we found the compliance rate of performing repositioning exercises increased 32.66% (from 21.75 ± 32.84 % to 54.41 ± 32.13 %) after the intervention of tablet VSC. [1] However, this result cannot be statistically proven because of the low number of participants in the study due to difficulty recruiting. We had to provide the participants with our research powered wheelchairs equipped with the VSC system rather than installing the VSC on their own wheelchairs. Unfortunately, because our research wheelchairs could not fit in their living environment, or because it was inconvenient for participants to have two wheelchairs at the same time, most of our participants dropped out. However, the new SVSC's capability to communicate with the Permobil powered wheelchairs and get seating angle information from the actuators via Bluetooth eliminates the necessity of installing external sensors on the powered wheelchairs, and so it seemed this improvement might potentially improve the issue of the low recruitment rate in the tablet VSC study.

In order to verify that the SVSC could also increase the compliance rates with respect to performing repositioning exercises, the main purpose of this chapter was to investigate the effectiveness of SVSC through recruiting Permobil powered wheelchair users. In addition, another phenomenon we found in the tablet VSC study was that the compliance rate reached a plateau where the compliance rate maintains in a stable number after the initial increment at the time of the intervention of VSC. This raised a question as to whether we could further increase the compliance rates with additional interventions. For this reason, two new feedback mechanisms (thermometer bar indicator and daily performance report) were introduced and expected to further facilitate the compliance rate.

Since the SVSC is an interactive application that generates reminders to users, it is very important to be able to generate effective reminders so that the users will follow the prompts. The would be a big challenge, because people may have different reactions toward or judgements of the same stimulus, depending on their context at the time of the reminder, such as location, time, identity, and current activity. [39] For example, previous research has shown that users' responsiveness toward a task-interrupting reminder varies based on many factors, including users' emotional state, the modality of the interruption, and the task that the users are doing [40]. For this reason, another purpose of this study was to investigate the decision that the user made -- to follow or cancel the reminder -- could be predicted by the context factors collected by the sensors on the wheelchair and the smartphone.

4.2 HYPOTHESES

Specific aim 1: To determine if the intervention of SVSC could increase the compliance rate for performing a repositioning exercises.

Hypothesis 1a: Participants will have higher compliance rate for performing repositioning exercises in the phase one period than at baseline after the intervention of SVSC.

Specific aim 2: To determine if a feedback mechanism (thermometer type indicator or daily performance report) plus SVSC can further increase compliance rate for performing repositioning exercises, then, if so, to investigate which feedback mechanism has more effects.

Hypothesis 2a: The participants will have higher compliance rate in phase two (SVSC plus one of the feedback mechanisms) than phase one (SVSC only).

Hypothesis 2b: There will be a significant difference in compliance rate between the thermometer type indicator group and daily performance report group.

Specific aim 3: To generate effective reminders that successfully facilitate users' performing repositioning exercises based on the context factors collected by the sensors on the wheelchair and smartphone.

Hypothesis 3a: The machine learning algorithms will be able to predict with more than 80% accuracy that the users will follow/cancel the reminder to perform repositioning exercises.

4.3 METHODS

4.3.1 Study Design

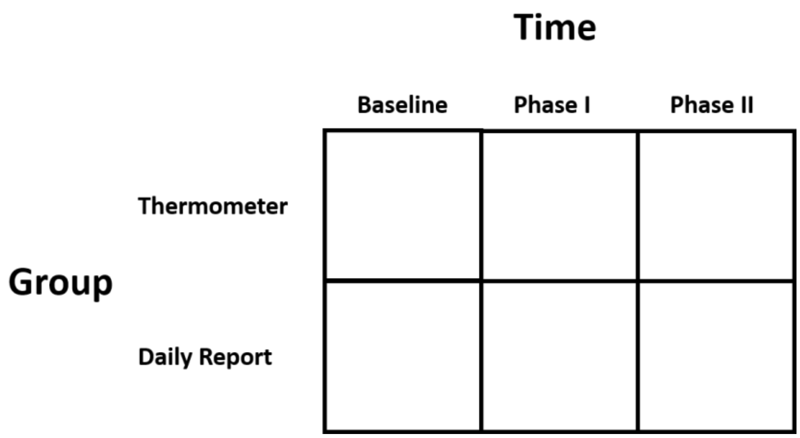


Figure 31. The study design diagram for investigating the effectiveness of SVSC, and two different feedback mechanisms.

This is a small randomized control trial (baseline is the control, phase I is the intervention of the SVSC, and phase II has two different additional feedback mechanisms in two groups) evaluating the effects on PSF usage after the intervention of the SVSC. (Figure 31) This study also investigated the effect of two feedback mechanisms (thermometer type indicator and daily performance report) and compared which feedback mechanism could result in better compliance. The thermometer type indicator is a smartphone widget which indicates how much time is left to the next repositioning exercise, and it allows users to perform the exercise ahead of schedule, enabling users to be aware of the repositioning exercise schedule based on clinical guidelines and to perform the exercises spontaneously based on their daily schedule. The second feedback mechanism, a daily performance report, provides users with a daily compliance rate report. This report was expected to encourage users to maintain or achieve a better compliance rate for performing repositioning exercises.

This study consisted of a three-week in-home trial with up to four visits. The three-week in-home trial included three phases (Figure 32).

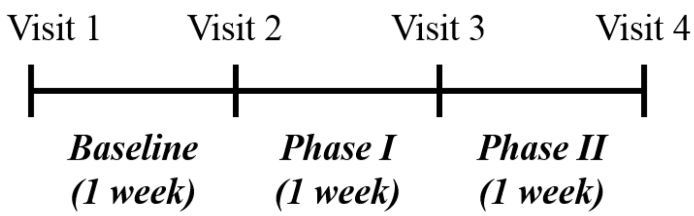


Figure 32. Three week in-home trial including three phases and up to four visits.

Baseline

During the first one-week baseline period, the SVSC was only recording the PSF usage data from the participants as their baseline information. The participants were asked to use their PSFs as normally as they did. During this period, the SVSC did not give any reminders to the users.

Phase I (Coaching)

In the second week of the study, the SVSC app started giving reminders to the users based on clinical recommendations. The reminders included a repositioning exercise reminder and safety warning reminders.

Phase II (Coaching with feedback mechanisms)

At the beginning of the study, participants were randomly assigned into either the thermometer type indicator group or the daily performance report group. In Phase II, while the SVSC continued to give the repositioning exercise reminder and the safety reminders to the participants, if the participants were assigned into the thermometer type indicator group, a thermometer widget was pulled out on the home screen of the smartphone (figure 33); if the participants were in the daily performance report group (figure 34), the SVSC gave them a daily report on their compliance for performing repositioning exercises for the previous day, which included their compliance rate and suggestions for improving their compliance.

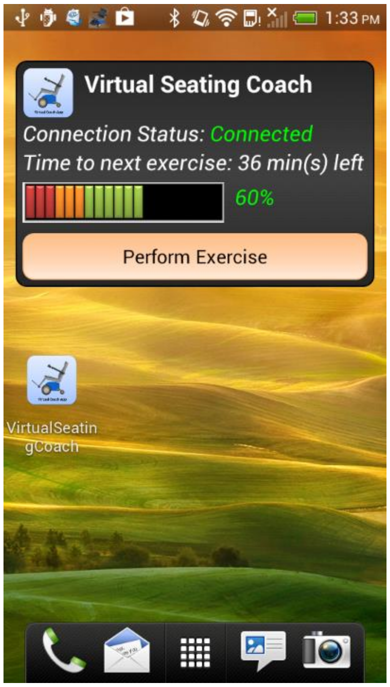


Figure 33. The widget on the smartphone desktop which indicates the connection status between the app and the wheelchair and how much time is left for the next repositioning exercise.

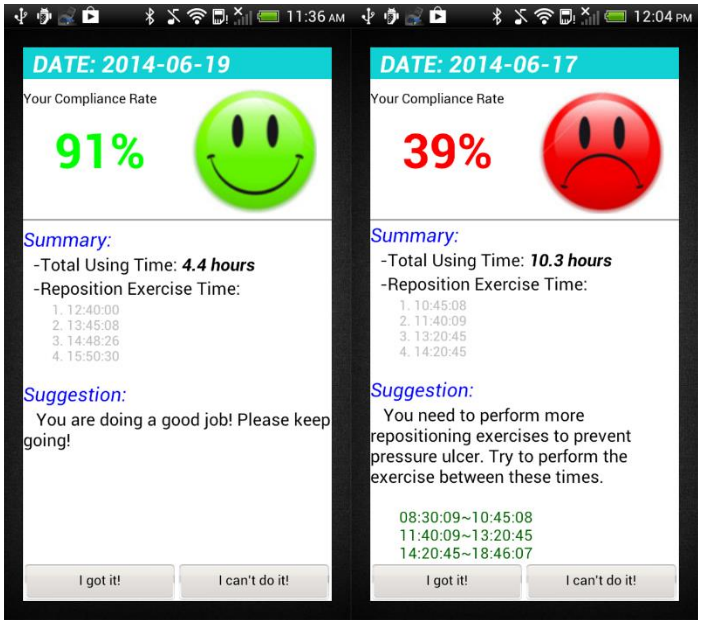


Figure 34. The daily performance report, which gives users the compliance rate report and suggestions if the compliance rate is too low.

4.3.2 Recruitment Procedure

Participants using a Permobil powered wheelchair equipped with PSFs were recruited for this study. The inclusion criteria were: (1) subject was 18 years of age or older; (2) subject used a Permobil wheelchair which supported PSF data transmission via Bluetooth. (3) subject used a power wheelchair equipped with PSFs (tilt in space, recline, elevating legrests, seat elevator (optional)). (4) subject was able to independently operate the power seat functions on the wheelchair. (5) subject had the ability to use and experience using a smartphone. The exclusion criteria are: (1) had any active pelvic, gluteal or thigh wound within the past 30 days, (2) had experienced a hospital stay of more than 5 days in the previous month.

During the first visit, the investigator conducted the screening process using the inclusion and exclusion criteria. Then a smartphone, Bluetooth device, and RAM X-Grip® Mount were installed the powered wheelchairs of those chosen to participate. The participants were asked to independently perform the following tasks: (1) recognize whether the smartphone was playing an auditory reminder with eyes closed; (2) clicked the SVSC app from the apps list to run the app; (3) clicked the button on the reminders screen to enter the instruction screen for the reminders; (4) read the text on the instruction page of a reminder; (5) pressed the "Home" button on the smartphone to return to the regular screen for phone use. These tasks were to screen the participants' visual, auditory and motor functions when using the smartphone and the app. The participants were then asked to fill out the demographic questionnaire and to take the Mini Mental State Examination (MMSE) for accessing mental status.

4.3.3 Variables

4.3.3.1 Independent Variables

Time: within-subjects effect

In order to compare the intervention of SVSC and the feedback mechanisms, outcome variables were measured repeatedly in three phases. The comparison between baseline and phase I demonstrated the effect of the SVSC only. The comparison between phase I and phase II demonstrated whether the feedback mechanisms could further intensify the effect on outcome variables.

Group: between-subjects effect

The participants were randomly assigned to two groups (thermometer and daily report). The group variable in each of the three phases gave different information. During the baseline period, all the outcome variables were expected to be equal and the variations in outcome variables were expected to be homogeneous between the two groups. The changes in outcome variables between the two groups in phase I were expected to be similar since both groups only had the intervention of SVSC. Similarities of the outcome variables in phase I would allow us to have equivalent comparisons of the data for the two feedback mechanisms in phase II.

4.3.3.2 Dependent Variables

Wheelchair Occupancy

There was no pressure sensor or seat switch on the Permobil wheelchair. In order to estimate wheelchair occupancy, the SVSC app recorded each time the users turned on/off their wheelchair every day. The time interval between the first time of turning on and the last time of turning off the wheelchair in a day was estimated as wheelchair occupancy. Wheelchair occupancy is an important variable because it governed compliance rates for performing repositioning exercises and frequency of using PSFs. Wheelchair occupancy also provided information about whether the participants increased or decreased their time in their wheelchair after the intervention of SVSC.

Compliance Rate for Performing Repositioning Regime

The repositioning exercise includes achieving a set frequency of repositioning, achieving the desired seating position (seating angles), and achieving the length of time that one participant should stay in the desired position for optimal effect according to clinical recommendations. This was one of the key variables used in this study to evaluate the effect of SVSC. The number of times the repositioning exercises were performed in a day was recorded. The intervals between two sets of repositioning exercises were also recorded to avoid false results if a user performed repositioning exercises several times in a short period of time. The number of times that the users performed at least one repositioning exercise in the recommended period was calculated as the compliance rate. For example, if the user sat in the wheelchair 4 hours and only performed two repositioning exercises every two hours, the compliance rate would be 50% (2/4 recommended x 100%).

The Numbers of Times Spontaneously Performing Repositioning Exercises

In order to investigate whether the SVSC can facilitate the participants' performing the repositioning exercise actively, the number of times that the participants performed the repositioning exercise during each of the three phases was calculated. Additionally, the SVSC app recorded not only the number of repositioning exercises performed but also how the participants performed them. Whether the users performed the repositioning exercises spontaneously or as a result of receiving a reminder was noted. For the participants in the thermometer group, the thermometer widget allowed them to enter the repositioning instruction screen by pressing the button on it to perform the repositioning exercises ahead of the schedule of the reminders. The number using the thermometer function was also recorded.

Frequency of Utilizing the Powered Seat Functions

Every time the users adjusted their PSFs, the SVSC app recorded the time and the angle changes, including the range of angles, the initial angle and the end angle of the changes, as shown in figure 26 in chapter 3. This study also categorized the ranges of angle change as minimum (0 – 15 degrees), median (15 – 30 degrees), or maximum (greater than 30 degrees).

Tool for Assessing Wheelchair discomfort (TAWC)

A TAWC questionnaire app (figure 27 in chapter 3) was created to allow the participants to answer questions regarding their general discomfort (Section II of TAWC questionnaire) and discomfort intensity (Section III of TAWC questionnaire). The questionnaire popped up on users' screen at 4pm each day during the study (figure 35). If the users cancelled the questionnaire, it came back on the screen again one hour later. The questionnaire only allowed the users to answer it once per day.

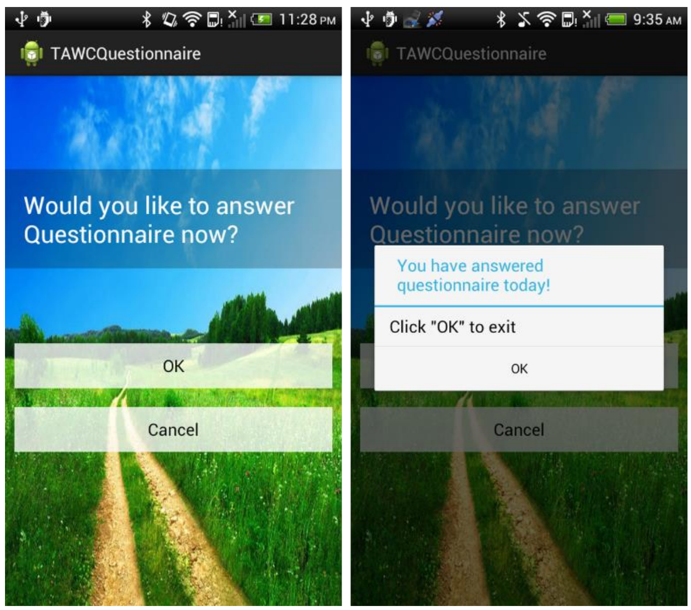


Figure 35. On the left: The TAWC questionnaire as it popped up on the screen. On the right: The message the users received if the users launched the questionnaire and it had already been answered that day.

4.3.3.3 Features Collected for Machine Learning Algorithms

Table 12 shows the features and target collected when a repositioning exercise reminder appeared on the smartphone screen. After the reminder popped up, the participants could either perform the repositioning exercise or cancel the reminder. The reminder lasted 90 seconds and it snoozed automatically. The decisions that the participants made with respect to the reminders were collected as the target classification for the machine learning algorithms to determine if the reminder was an effective reminder.

Table 12. The features and target collected for machine learning algorithms when a repositioning exercise reminder came up.

Features	***Description***
Time	The time when a reminder appears.
Ringtone	The volume of the ringtone when a reminder appears.
Seating Angle of all PSFs	The seating angles of all PSFs (tilt, recline, legrests and seat elevation) when a reminder appears.
Acceleration	The built-in accelerometer in the smartphone. Once the reminder appears, the 3-axis acceleration values were collected for 5 seconds (sampling rate: 50Hz). The average and standard deviation of the 3 axis acceleration values were recorded.
Sound	The intensity (decibel) of the sound in the surrounding environment when a reminder appears. The sound was collected via the microphone of the smartphone for 5 seconds (sampling rate: 5Hz). The average and standard deviation of the intensity of the sound were recorded.
Light	The light illuminance when a reminder appears. The illuminance was collected via light sensor on the smartphone for 5 seconds (sampling rate: 5Hz). The average and standard deviation of the illuminance were recorded.
GPS	The location (latitude and longitude) when a reminders appears.
Target	***Description***
Perform the exercise	Whether the participant performed the exercise, cancelled the reminder, or the reminder snoozed automatically.

4.3.4 Data Analysis

Descriptive statistics (means and standard deviations) were calculated and reported for all outcome variables. The normality test and homogeneous test were performed to determine parametric or non-parametric data analysis in the statistics. A paired-sample t-test was performed to compare all outcome variables with two combined groups at baseline and phase I. A two-way mixed model ANOVA was performed to compare all the outcome variables in phase I and phase II for within-subjects effect and the group between-subjects effect. If there was any main effect or interaction effect, a post hoc comparison with a Bonferroni adjustment was performed.

All features were preprocessed using the following steps before conducting machine learning algorithms:

1. Data cleaning: If there was any missing value in the dataset, the mean (continous data) or mode (discrete data) of all examples filled in the missing values. Any outlier was identified and removed in this step.
2. Data transformation: Some algorithms, such as logistic regression, required the feature data to be normalized to prevent a huge scale of data from weakening the effects of features with a small scale. The normalization process scaled the data using mean and standard deviation.
3. Discretization: Some algorithms require discrete data such as CART (classification and regression tree), so the continous variables were discretized.
4. Feature selection: all of the features were first evaluated using correlation-based feature subset selection [41] to select the features highly correlated with the target.

The best first search method was then used to select the features with better performance with respect to classification to the data.

After the data preprocessing, six common machine learning algorithms were conducted. The algorithms were logistic regression (linear model), support vector machine (kernel model), naïve bayes (probability model), k nearest neighbors (non parametric model), Random Forest Tree and Best First Tree (decision tree). To evaluate the performance of the algorithms, 10-fold cross-validation was performed and the accuracy, precision and recall values were reported. The first analysis (called overall analysis in this study) took three conditions (the users (1) followed the reminders; (2) canceled the reminders or (3) the reminders snoozed automatically) as the classifications and performed the machine learning algorithms. The second analysis, called users' attention, grouped the users' response as one group and non-response (the reminders' snoozing automatically) as another as classifications in the machine leanring algorithms. This analysis was aimed at investigating if the users noticed the reminders and responded to them. The third analysis, called users' decision, only took the users' decisions (follow or cancel the reminders) as classifications in the machine learning algorithms. The purpose of this analysis focused on whether the users decided to follow the reminders or not.

A correlation test was conducted to test the relationship between years of using PSFs and changes in PSF usage with the SVSC. The variables of the changes in PSF usage were the percentage of responding a reminder when a reminder came out, the percentage of following a reminder when a reminder came out, the compliance rate in baseline, and the change of compliance rate with the SVSC.

4.3.5 Results

4.3.5.1 Participants

Ten participants (Five males and five females) completed this three-week in-home trial. Table 13 shows the demographic information of the participants. The mean and standard deviation of the MMSE scores among all participants is 29.3±0.82 (total score is 30), meaning that the participants in this study do not have cognitive impairment (24-30: No cognitive impairment, 18-23: Mild cognitive impairment, 0-17: Severe cognitive impairment). The years of participants using PSFs are 8±5.61 in thermometer group and 10.6±5.36 in daily report group.

Table 13. The demographic data of the participants.

Subject	*Gender*	*Height (Inch)*	*Weight (lb)*	*Diagnosis*	*Wheelchair*	*Years of using PSFs*
1	F	65	133	Muscular Sclerosis	M300	3
2	M	82	190	Spinal Cord Injury	C400	8
3	F	65	150	Muscular Sclerosis	M300	2
4	M	69	205	Quadriplegia	C300	15
5	M	70	270	Tetraplegia	M300	12
6	F	64	190	Ehlers Danlos type III	C300	7
7	M	74	180	Muscular Sclerosis	C500	15
8	M	68	190	Spinal Cord Injury	M300	3
9	F	69	180	Spinal Cord Injury	C300	15
10	F	63	140	Muscular Sclerosis	C300	13
	M: 5 F: 5	68.9±11.3	182.8±77.9			9.3±5.36

4.3.5.2 Wheelchair Occupancy

A paired-sampled t-test was conducted to compare wheelchair occupancy at baseline (without the SVSC) and phase I (with the SVSC). There was not a significant difference in the hours for wheelchair occupancy at baseline (Mean: 11.331, SE = 1.076) and at phase I (Mean: 11.898, SE = 1.272); t(9) = -1.070, p = .312.

A 2 × 2 mixed ANOVA was performed on wheelchair occupancy as a function of time and group. The within-subjects independent variable was time, with 2 levels (phase I and phase II). The between-subjects independent variable was group, with 2 levels (therometer and daily report). The assumption of homogeneity of variance and homogeneity of covariance were met: Box's M = 8.396, F (3, 11520) = .106, p = .543 (α = .001), Mauchly's W = 1.000. All other assumptions were also met.

The pattern of difference on wheelchair occupancy was not significantly different between the two groups F (1, 8) = .118, p = .740, η_p^2 = .015, among the three phases F (1, 8) = 2.280, p = .170, η_p^2 = .222, or between the two groups at different phases F (1, 8) = 0.487, p = .505, η_p^2 = .057. Table 14 shows the wheelchair occupancy between the two groups and among the three phases.

Table 14. The wheelchair occupancy (hours/day) between the two groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	10.31±4.50	11.63±5.69	10.73±4.48
D	12.35±1.78	12.17±1.97	11.83±1.74
All	11.33±3.40	11.90±4.02	11.28±3.26

4.3.5.3 Compliance Rate for Performing Repositioning Exercises

A paired-sampled t-test was conducted to compare compliance rate for performing repositioning exercises at baseline (without the SVSC) and phase I (with the SVSC). There was a significant difference in compliance rate at baseline (Mean: 13.975, SE = 3.480) and at phase I (Mean: 57.872, SE = 6.876); t(9) = -5.782, $p < .001$.

A 2 × 2 mixed ANOVA was performed on compliance rate for performing repositioning exercises as a function of time and group. The assumption of homogeneity of variance and homogeneity of covariance were met: Box's M = 3.659, F (3, 11520) = .889, p = .446 (α = .001), Mauchly's W = 1.000. All other assumptions were also met.

The pattern of difference on compliance rate for performing repositioning exercises was not significantly different between the two groups F (1, 8) = .314, p = .591, η_p^2 = .038, among the three phases F (1, 8) = 2.658, p = .142, η_p^2 = .249, or between the two groups at different phases F (1, 8) = 2.741, p = .136, η_p^2 = .255. Table 15 shows the compliance rate for performing repositioning exercises between the two groups and among the three phases.

Table 15. The compliance rate (%) for performing repositioning exercise between two groups and among the three phases. The ANOVA with mixed model shows the main effect (different phases) is significant. [a]: The compliance rate in phase I is higher than at baseline. [b]: The compliance rate in phase II is higher than at baseline.

	Baseline	*Phase I*	*Phase II*
T	16.43±13.37	55.95±26.13	77.57±21.89
D	11.51±8.88	59.79±19.29	59.62±21.99
All	13.98±11.01	57.87±21.74[a]	68.60±22.74[b]

4.3.5.4 The Number of Times Spontaneously Performing Repositioning Exercises

Figure 36 shows the proportion of that the participants performed the repositioning exercise spontaneously, as a result of receiving a reminder or as a result of pressing the button on the widget. Since the intervention of SVSC started at phase I, the only data in the baseline was regarding the average number of participants performing the repositioning exercises spontaneously. During the baseline, the participants spontaneously performed the repositioning exercises 1 to 2 times per day (Thermometer group: 0.834±0.882 times/day, Daily report group: 1.91±1.520 times/day). In phase I, analysis of the data shows that the reminders generated by the SVSC app helped the participants perform repositioning exercises an additional 4 to 6 times each day (Thermometer group: 4.306±2.421 times/day, Daily report group: 5.504±2.792 times/day). Furthermore, the thermometer group used the button on the widget to perform repositioning exercise spontaneously 2 to 3 times per day (2.604±2.393 times/day) in phase II.

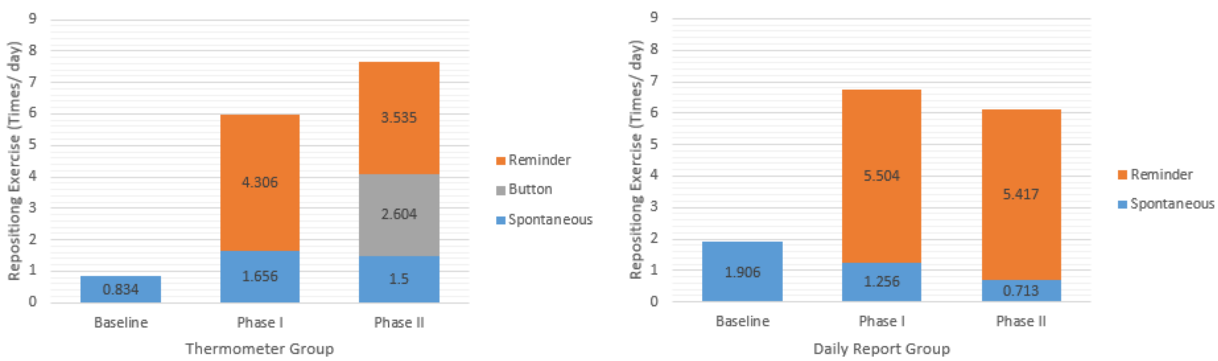


Figure 36. The proportion of the participants that performed the repositioning exercise spontaneously, upon receiving a reminder or after pressing the button on the widget in each of the three phases.

4.3.5.5 Frequency of Utilizing the Powered Seat Functions

A paired-sampled t-test was conducted to compare compliance rate for tilt, recline legrests and seat elevation at baseline (withour the SVSC) and phase I (with the SVSC). There was not a significant difference in the frequency of using tilt function at baseline (Mean: 34.188, SE = 7.125) and at phase I (Mean: 40.196, SE = 6.148); t(9) = -1.887, p = .092. There was not a significant difference in the frequency of using recline function at baseline (Mean: 28.640, SE =

9.804) and at phase I (Mean: 30.915, SE = 9.776); t(9) = -.298, p = .773. There was not a significant difference in the frequency of using legrests function at baseline (Mean: 15.268, SE = 3.852) and at phase I (Mean: 14.302, SE = 3.955); t(9) = .759, p = .467. There was not a significant difference in the frequency of using seat elevation at baseline (Mean: 2.888, SE = 1.485) and at phase I (Mean: 2.202, SE = 1.120); t(9) = 1.753, p = .113.

A 2 × 2 mixed ANOVA was performed on the frequency of use of the tilt function as a function of time and group. The assumption of homogeneity of variance and homogeneity of covariance were met: Box's M = 1.130, F (3, 11520) = .275, p = .844 (α = .001), Mauchly's W = 1.000. All other assumptions were also met.

The pattern of difference on the frequency of use of the tilt function was not significantly different between the two groups F (1, 8) = 0.003, p = .956, $\eta_p^2 < .001$, among the three phases F (1, 8) = 0.186, p = .677, η_p^2 = .023, or between the two groups in different phases F (1, 8) = 2.030, p = .192, η_p^2 = .202. (Table 16).

Table 16. The frequency of using the tilt function (times/day) between the two groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	35.30±26.20	38.43±17.97	43.86±13.98
D	33.07±21.27	41.96±22.80	39.05±18.41
All	34.19±22.53	40.20±19.44	41.46±15.62

A 2 × 2 mixed ANOVA was performed on the frequency of using the recline function as a function of time and group. The assumption of homogeneity of variance and homogeneity of covariance were met: Box's M = 5.007, F (3, 11520) = 1.217, p = .302 (α = .001), Mauchly's W = 1.000. All other assumptions were also met.

The pattern of difference on the frequency of using the recline function was not significantly different between the two groups F (1, 8) = 0.372, p = .559, η_p^2 = .044, among the three phases F (1, 8) = 1.951, p = .200, η_p^2 = .196, or between the two groups in different phases F (1, 8) = 0.074, p = .793, η_p^2 = .009 (Table 17) .

Table 17. The frequency of using the recline function (times/day) between the two groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	34.00±30.49	35.26±32.23	32.89±29.06
D	23.28±34.07	23.08±31.92	21.48±29.30
All	28.64±31.00	29.16±30.91	27.19±28.16

A 2 × 2 mixed ANOVA was performed on the frequency of using the legrests function a function of time and group. The assumption of homogeneity of variance and homogeneity of covariance were met: Box's M = 13.468, F (3, 11520) = 3.272, p = .020 (α = .001), Mauchly's W = 1.000. All other assumptions were also met.

The pattern of difference for the frequency of using the legrests function was not significantly different between the two groups F (1, 8) = 0.001, p = .977, η_p^2 < .001, among the three phases F (1, 8) = 0.355, p = .568, η_p^2 = .043, or between two groups in different phases F (1, 8) = 1.888, p = .207, η_p^2 = .191 (Table 18) .

Table 18. The frequency of using the legrests function (times/day) between two the groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	14.57±11.15	15.44±13.01	14.29±8.94
D	15.96±14.43	13.16±13.40	16.08±16.16
All	15.26±12.18	14.30±12.51	15.18±12.35

A 2 × 2 mixed ANOVA was performed on the frequency of using the seat elevation function as a function of time and group. The assumption of homogeneity of variance and homogeneity of covariance were met: Box's M = 24.558, F (3, 11520) = 5.967, p < .001 (α = .001), Mauchly's W = 1.000. Since the assumption of homogeneity of covariance was violated, The Greenhouse-Geiser was used to do the adjustment. All other assumptions were met.

The pattern of difference for the frequency of using the seat elevation function was not significantly different between the two groups F (1, 8) = 1.467, p = .260, η_p^2 = .155, among the three phases F (1, 8) = 1.104, p = .324, η_p^2 = .121, or between the two groups in different phases F (1, 8) = 1.158, p = .313, η_p^2 = .126. (Table 19)

Table 19. The frequency of seat elevation function (times/day) between two the groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	1.16±1.42	0.87±1.17	0.85±1.15
D	4.61±6.33	3.54±4.74	4.67±7.04
All	2.89±4.69	2.20±3.54	2.76±5.16

Table 20-22 show the results for the frequency of changing PSF in different angle ranges, respectively. As can be seen, the numbers of angle range changes in the tilt function occurred in the medium and maximal range. For the recline and legrests function, there was no obvious change among the different angle ranges.

Table 20. The frequency of different angle changes of the tilt function (times/day) between two the groups and among the three phases.

	Min			*Med*			*Max*		
	Baseline	Phase I	Phase II	Baseline	Phase I	Phase II	Baseline	Phase I	Phase II
T	26.33±17.45	25.99±15.63	27.85±10.25	6.53±7.40	9.45±4.62	12.42±6.35	2.44±1.99	2.98±1.92	3.59±2.98
D	20.04±11.18	21.41±14.52	18.72±12.48	8.65±6.92	10.19±9.24	11.01±6.91	4.38±5.34	7.77±3.14	7.06±2.34
All	23.19±14.20	23.70±14.43	23.28±11.79	7.59±6.85	9.83±6.90	11.71±6.30	3.41±3.94	5.37±3.52	5.33±3.12

Table 21. The frequency of different angle changes of recline function (times/day) between the two groups and among the three phases.

	Min			*Med*			*Max*		
	Baseline	Phase I	Phase II	Baseline	Phase I	Phase II	Baseline	Phase I	Phase II
T	22.81±21.02	25.11±23.48	24.80±21.09	8.05±8.84	7.95±10.97	6.03±7.29	2.80±3.84	2.19±2.81	2.06±3.54
D	17.47±22.98	20.05±24.56	16.80±22.33	5.50±6.52	3.90±3.65	3.51±3.08	4.88±8.43	4.04±6.96	5.38±7.48
All	20.44±20.66	22.87±22.56	21.25±20.66	6.92±7.54	6.15±8.35	4.91±5.65	3.72±5.93	3.01±4.80	3.52±5.50

Table 22. The frequency of different angle changes of legrests function (times/day) between the two groups and among the three phases.

	Min			*Med*			*Max*		
	Baseline	Phase I	Phase II	Baseline	Phase I	Phase II	Baseline	Phase I	Phase II
T	7.74±6.24	7.64±5.04	8.15±5.70	3.76±1.74	3.14±1.44	3.19±1.21	4.42±4.46	4.66±7.44	2.95±3.31
D	4.17±4.27	4.40±5.71	5.05±6.58	3.65±2.18	3.54±2.57	3.60±2.49	7.46±8.49	5.22±5.65	7.42±7.77
All	5.96±5.38	6.02±5.35	6.60±6.03	3.71±1.86	3.34±1.98	3.40±1.86	5.95±6.59	4.94±6.23	5.19±6.10

4.3.5.6 Tool for Assessing Wheelchair discomfort (TAWC)

A paired-sampled t-test was conducted to compare the TAWC (general discomfort and discomfort intensity at baseline (withour the SVSC) and phase I (with the SVSC). There was not a significant difference in the score of general discomfort at baseline (Mean: 36.962, SE = 3.003) and at phase I (Mean: 36.490, SE = 3.329); t(9) = .306, p = .766. There was not a significant difference in the score of discomfort intensity at baseline (Mean: 17.657, SE = 3.747) and at phase I (Mean: 15.593, SE = 3.533); t(9) = 1.826, p = .101.

A 2 × 2 mixed ANOVA was performed on the TAWC (general discomfort and discomfort intensity) as a function of time and group. The assumption of homogeneity of variance and homogeneity of covariance were met, with Box's $M = 8.771$, F (3, 11520) = 2.131, $p = .094$ ($\alpha = .001$) and Mauchly's $W = 1.000$ for general discomfort and Box's $M = 5.265$, F (3, 11520) = 1.279, $p = .280$ ($\alpha = .001$) and Mauchly's $W = 1.000$ for discomfort intensity. All other assumptions were all met for general discomfort and discomfort intensity.

The pattern of difference for general discomfort (table 23) was not significantly different between the two groups F (1, 8) = 0.184, $p = .680$, $\eta_p^2 = .022$, among the three phases F (1, 8) = 0.151, $p = .708$, $\eta_p^2 = .019$, or between the two groups in different phases F (1, 8) < 0.001, $p = .993$, $\eta_p^2 < .001$.

The pattern of difference for discomfort intensity (table 24) was not significantly different between the two groups F (1, 8) = 0.127, $p = .731$, $\eta_p^2 = .016$, among the three phases F (1, 8) = 0.142, $p = .717$, $\eta_p^2 = .017$, or between the two groups in different phases F (1, 8) = 0.679, $p = .434$, $\eta_p^2 = .078$.

Table 23. The general discomfort scores between the two groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	35.94±5.74	38.03±6.48	38.37±5.96
D	37.98±12.94	34.94±14.19	35.30±15.66
All	36.96±9.50	36.49±10.52	36.84±11.29

Table 24. The discomfort intensity scores between the two groups and among the three phases.

	Baseline	*Phase I*	*Phase II*
T	17.46±6.33	14.42±6.41	14.23±6.02
D	17.86±16.60	16.77±15.47	17.29±16.26
All	17.66±11.85	15.59±11.17	15.75±11.67

4.3.5.7 Analyses of Effective Reminders

Some new features were created for training the algorithms, which includes the amplitude of the 3 axis acceleration, square values of each individual axis acceleration, multiplications of all pairs of each axis of acceleration, and the multiplication of mean value and standard deviation of sound amplitude.

The total number of data points from the ten participants was 2,294, including 676 data points for performing the repositioning exercise (29.5%), 420 data points for cancelling the reminders (18.3%), and 1,198 data points for the automatically snoozing reminders (52.2%). Table 25 shows the distribution of the data points collected during the last two weeks of the study (12 days, the first and the last days are excluded) for each participant. As can be seen, the variations of the data points in the three categories among each participant have large differences. Some participants seldom cancelled the reminders and some participants had a large number of the reminders snoozing automatically.

Table 25. The total data points in the three classifications from each participant in the last two weeks of the three week in-home trial. The first and the last day were excluded, so the total number of days was 12. The average values are the total values divided by the number of days.

Subject	***Perform***		***Cancel***		***Auto Snooze***	
	Total	Average	Total	Average	Total	Average
1	62	5.17	29	2.42	138	11.5
2	29	2.42	77	6.42	173	14.42
3	55	4.58	7	0.58	20	1.67
4	109	9.08	35	2.92	99	8.25
5	89	7.41	19	1.58	239	19.92
6	36	3	89	7.42	303	25.25
7	40	2.5	69	5.75	37	3.08
8	48	4	4	0.33	65	5.42
9	122	10.17	28	2.33	9	0.75
10	96	8	63	5.25	115	9.58
	67.6±34.02	5.63±2.83	42±30.21	3.5±2.52	119.8±96.31	9.98±8.03

Table 26. The features used for the overall, users' attention and users' decision analyses. The features underlined in the users' attention and users' decision analyses are the same features picked for the overall analysis during the feature selection process.

	Feature Groups	*Features Used*
Overall	**Time**	Hour
	Ringtone	Ringtone volume
	PSFs	Tilt, Recline, Legrest, Seat Elevation
	Acceleration	Mean of Y axis, Mean of Z axis, Standard deviation of X axis, the total amplitude of the 3 axes,
	Sound	Mean of the sound amplitude, Standard deviation of the sound amplitude, the multiplication of mean and standard deviation of sound amplitude
	Light	Mean of the light illuminance
	GPS	None
Users' Attention	**Time**	Hour
	Ringtone	Ringtone volume
	PSFs	Recline
	Acceleration	Mean of Z axis, Standard deviation of X axis, Standard deviation of Y axis, the multiplication of Y and Z axes
	Sound	Mean of the sound amplitude, Standard deviation of the sound amplitude, the multiplication of mean and standard deviation of sound amplitude
	Light	Mean of the light illuminance
	GPS	None
Users' Decision	**Time**	Hour
	Ringtone	Ringtone volume
	PSFs	Tilt, Legrests, Seat elevation
	Acceleration	The total amplitude of 3 axes
	Sound	None
	Light	None
	GPS	None

Table 26 shows the results for feature selection in overall, users' attention, and users' decision analyses from all of the pooled data points. Most of the features in the users' decision and users' attention analyses are the same features picked in the overall analysis. Table 27 shows the performance results for different machine learning algorithms. As can be seen, the k-nearest neighbors and the random forest tree have better performance on accuracy, precision and recall values for the three classifications. The accuracies of these two algorithms are 72.76% for the k-nearest neighbors and 74.54% for the random forest tree, respectively. The poorest predictions for all of the algorithms was in predicting cancellation of the reminders. The precision and the recall values were relatively low for all of the algorithms.

Table 28 shows the results of the analysis of different machine learning algorithms for users' attention. Again, the k-nearest neighbors and the random forest tree show better accuracy, and the precision and recall values are around 0.8. Additionally, the overall performance of all algorithms showed a good ability to predict if the reminders would snooze automatically.

Table 29 shows the performance of different algorithms at predicting users' decisions. The k-nearest neighbors and the random forest tree again had the best performance predicting users' decisions regarding the reminders. Although the accuracies of all of the algorithms in the users' decision analysis are only slightly better than in the overall analysis, the results for precision and recall values are much better in the users' decision analysis.

Table 30 and 31 present the results of applying the k nearest-neighbors model with the features selected from a pooled dataset on each of the individual participants. The average accuracies for predicting users' attention and users' decisions is around 80%. However, the variations in precision and recall values are very large among the participants.

Table 27. The performance of different machine learning algorithms for overall analysis.

Algorithm	*Accuracy*	*Precision (Perform)*	*Recall (Perform)*	*Precision (Cancel)*	*Recall (Cancel)*	*Precision (Auto Snooze)*	*Recall (Auto Snooze)*
***KNN**	**72.76%**	**0.708**	**0.678**	**0.574**	**0.395**	**0.77**	**0.872**
Naïve Bayes	**58.89%**	**0.487**	**0.629**	**0.363**	**0.279**	**0.736**	**0.675**
SVM	**64.86%**	**0.535**	**0.672**	**0.561**	**0.076**	**0.722**	**0.836**
BFTree	**69.13%**	**0.693**	**0.595**	**0.465**	**0.288**	**0.731**	**0.887**
***RandomForest**	**74.54%**	**0.732**	**0.712**	**0.596**	**0.379**	**0.781**	**0.893**
Logistic	**63.34%**	**0.514**	**0.615**	**0.627**	**0.088**	**0.702**	**0.835**

Table 28. The performance of different machine learning algorithms for users' attention analysis.

Algorithm	*Accuracy*	*Precision (Perform/Cancel)*	*Recall (Perform/Cancel)*	*Precision (Auto Snooze)*	*Recall (Auto Snooze)*
***KNN**	**80.78%**	**0.818**	**0.769**	**0.8**	**0.843**
Naïve Bayes	**64.52%**	**0.587**	**0.872**	**0.789**	**0.437**
SVM	**73.06%**	**0.706**	**0.748**	**0.756**	**0.715**
BFTree	**76.16%**	**0.773**	**0.71**	**0.753**	**0.809**
***RandomForest**	**80.30%**	**0.806**	**0.806**	**0.8**	**0.83**
Logistic	**71.01%**	**0.692**	**0.692**	**0.727**	**0.712**

Table 29. The performance of different machine learning algorithms for users' decision analysis.

Algorithm	*Accuracy*	*Precision (Perform)*	*Recall (Perform)*	*Precision (Cancel)*	*Recall (Cancel)*
***KNN**	**74.46%**	**0.768**	**0.84**	**0.697**	**0.59**
Naïve Bayes	**68.16%**	**0.697**	**0.855**	**0.633**	**0.402**
SVM	**68.89%**	**0.675**	**0.954**	**0.78**	**0.262**
BFTree	**72.63%**	**0.718**	**0.916**	**0.756**	**0.421**
***RandomForest**	**73.81%**	**0.758**	**0.846**	**0.695**	**0.564**
Logistic	**67.70%**	**0.678**	**0.907**	**0.672**	**0.307**

Table 30. The performance of the k nearest-neighbors on each individual participants for users' attention analysis.

Subject	*Accuracy*	*Precision (Perform/Cancel)*	*Recall (Perform/Cancel)*	*Precision (Auto Snooze)*	*Recall (Auto Snooze)*
1	**71.81%**	**0.712**	**0.472**	**0.72**	**0.877**
2	**80.8%**	**0.784**	**0.67**	**0.819**	**0.89**
3	**82.93%**	**0.875**	**0.903**	**0.667**	**0.6**
4	**77.22%**	**0.817**	**0.835**	**0.684**	**0.657**
5	**78.84%**	**0.726**	**0.5**	**0.805**	**0.916**
6	**86.04%**	**0.856**	**0.674**	**0.862**	**0.947**
7	**71.79%**	**0.6**	**0.243**	**0.736**	**0.929**
8	**87.5%**	**1**	**0.833**	**0.667**	**1**
9	**96.53%**	**1**	**0.333**	**0.965**	**1**
10	**70.96%**	**0.764**	**0.72**	**0.645**	**0.696**
	80.45±8.14	**0.813±0.126**	**0.618±0.223**	**0.757±0.103**	**0.851±0.146**

Table 31. The performance of the k nearest-neighbors on each individual participants for users' decision analysis.

Subject	*Accuracy*	*Precision (Perform)*	*Recall (Perform)*	*Precision (Cancel)*	*Recall (Cancel)*
1	**67.42%**	**0.72**	**0.871**	**0.429**	**0.222**
2	**67.96%**	**0.417**	**0.345**	**0.759**	**0.811**
3	**91.94%**	**0.917**	**1**	**1**	**0.286**
4	**81.87%**	**0.835**	**0.974**	**0.333**	**0.065**
5	**83.96%**	**0.84**	**1**	**0**	**0**
6	**73.05%**	**0.429**	**0.167**	**0.764**	**0.924**
7	**86.9%**	**0.75**	**0.231**	**0.875**	**0.986**
8	**87.67%**	**0.889**	**0.985**	**0**	**0**
9	**85.98%**	**0.867**	**0.986**	**0.667**	**0.16**
10	**64.33%**	**0.7**	**0.729**	**0.544**	**0.508**
	79.11±9.96	**0.736±0.180**	**0.729±0.345**	**0.537±0.346**	**0.396±0.385**

4.3.5.8 The relationship between years of using PSFs and changes in PSF usage with the SVSC

Table 32 shows the correlation matrix among years of using PSFs, the percentage of following reminders when reminders came out (follow reminders), the percentage of responding reminders when reminders came out (respond reminders), the compliance rate in the baseline, and the compliance rate change with the SVSC. The result shows that years of participants using PSFs do not have any correlation with other variables. However, there is a positive correlation between the percentage of responding reminders and the compliance rate change with the SVSC.

Table 32. The correlation matrix among years of using PSFs, the percentage of following reminders when reminders came out (follow reminders), the percentage of responding reminders when reminders came out (respond reminders), the compliance rate in baseline, and the compliance rate change with the SVSC.

	Follow reminders	**Respond reminders**	**Compliance rate in baseline**	**Compliance rate change w/ the SVSC**
Years of PSF usage	-.176 (***p*** **= .628)**	.383 (***p*** **= .275)**	-.478 (***p*** **= .162)**	.091 (***p*** **= .802)**
Follow reminders		.293 (***p*** **= .411)**	-.280 (***p*** **= .433)**	.528 (***p*** **= .117)**
Respond reminders			-.200 (***p*** **= .579)**	.708* (***p*** **= .022)**
Compliance rate in baseline				-.530 (***p*** **= .115)**

4.3.6 Discussion

4.3.6.1 Wheelchair Occupancy

Wheelchair occupancy did not change over the course of the study, indicating that the intervention of SVSC did not increase/decrease the time that they were in the wheelchair. Wheelchair occupancy governed two important variables in this study, compliance rates for performing repositioning exercises and the frequency of using PSFs. If the wheelchair occupancy had decreased, increases in the two variables could have been a result of reduction of wheelchair occupancy and the unchanged values for compliance rate and frequency of using PSFs. However, result of no change in wheelchair occupancy in this study allows us to observe that the differences in compliance rate and frequency of using PSFs had to have come from change in participant behavior with respect to PSFs rather than a decrease in their time in the wheelchair.

4.3.6.2 Compliance Rate for Performing Repositioning Exercises

After the intervention of SVSC, the compliance rate for performing repositioning exercises increased from 13.98% to 57.87%. This boost in the compliance rate is similar with the results from our tablet VSC study, which showed an increase in compliance rate from 21.75% to 54.41% after the intervention[1]. Previous studies showed that an effective repositioning exercise requires a user to tilt the chair at least 35 degrees and recline at 120 degrees, or tilt at 25 degrees and recline at 120 degrees. [8, 11] However, most of the current powered wheelchairs on the market do not provide users with seating angle information, meaning that the users have no way to know their tilt and recline angles to perform an effective repositioning exercise. For this reason, the reminders that SVSC gives to the participants not only display the angle information, but also show angle meter bars (Figure 37) that indicate the target angles that the users need to adjust to achieve an effective repositioning exercise. The reminder to do the repositioning exercises also has a timer to encourage users to stay in this position for a certain period of time. In this study, most of the users followed the reminders and increased the frequency of performing the repositioning exercises each day, rather than only doing them when they realized they had to as before.

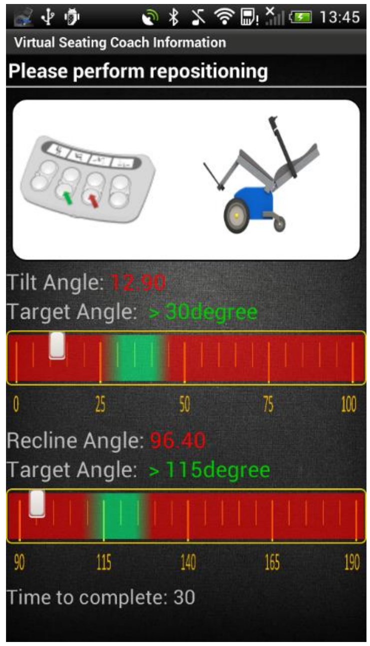


Figure 37. The angle meters indicate the target angles that a user needs to adjust to in order to achieve an effective repositioning exercise.

Even though the results for the intervention of thermometer and daily report are not statistically significant, the compliance rate in the thermometer group slightly increased when the participants had the thermometer widget in their app. Participants in the thermometer group reported that the widget gave them active control over the repositioning exercise schedule, so they were able to adjust the schedule according to their daily activities.

However, the compliance rates in the daily report group did not show any change. The effectiveness of the performance feedback is debated. [42-45] Some studies have asked participants to solve a series of problems within a specific time and then given them feedback about how close they were toward the goal after half the given time had elapsed. [42, 43] They found that those with greater progress at the halfway point, who knew they were close to the goal, had a better expectancy of reaching the goal and achieving satisfaction with their performance, but those with less progress actually showed a decrease in expectancy of reaching the goal and in satisfaction after knowing their progress. This study used a smiling face to give the performance feedback to the participants. If their compliance rates were higher than 80%, they got a green, fully smiling face. If the compliance rates were lower than 60%, they got a red sad face. Among the five participants in the daily report group, one participant who had a higher compliance (around 90%) had a slightly increased compliance rate when receiving the feedback. However, one participant with 50% compliance rate in phase I showed a decrease in compliance rate around 10% in the last week when getting the feedback; on the other hand, another participant with a 40% compliance rate in phase I increased compliance rate by 10% in the last week. Unfortunately, this study was unable to tell if the feedback was effective or not.

4.3.6.3 The Numbers of Times Spontaneously Performing Repositioning Exercises

To further investigate how the SVSC increased the compliance rate for performing repositioning exercise, we calculated the average numbers that the users performed the exercise either spontaneously or after getting the reminders each day. As can be seen in the results, the number of performing repositioning exercises spontaneously did not increase; rather, the increases in number of performing exercises resulted mainly from receiving the reminders, meaning that increased compliance rates were due to the intervention of the SVSC. One interesting finding is that the participants in the thermometer group did use the button on the widget to perform the repositioning exercises before the reminders came out. Two participants reported that the reason that they performed the exercises beforehand by using the widget was because they did not want to be bothered during activities they knew were coming up. Another reason was that the participants wanted the angle meters on the app to give them the visual feedback so that they could perform an effective repositioning exercise when they have the chance to do so. Although the participants in the thermometer group decreased one time of performing repositioning exercise via reminders (phase I: 4~5 times/day; phase II: 3~4 times/day), they used the widget to perform additional exercises 3~4 times/day in the last week. It could be concluded that the widget allows the participants to actively perform the repositioning exercises based on their daily routine, which further increased their compliance rate for performing the repositioning exercises. Another interesting finding is that the number of performing repositioning exercises spontaneously slightly decreased in the daily report group over the course of the study. The reason is difficult to investigate because with only 5 participants in each group, the decreased values could be just variation in the data. However, it is important to investigate this phenomenon in the future to see if the participants increase their dependence on the reminders and decrease their active behaviors due to the intervention of the SVSC.

4.3.6.4 Frequency of Utilizing the Powered Seat Functions

The frequency of using PSFs in the two groups did not show any significant difference among the three phases. The only difference is the frequency of using the tilt function, but the incremental increase did not achieve statistical significance. The participants in two groups increased their use of the tilt function around 5 to 8 times after the intervention of SVSC. When breaking down the ranges of angle changes into different range categories (minimum, medium and maximum), the increment of frequency mainly occurred in the medium and maximum angle ranges. Based on these results, the increased frequency in using the tilt function might have resulted from the rise in compliance rate of performing repositioning exercises, since the participants had to tilt backward from an upright position to at least a 30-degree tilt angle when performing the repositioning exercises. Since the current SVSC does not have the functionality to encourage the users to change their seating angles periodically, it is reasonable that the results of the frequency of PSF usage did not significantly change in this study.

4.3.6.5 Tool for Assessing Wheelchair discomfort (TAWC)

In this study, all participants were able to answer the TAWC showed on the smartphone. The SVSC app displayed the TAWC at 4pm each day and reminded the participants to answer it. By using this method, the number of days that the participants answered the TAWC was 4.32±1.87 times/week. When looking at each individual phase, the numbers were 3.4±1.95 at baseline, 4.67±1.73 at phase I and 5±1.66 at phase II. The result shows that answering the TAWC seemed to gradually become a daily routine for each participant.

As in the tablet VSC study, the results for the general discomfort score and discomfort intensity score in the TAWC were not significantly different. [1] Wheelchair seating discomfort is a very common problem for wheelchair users. [18, 36-38] Frank et al. reported that duration of using powered wheelchair is positive correlated with seating discomfort or pain [46, 47]. Of the participants in their study 59% (38 out of 64) felt that their pain was influenced by their powered wheelchairs, but only 5% reported that they used tilt and/or recline to decrease pain [46]. Many powered wheelchair users do not use their PSFs to adjust their posture frequently to lessen seating discomfort. Changing the posture on the chair not only helps the pressure distribution or skin perfusion, but also allows contractile and non-contractile tissue to stretch or relax. [48, 49] It is impossible for people to sit on a chair without any movement and not feel discomfort. In this study, the insignificant change of the frequency of PSF usage could be the reason that the wheelchair discomfort levels did not change after the intervention of SVSC. In the four PSFs, only the frequency of using tilt function slightly increased after the intervention of the SVSC. When performing correlation test between PSF usage and discomfort intensity, only the frequency of using tilt function was significant correlated with discomfort intensity (tilt: -.496*, p = 0.26, recline: -.112, p = 0.640, legrests: -.01, p = 0.967, compliance rate: .357, p = 0.122).

The result is similar with the result in the next chapter (tilt = -.353*, p = 0.032). The next chapter will discuss the negative relationship between increased frequency of using PSFs and decreased intensity of wheelchair discomfort. For this reason, a future feature to consider for the SVSC could be a reminder that encourages users to adjust their posture frequently, even for a small range, or having additional exercise programs in the app to instruct the user to move their knee and hip joints. Alternatively, powered wheelchairs also could be programed to conduct automatic seating angle changes periodically, like some hospital beds do.

One unexpected result is that the change of compliance rate for performing repositioning exercises was not correlated with the discomfort intensity. An effective repositioning exercise can help relax trunk and neck muscles, release pressure on the back and buttock, and increase circulation of the lower limbs. [3] However, the discomfort intensity only measures the level of discomfort on different body parts and impaired sensory function might make it difficult for powered wheelchair users to identify significant improvements in their comfort. Future studies should consider other factors such as fatigue, skin redness on the compressed areas and lower limb swelling to further discover the physiological benefits of performing repositioning exercises.

4.3.6.6 Analyses of Effective Reminders

The machine learning algorithms were applied to investigate whether the users' decision of whether to follow the reminder's direction to perform repositioning exercises or not could be predicted by some context factors. These results could be useful for our SVSC app to determine the proper contexts to generate a reminder for the users. The overall analysis shows that the context factors captured by the accelerometer and light and sound sensors from the smartphone combined with the PSF information could predict to approximately 74% accuracy whether the user would perform the repositioning exercises or cancel the reminders, or whether the reminders would snooze automatically. However, when looking more closely at the precision and recall values, the performance for predicting cancelling the reminders is very poor, even for the algorithm with the best performance. Specifically, the precision values for the better performance algorithms are just close to 0.6, meaning that in situations where a user might cancel a reminder or not, the algorithms only have a 60% chance of getting the right answer; this is only a slightly better accuracy than flipping a coin would offer. Moreover, the recall values are less than 0.4, meaning that if the algorithms determine a user wants to cancel a reminder, only four out of ten times would the algorithm be correct.

For this reason, when looking further into the decision process from getting a reminder to making the decision to follow the prompt, the process might be broken down into two steps. When a reminder is presented on the screen, the reminder first needs to catch the user's attention and then the user can determine if he or she wants to follow the reminder (users' decision). The results show that the accuracy of predicting whether users' attention will be caught by a reminder can reach 80%. For the algorithms with better performance, the precision and recall values are both around 0.8 for predicting whether the users would respond to the reminders or the reminder would snooze automatically.

Moreover, analysis of the decisions users made shows that the better performance algorithms can have around 74% accuracy at predicting which decision the user will make, a similar accuracy to that of the overall analysis; in fact, the precision and recall values were actually better than those of the overall analysis, especially for predicting cancelling the reminders, where the precision value is around 0.7 and the recall value is around 0.6. However, unlike for the users' attention analysis, where most of the environmental factors are selected in the prediction process, only one feature (the total amplitude of the 3 axis acceleration) is selected in the prediction of users' decision. This could indicate that environmental factors have a stronger impact on the users' attention toward the reminders than users' decision.

The reason for using the pooled data points from all the participants was to try to find a model with a good generalization. Since the k nearest-neighbors is a non-parametric model, where the model tries to search for similar results from previous data in the database, it is suitable for a small dataset. The k nearest-neighbors was widely tested for activity recognition in previous studies. For example, several studies have investigated using wearable sensors or sensors on the smartphone to recognize different daily activities such as standing, walking, sitting, etc. and the k nearest-neighbors algorithm could have relative good performance. [50-52] In our results of applying the k nearest-neighbors algorithm on the individual participants, the average accuracies for predicting users' attention and decision are around 80%. However, the variations in the precision and recall values with regards to users' attention and decision among participants are relatively large. For those participants with worse performance on either precision or recall values, the amount of the data points in each category were really uneven. As more and more samples are collected in those small sample size categories, the performance of the model could be possibly improved. Unfortunately, the challenge that long-term activity recognition faces is that collecting data over a long period of time is burdensome and time consuming [53]. Moreover, some activities might only occur once or twice a day, resulting in datasets insufficient in size for algorithms to be able to make an accurate prediction. Unfortunately, this study was unable to answer what amount of data is sufficient for the algorithms to have a good performance predicting users' attention and decision. In addition, using information to help predict human behaviors is not like using information to predict physical activities, in which last case training samples can be easily collected by asking the participants to perform those different physical activities. Different factors such as time, location, mood, the activities they are doing etc. could lead to different behaviors or decision making. These real-life contexts are difficult to simulate in lab, making it a challenge to collect a sufficient amount of samples to enable highly accurate prediction.

4.3.6.7 The relationship between years of using PSFs and changes in PSF usage with the SVSC

The range of years of using PSFs in our participants is from two to fifteen years. The total years of using PSFs did not have any correlation with the compliance rate for performing repositioning exercises at the baseline and the change of compliance rate after the intervention of the SVSC. This means that the years of using PSFs might not result in their initial compliance rate and their willingness to change their behavior of performing repositioning exercises. Furthermore, the years of using PSFs did not show any correlation with the rate that the participants followed the reminders to perform repositioning exercises and the rate that the participants responded the reminders. These results indicate that the effect of the SVSC on powered wheelchair users was not biased on experienced or novice powered wheelchair users. However, the results show the positive correlation between the change of compliance rate and the rate that the participants responded to the reminders of repositioning exercises. This indicates that if a participant is more likely to notice reminders and respond to them, their compliance rate would be increased. According to the results from the users' attention analysis, most environmental context factors might be correlated with the chance that a participant would notice a reminder and respond to it. Generating a reminder in the right context that can catch users' attention could be an important factor that the SVSC can change users' compliance rates for performing repositioning exercises.

4.3.7 Study Limitations

The main limitation in this study is the small sample size. Although five participants in each group were enough to obtain a result with significant difference in the comparison of compliance rate between baseline and phase I, this number was insufficient for the rest of the comparisons. For example, the thermometer group seemed to increase their compliance rate in the last week of the study, but the results were not statistically significant. According to the effect size (d = 0.818) between the two groups in phase II, each group needs to have 28 subjects (adjusted α = 0.0167, power = 0.8) or 20 subjects (α = 0.05, power = 0.8) based on power analysis. The small sample size also resulted in an insignificant result for the comparison of the last two weeks of the thermometer group. Based on the effect size (dz = 0.89) of the compliance rate between phase I and phase II in the thermometer group, 14 (adjusted α = 0.0167, power = 0.8) or 10 people (α = 0.05, power = 0.8) would needed in the group to achieve results of statistical significance.

The Hawthorne effect [54, 55] could be another limitation in this study. The Hawthorne effect is defined as the tendency of people to change their behaviors while being observed. The participants in this study might have complied with the reminders to perform repositioning exercises because they knew they were in a study and their performance was being watched. However, at the same time, the Hawthorne effect could be considered an ally of the SVSC application, meaning that the users might try to comply with the clinical recommendations because they are being watched by their clinicians and they know that the clinicians might warn them if their compliance is poor. This is the main reason we created the web service for clinicians -- to review their clients' behaviors of using PSFs so that they would be able to provide their clients with their feedback or encourage their clients to use PSFs. However, further studies are still needed to investigate whether the performance induced by the SVSC will decline over the course of a long-term intervention or after withdrawing the SVSC.

Another limitation in the analysis of users' attention toward the reminders is that it is difficult to know if the ignorance of the reminders was because the reminders were unable to attract users' attention or because the users were not in the wheelchair at the time. The accuracy of predicting users' attention could be higher if a pressure sensor or seat switch was installed on the wheelchair to detect if the users are in their wheelchair. If in the future such a sensor were utilized then, the number of useless reminders could be decreased.

4.3.8 Conclusion

This study investigated the effectiveness of the SVSC. Results show that the compliance rate for performing repositioning exercises increased around 44% with use of the SVSC. In addition, the k nearest-neighbors algorithm could predict with around 80% accuracy whether users would pay attention to the reminders using some context factors. These results could be valuable for improving the SVSC app's ability to generate the reminders in the right contexts so that users would be more likely to pay attention to them. Levels of wheelchair discomfort did not change after the three week in-home trial, but this might be a result of the fact that PSFs usage remained unchanged. The next chapter will discuss the relationship found between the intensity of wheelchair discomfort and the frequency of changing PSFs.

5.0 ENCOURAGE USERS TO CHANGE POWERED SEAT FUNCTIONS PERIODICALLY TO DECREASE WHEELCHAIR DISCOMFORT

5.1 INTRODUCTION

Historically, a dynamic sitting posture with frequent small postural changes has been viewed as a healthy sitting posture. [56] Previous studies have shown that there is not an optimal static sitting posture, because sitting postures increase the strain on active (muscle) and passive (tendon or ligament) spinal structures. [48, 49] People naturally change their postures frequently while sitting, including head, trunk and pelvis angles. Spontaneous postural change can potentially decrease sitting discomfort, since a prolonged stretched condition on contractile and non-contractile tissues and a long duration of low muscular activity might be risk factors for pain or injury. [57]

Wheelchair seating discomfort is a very common problem for wheelchair users. [18, 36-38] This problem could be worse for powered wheelchair users who spend most of their time in their wheelchair and may not be able to adjust their sitting posture as frequently as needed independently. In addition, other issues such as prolonged shear force on the back and buttock area or a slumping posture due to weak trunk control ability [3] might cause wheelchair sitting discomfort. For this reason, powered seat functions (PSFs) become an important means for powered wheelchair users to change their posture dynamically. PSFs include tilt-in-space, backrest recline, legrests/leg support, and seat elevation, all of which allow powered wheelchair users to reposition themselves in their wheelchair, to redistribute pressure on areas that have a high probability of skin breakdown, to increase functional ability such as reaching overhead objects, and to stabilize their position while moving. [3] Previous studies have mainly focused on the effect of using PSFs on preventing pressure ulcers and improving driving safety [5-7, 9, 12], and a few studies reported that wheelchair users tend to use tilt and recline functions to improve seating discomfort. [10, 11, 18] The results from these studies are, however, based on users' reports or surveys, and no study has attempted to investigate if changing the frequency of adjusting posture in a wheelchair is able to alleviate wheelchair sitting discomfort. The aim of this study is to investigate correlations between PSF usage and wheelchair discomfort.

5.2 METHODS

Participants

Thirteen individuals participated in an 8-week experiment in their home/community. (Table 32) The inclusion criteria for selection of powered wheelchair users was 18 years or older and with the ability to operate a power wheelchair equipped with PSFs as their primary means of mobility. All the participants had been approved for a new powered wheelchair with PSFs when we recruited them for this study, and we used the window of the time while they were waiting for their new powered wheelchair to conduct this study. In order to accommodate preferences for using different driving wheel configurations, we prepared front- (Permobil C500, seat width: 19"W x 18"D), mid- (Pride Quantum 6400Z, seat width: 18"W x 18"D), and rear-wheel

(Permobil Street, seat width: 19”W x 18”D) drive wheelchairs for this study. When a person agreed to participate in this study, our powered wheelchair was delivered to his/ her home environment. A clinician who was also an Assistive Technology Professionals (ATP) with more than 10 years of experience providing powered wheelchairs with PSFs verified that the powered wheelchair would be suitable in his/ her environment. This study was approved by the Institutional Review Board at the University of Pittsburgh and the Department of Veterans Affairs Institutional Review Board.

Table 33. Demographic data of participants

Subject	Gender	Age (year)	Height (Inch)	Weight (lb)	Diagnosis	New PSFs Users
1	M	48	72	145	Muscular Dystrophy	No
2	M	59	71	192	Multiple Sclerosis	Yes
3	M	44	66	140	Cerebral Palsy	No
4	F	62	66	280	Poliomyelitis	Yes
5	M	47	68	153	Muscular Dystrophy	Yes
6	M	45	67	244	Spinal Cord Injury	Yes
7	F	67	64	174	Inclusion Body Myositis	Yes
8	F	44	65	140	Multiple Sclerosis	No
9	M	39	69	215	Spinal Cord Injury	Yes
10	M	57	70	248	Spinal Cord Injury	No
11	F	57	63	200	Degenerative Joint Disease	Yes
12	F	65	65	180	Multiple Sclerosis	Yes
13	F	43	66	158	Multiple Sclerosis	Yes
		52.07±9.40	67.08±5.51	189.92±91.07		

Measurement of PSF usage

Each study powered wheelchair was equipped with rotary encoders (A2K Absolute Optical Encoder, US Digital, Vancouver WA)[a] to record angle changes for tilt, recline, legrests, and seat elevation. Two rotary encoders (E2 Optical Kit Encoder, US Digital)[a] mounted on both wheels recorded the wheelchair driving distance. A customized seat switch was placed between the seat cushion and seat pan to detect wheelchair occupancy. All the sensors were mounted on the wheelchair securely with customized cases and were calibrated before each participant received the wheelchair. (Figure 38) A personal computer was attached behind the backrest of the wheelchair and the sensors were all interfaced to the computer.

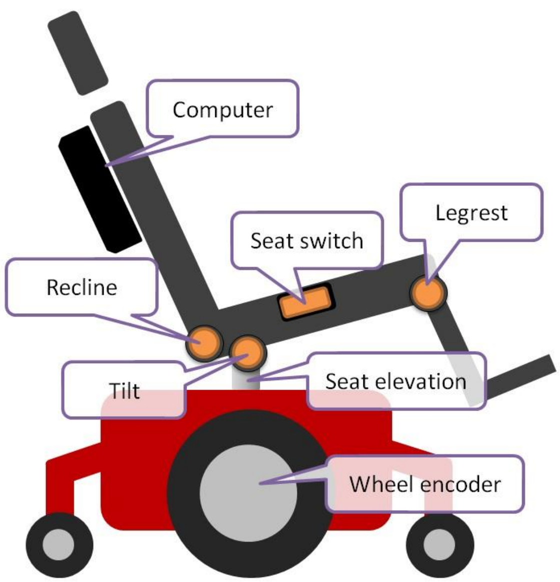


Figure 38. The sensors to record PSFs for instruction group in tablet virtual seating coach study.

Measurement of wheelchair discomfort

This study used the Tool for Assessing Wheelchair disComfort (TAWC) for measuring wheelchair discomfort. [34, 35] The TAWC consists of three sections. Section I is general information about factors that directly affect wheelchair-related discomfort. Section II contains eight statements related to discomfort and five statements related to comfort. These 13 statements are rated on a seven-point Likert scale where 1 is “strongly disagree” and 7 is “strongly agree” (score range: 13 - 91). In Section III, seven body areas (back, neck, buttocks, legs, arms, feet, and hands) are rated for a degree of discomfort intensity on a scale of 0 (no discomfort) to 10 (severe discomfort). It also provides spaces which allow users to list any additional body areas, and the general discomfort intensity is also rated on the same 0–10 scale. This study only calculated the seven default body areas (score range: 0 - 70). Section II and III form two measures of discomfort – the 13 items in Section II are called the General Discomfort Score (GDS) and the seven items in Section III are the Discomfort Intensity Score (DIS). The TAWC has been reported as a reliable and stable tool for quantifying wheelchair seating discomfort. [58] For the responsiveness measures, the average change on the GDS and DIS were 8.7 and 7.7. [35]

Procedure

The total length of the study was 8 weeks. The study period included 5 visits (4 phases: baseline and phases 1, 2 and 3), and the interval between each visit was 2 weeks. During the study, participants were instructed to go about their daily activities as they normally would. The study wheelchair tracked their usage of the wheelchair (e.g., driving distance and wheelchair occupancy) and seating habits (e.g., frequency of using PSFs and frequency of repositioning exercise). In addition, they were asked to fill out the TAWC each day.

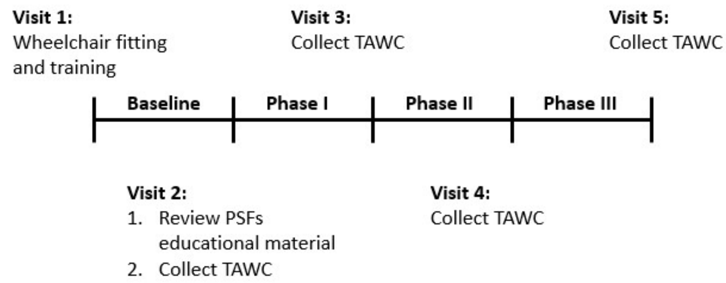


Figure 39. Five visits to collect TAWC.

Visit 1 was either performed on the same day of the participants' initial wheelchair assessment or scheduled at a time convenient for the participants within 2 weeks after their initial assessment. Our research wheelchair was brought into the participant's home environment and was fitted and tuned to the subject's needs by the clinician. Once the participant transferred to our research wheelchair, the clinician instructed him/her to drive the wheelchair and access the PSFs to allow the participant to be familiar with our study wheelchairs. If our study wheelchairs were unable to fit participants' environment, the participants were withdrawn from the study.

In Visits 2 – 5, our research team collected the TAWC forms and downloaded the PSF usage data from the computer. In Visit 2, all participants reviewed a study pamphlet, pocket-size reminder cards, and compact disc containing educational materials on PSF usage. These educational materials included information on using PSFs for body position, posture realignment, transfers, and repositioning exercises. The materials included guidelines on driving in different environments, such as slopes. We expected to observe if the participants changed their behavior of using PSFs after reviewing the materials and if these changes in PSF usage were correlated with changes in wheelchair discomfort.

Data Analysis

All the variables including the potential predictors and outcome variables (Table 33) within one phase were first averaged. Because the scores from TAWC are subjective to participants' personal feeling, the data of the other phases was normalized to the baseline. The reason for preprocessing the data with this method is that each participant had their own pattern of using PSFs and wheelchair discomfort is a subjective measurement, so only the changes of all variables from the baseline were analyzed. The total data points in the analysis were 39 (13 participants multiplied by three phases).

Table 34. The definition of all variables.

Name	Definition
Potential Predictors	
Freq_Tilt	The frequency of using tilt function within a day.
Freq_Recl	The frequency of using recline function within a day.
Freq_Legr	The frequency of using legrests function within a day.
Freq_Seat	The frequency of using seat elevation function within a day.
WOCO	Wheelchair occupancy (hour/ day)
Freq_Repo	The frequency of performing repositioning exercise within a day (number/ day). The repositioning exercise is defined if the users tilt backward to 30 degree and stay in that position for 30 seconds every hour in this study.
Distance	The driving distance of wheelchair (mile/ day).
Outcome Variables	
GDS	General discomfort score in TAWC
DIS	Discomfort intensity score in TAWC

A test for normality was performed before other analyses. Correlation coefficients were calculated to determine predictor(s) for the linear regression model. Linear regression analysis using a backward stepwise method was performed to determine if TAWC wheelchair discomfort scores were predicted by the correlated variables. Correlation and linear regression analyses were performed using SPSS 22.0[c].

In order to find the cut-off points that make the meaningful changes for GDS and DIS, the GDS and DIS results were classified as discomfort decreased (decreased), discomfort increased (increased), and discomfort not changed (neutral) based on the responsiveness (8.7 for GDS and 7.7 for DIS). [35] Weka [59] was used to perform the best-first decision tree learning [60]. The variables correlated with the GDS or DIS were used as the features to classify discomfort changes. The performance of predicting the GDS or DIS was evaluated using ten-fold cross validation.

5.3 RESULTS

Table 34 shows median and interquartile range of all variables in each phase of the study. Most variables except wheelchair occupancy, general discomfort, and discomfort intensity were not normally distributed. Two outliers were removed, because data points were greater than 3 standard deviations beyond the mean. For this reason, Spearman correlation was performed to calculate the correlation matrix among all variables (Table 35). The results show that the frequency of using the tilt, recline, and legrests functions were significantly correlated with discomfort intensity, so these three variables served as the predictors in the linear regression analysis. The assumptions for linear regression were all met. The assumption of multocollinearity among three predictors was not violated, since there was no significant correlation among the predictors. (Table 35) The results of backward stepwise regression indicated that these predictors can explain 43.8% of the variance (R^2=.438, $F(3,33)$=8.588,

$p<.01$) in discomfort intensity (Table 36 and Figure 40). The value of Durbin-Watson test was 1.332, showing that the errors from each predictor were independent. Figure 41 shows the result of homoscedasticity. As can be seen, the residuals were randomly distributed at each level of the predictors and slope of linear curve fitting is close to 0, meaning that the residuals had the same variance at each level of the predictors. The Shapiro-Wilk (value = .983, p = .825) also indicated the errors of the linear regression model are normally distributed.

Best-first decision tree learning was performed to classify discomfort intensity. The frequency of using the tilt, recline, and legrests functions was the feature in the learning algorithm. The results of the decision tree are shown in Figure 42. The frequency of using the legrests was the top node of the decision tree, followed by recline and tilt. The overall accuracy of prediction of discomfort intensity with ten-fold cross validation was 79.4%.

Table 35. The median and interquartile range (IQR) of all variables in each phase of the study.

		Baseline	Phase 1	Phase 2	Phase 3
Freq_Tilt (numbers/ day)	Median	3.94	4.33	4.00	4.78
	IQR	2.02	3.45	3.13	2.88
Freq_Recl (numbers/ day)	Median	3.30	2.58	3.38	3.16
	IQR	1.67	4.25	2.02	3.03
Freq_Legr (numbers/ day)	Median	4.76	3.31	3.38	3.31
	IQR	4.97	8.99	7.19	6.71
Freq_Seat (numbers/ day)	Median	0.31	2.46	0.42	0.73
	IQR	1.32	1.33	2.15	2.26
WOCO (hours/ day)	Median	5.30	6.08	6.32	5.31
	IQR	5.13	3.76	3.74	5.01
Freq_Repo (numbers/ day)	Median	0.19	0.78	0.50	0.71
	IQR	0.54	1.58	0.46	1.22
Distance (miles/ day)	Median	0.87	1.20	1.26	1.15
	IQR	1.18	1.39	1.13	1.70
GDS (score/ day)	Median	40.11	39.21	40.95	42.15
	IQR	16.54	11.40	14.36	13.02
DIS (score/ day)	Median	20	18.13	13.86	14.97
	IQR	12.33	14.69	16.57	15.28

Table 36. The correlation matrix of all variables.

	Freq_Recl	Freq_Legr	Freq_Seat	Freq_Repo	WOCO	Distance	GDS	DIS
Freq_Tilt	.281	.280	.104	.661**	.140	.075	.030	-.353*
Freq_Recl		-.277	.095	.0.94	-.242	-.093	-.002	-.543**
Freq_Legr			.065	.450**	.203	-.025	-.186	.353*
Freq_Seat				.390*	.104	.272	-.003	-.081
Freq_Repo					-.017	.121	.027	-.066
WOCO						-.139	-.287	.114
Distance							-.011	-.149
GDS								.139

*: $p < 0.05$

**: $p < 0.01$

Table 37. The result of multiple regression using backward stepwise method to predict DIS.

	Unstandardized Coefficients		Standardized Coefficients		
Model	B	Std. Error	Beta	t	Sig
Constant	-1.524	.880		-1.732	.093
Freq_Tilt	-.252	.105	-.356	-2.414	.022
Freq_Recl	-.897	.384	-.344	-2.3363.360	.026
Freq_Legr	.734	.303	-.357	2.425	.021

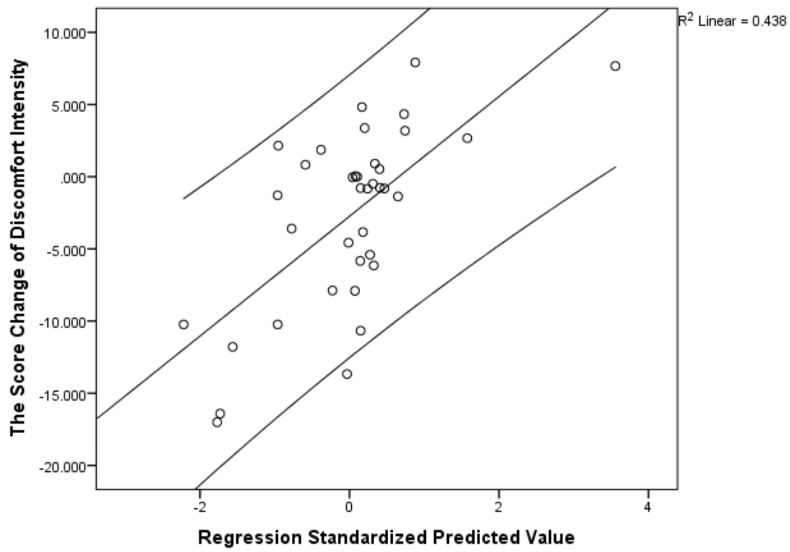


Figure 40. The result of multiple linear regression model shows that the score change of discomfort intensity can be 43.8% predicted by the frequency change of using tilt, recline and legrests functions.

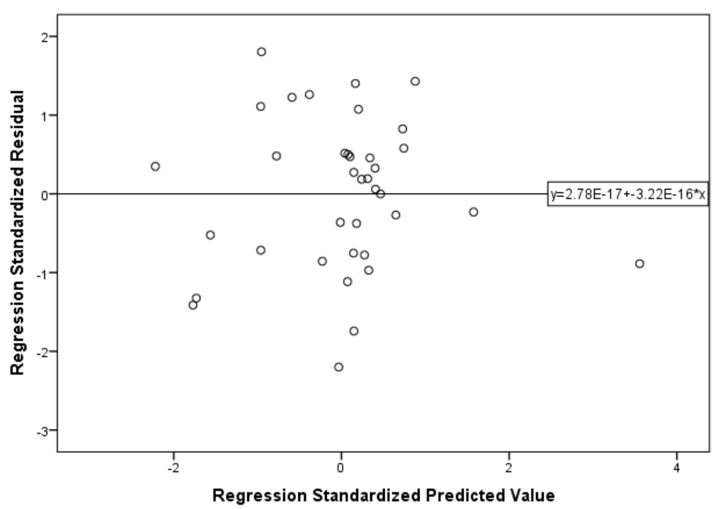


Figure 41. The assumption of homoscedasticity shows that the residuals had the same variance at each level of the predictors.

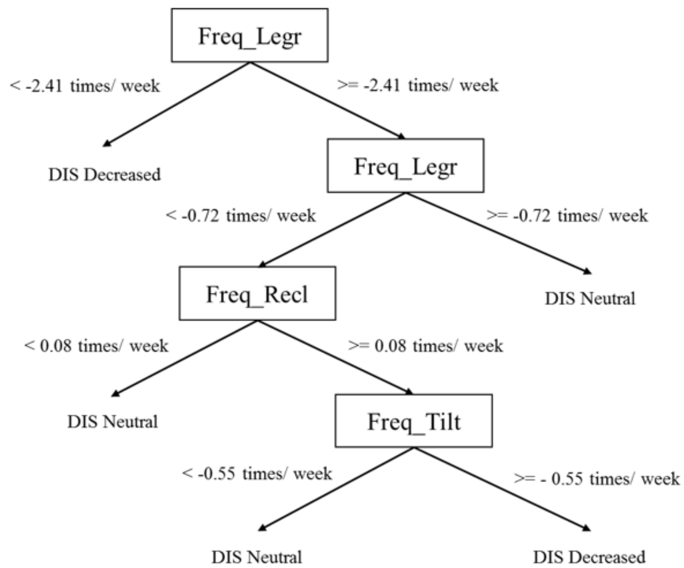


Figure 42. The result of Best first decision tree.

5.4 DISCUSSION

This study investigated the correlation between PSF usage and wheelchair discomfort. The results from correlation analyses showed that wheelchair discomfort intensity is correlated with the frequency of using tilt, recline, and legrest functions. Correlation analysis also showed that the frequency of using the tilt, recline, and legrest functions were not correlated with each other. This may indicate that all three PSFs contribute to changing wheelchair discomfort intensity. Multiple linear regression with backward stepwise modeling supported this result, since none of the functions were eliminated from the model. Also, the assumptions for the regression model were all met, so the model was able to show an unbiased result. The negative correlation indicates that increasing the frequency of using tilt and recline decreases wheelchair discomfort intensity. This result confirms previous studies showing that users tend to use the tilt and recline functions to improve seating discomfort. [17-19] The tilt function is a gravity-assisted way to realign users in their wheelchairs. [2, 3] It is also an important method for relieving seating pressure and restoring skin perfusion. [11] In addition, the posture achieved using the recline function is believed to relax the lower back muscles. [61] Using the recline function can change the length and tension of contractile and non-contractile tissue in the lumber and pelvic area, which is able to prevent prolonged low-level muscle activity which might impair muscle oxygenation and cause pain, [62] thus resulting in sitting discomfort.

One unexpected finding is the positive correlation between the frequency of using legrests and wheelchair discomfort intensity. Elevating legrests are a common way for powered wheelchair users to deal with edema [63, 64] and contractures of knee joints. [2] When elevating the legrests, it is recommended that the backrest be reclined to prevent tight hamstring muscles from rotating the pelvis posteriorly leading to a slouching posture. This result indicates that caution is needed when using elevating legrests and emphasizes the importance of education. The virtual seating coach is a system which educates powered wheelchair users in utilizing their PSFs appropriately via reminders. [14, 20, 65] The system monitors how users utilize the PSFs by adding sensors on the powered wheelchairs and it can detect that the users might be in a poor posture resulting from inappropriate PSF adjustments. In this case, the system reminds the users to recline backward when elevating the legrests to a large angle.

Best-first decision tree analysis was performed to find cut-off points to understand levels of change in tilt, recline and legrests angles that results in significant differences in discomfort intensity. An advantage of decision tree algorithms is that they can describe a pathway and define thresholds for decision nodes to provide quantitative information on the degree of adjustment of PSF usage that can change wheelchair discomfort. The algorithm selected the frequency of legrests usage as the first decision node. Decreased discomfort intensity occurred when the frequency of using legrests was below 2.41 times per week. Increasing frequency of tilt and recline usage was observed to mitigate discomfort due to increasing frequency of legrests elevation usage.

Study Limitations

One limitation to this study is that even though this is a longitudinal observation of PSFs and wheelchair discomfort, the inherent disadvantage of correlation tests is that they do not prove causation. However, it is reasonable to postulate that the PSF usage ameliorates wheelchair discomfort, because it would be difficult to explain a user feels more comfortable, so he/she wants to increase the PSF usage. Another limitation is that there were only thirteen participants. The reasons that some participants dropped out of the study are (1) they received their new powered wheelchair before the end of the study, and their living environment did not allow them to have two wheelchairs; (2) the participants could not fit into our research wheelchairs, since we only prepared the research wheelchairs with the size that most people can fit in according to the statistics from the clinics; (3) our study wheelchairs did not fit into users' apartment and the users could not accommodate them; and (4) the participants could not answer the TAWC questionnaire each day. In addition, we provided the educational materials to the participants in visit 2 and expected that they would lead to increased PSF usage, so we would be able to observe the decrease of wheelchair discomfort. However, some of our participants did not increase or decrease PSF usage. Nonetheless, the multiple linear regression model can reflect the increasing and decreasing change of discomfort intensity explained by the changes of tilt, recline and legrests functions usage. The limitation of the decision tree model is that most of the changes were below the responsiveness score (7.7 for discomfort intensity score) and we only observed a few data points with meaningful discomfort intensity decrease (only 7 discomfort intensity decrease from 37 data points). The imbalance of the data points could weaken the generalization of the decision tree model. Future studies should utilize an intervention which could significantly and continuously facilitate users in utilizing their PSFs, so it can further consolidate the relationship between using PSFs and wheelchair discomfort and verify the effect of any intervention. Furthermore, this study reports that powered wheelchair users should utilize a dynamic sitting posture (changing their posture periodically by PSFs) in order to have better wheelchair comfort, rather than staying in a posture for a relatively long time. However, the wheelchair discomfort might result from other medical or physiological factors and the maximal improvement of wheelchair comfort that the PSFs can achieve should be further investigated.

5.5 CONCLUSION

This study investigated the relationship between PSF usage and wheelchair discomfort for powered wheelchair users. The evidence from the quantitative data indicates that increasing the frequency of using PSFs - especially the tilt and recline functions - can potentially decrease wheelchair discomfort. Future studies should have the intervention which can significantly change the PSF usage and observe the improvement of the wheelchair discomfort.

6.0 CONCLUSION AND FUTURE WORK

The VSC system has gone through several improvements from the seating function data logger to the SVSC (Appendix D shows the history of the VSC development). The latest version of the SVSC receives the seating angle data from the built-in actuators on Permobil powered wheelchairs via Bluetooth communication. This eliminated the process of installing external sensors and additional wires for data transmission between the wheelchair and smartphone. The findings in the usability test on the first prototype of the SVSC showed that most powered wheelchair users preferred reminders that popped out on the screen rather than reminders being shown in the navigation bar as a text message, so they can notice the reminders easily and make the PSF adjustments immediately. This finding also brought out the issue that some powered wheelchair users are unable to use the smartphone or find it hard to perform some smartphone functions because of impaired fine motor control. Smartphones and tablets have become popular on the market. However, there are no well-designed alternative controllers for powered wheelchair users to use smartphones and tablets. Voice control is one of the solutions, but it is sometimes burdensome for users to complete a simple task. Since the SVSC can communicate with the wheelchair, using the joystick to control apps might be another application.

Another finding from the usability test was that the reminders for powered wheelchair users should be clear and easy to understand, so they can adjust their PSFs quickly and intuitively. One possible future application for this could be that the wheelchairs are able to adjust the PSFs automatically when the users approve the adjustment from their smartphones. Once the users approve the adjustment, the smartphones send the message to the powered wheelchairs and the wheelchairs adjust the PSFs to the target angles automatically.

The web service created for the SVSC application is a potential solution to store longitudinal data from different users and allow clinicians to review their clients' PSF usage remotely and periodically. It is also a platform for users to provide feedback about how they feel while sitting in their wheelchairs. This can increase the communication between clinicians and their clients and optimize the user's satisfaction toward their wheelchair. However, the relationship between SVSC usage and users' ability of performing transfers or weight shift should be further explored, so clinicians can target most needed population of the SVSC. Moreover, the idea of this web service in the future could be a standard tool in clinical practice to review the PSF usage data and used as a research database to investigate the longitudinal effect of using PSFs on health related issues. Future study should first evaluate the value and usefulness of this web service for clinicians to gather their feedback about the information they need to evaluate PSF usage and how the information should be presented. After successfully applying the web service in clinical practice, the database allows researchers to conduct longitudinal studies such as investigating the relationship between the compliance rates for performing repositioning exercises and the probability of developing pressure ulcers.

Permobil is ready to launch their SVSC application to their clients. With the large amount of Permobil wheelchair users, the big data analysis will be the next potential application. For example, by collecting the large amount of the data including personal health condition, diagnosis, PSF usage, etc., the big data analysis could potentially categorize the population who might have higher possibility to have health related issues such as pressure ulcers, or discover potential users who may abandon their wheelchair. The large amount of data also allow researchers to quantify the association between the SVSC and the outcome variables that researchers are interested in, such as the odds ratio of compliance rate for performing repositioning exercises after the intervention of SVSC. In this study, the odds ratio of the compliance rate greater than 45% (greater than two standard deviation from the baseline) is 21. The odds ratio value is large because only ten participants in the study and only one participant's compliance rate greater than 45% in the baseline. The odds ratio would be more accurate when the sample size increases.

The effectiveness study shows that the intervention of the SVSC can increase the compliance rate for performing repositioning exercises by approximately 44%. Even though the difference in compliance rates between two feedback mechanisms (thermometer bar and daily report) was not statistically significant, the increment of compliance rate in the group with thermometer bar indicates that the SVSC app should allow the user to adjust their schedules based on their daily activities to perform repositioning exercises. Future research might recruit more participants (at least 14 participants based on the power analysis in the effectiveness study) to consolidate the effect of using this kind of feedback mechanism which gives users active control of their schedule. In addition, the participants recruited in the study do not have any cognitive issue and have no difficulty to understand the information showing on the SVSC app. Future work should evaluate the cognitive level required to be able to use the SVSC app.

The analysis on the reminders' effectiveness indicates that the context factors collected from smartphone sensors can be used to predict if the reminder can catch the user's attention. However, the large variation in the prediction model among individual participants points out the weakness of prediction models due to insufficient sample size and uneven samples in each predictive category. Future work should try to find the amount of samples for the model training to achieve a good prediction accuracy. In the future, there should be a protective mechanism for implementing the model in the SVSC app to prevent the users from never receiving reminders.

Although wheelchair discomfort did not show a significant change in the SVSC effectiveness study, the negative correlation between the change of wheelchair discomfort and the change of frequency of using tilt and recline functions points out the importance of dynamic sitting posture in the wheelchair. This could be a future feature for SVSC which reminds the users to adjust the tilt and recline angle periodically, even in a small adjustment. However, this could be a burdensome task for users and the recurrent reminders might interrupt the tasks that the users are performing. One potential application would be that powered wheelchairs are programmed to adjust the seating angles automatically and periodically in specific angle ranges. Some hospital beds nowadays have this functionality to automatically adjust the hip and knee angles to prevent the people from maintaining the same posture for a long time.

The TAWC is the only health related outcome measurement to evaluate the effectiveness of the SVSC, and it did not show any significant change with the increased compliance rate for performing repositioning exercises. The TAWC evaluates users' discomfort issues including pain, soreness, etc. However, impaired sensory function might make it difficult for powered wheelchair users to identify significant improvements in their comfort. Future study should measure other factors such as fatigue by using the fatigue severity scale [66], skin redness on the compressed areas by measuring the skin temperature [67] or lower limb swelling by measuring the lower limb circumstance, since periodically performing repositioning exercises can help relax trunk and neck muscles, release pressure on the back and buttock and increase circulation of the lower limbs. [3] Additionally, wearable physiological sensors can be used to measure the change of physiological signals such as blood pressure or oxygen consumption. Combined with the physiological sensors, the SVSC could show the physiological needs of the human body to perform repositioning exercises or change seating angles, so the users would increase their compliance of following the reminders. The physiological sensors could also be used to evaluate users' emotion toward the reminders of the SVSC, so the SVSC app would not generate reminders in an appropriate situation.

Since the SVSC has the ability to monitor PSF usage continuously, other interesting studies could be conducted in the future. One study could explore wheelchair driving safety. Recording PSF data allows researchers to construct the scenario about the seating angles when an accidents occur. Another study could monitor the seating angle when users or caregivers perform transfers. Adding a pressure sensor could allow the SVSC to accurately detect if users are in the wheelchair. If the SVSC can correctly detect that one user is performing transfers, one new feature of the SVSC is that the SVSC provides users or caregivers with an instruction to perform transfers step by step.

APPENDIX A

SIGNAL CONDITIONING OF THE ACCELEROMETER SIGNALS

Material

The Android smartphone was mounted on the left armrest of a powered wheelchair (Permobil Corpus C500, Permobil Product Corp.) by a smartphone holder. A standard inclinometer was place on the seat pan as a gold standand next to the accelerometer to measure the tilt angle of the powered wheelchair. In order to have a stable angle from the accelerometer, Kalman filter (initial state covariance (P) = 1, state noise covariance (Q) = 0.0001, measurement noise covariance (R) = 0.15) with moving average (window size = 3 data points) was applied. The sampling rate was set as 5 data points/ second. To avoid the angle variation caused by the voltage fluctuation, the angle calculated by accelerometer was rounded off to the nearest integer.

Procedure

For this test, we moved the tilt angle from 4 degree (minimal tilt position related to ground) to 40 degree with 1 degree interval. We recorded both angle from the inclinometer and accelerometer respectively, and performed linear regression.

Result

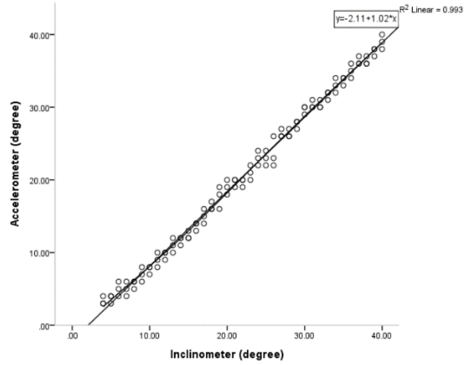


Figure 43. The linear correlation between the angles measured by the inclinometer with angles calculated by the accelerometer.

As can be seen, the angles from the inclinometer and accelerometer have a very high correlated relationship ($R^2 = 0.993$). The linear regression formulation is shown as follows:

Accelerometer = 1.0245 * Inclinometer + Normal (-2.10653, 0.892641)

Where the Normal (-2.10653, 0.892641) shows the 95% confident interval of the interception of this linear regression. As a result, the variation of angle error between accelerometer with inclinometer is -1.57±1.86 degree with this Kalman filter and moving average setting.

APPENDIX B

ACCURACY OF SMARTPHONE EMBEDDED ACCELEROMETER TO DETECT THE ANGLE CHANGE

To evaluate the accuracy of smartphone embedded accelerometer for angle change, we conducted the follow test.

Material

A smartphone with an Android operating system was used in this study. The smartphone was mounted on the left armrest of a powered wheelchair (Quantum Q6400Z, Pride Mobility Product Corp.) by a smartphone holder. A standard inclinometer was also mounted on the left armrest next to the smartphone holder as a gold standard to measure the change of the tilting angle of the powered wheelchair. With this setting, the smartphone and inclinometer are on the same plane to measure the tilting angle change of the seat of the powered wheelchair.

Mechanism

A customized Android app is used to detect the single axis rotation angle change of the smartphone associated with the tilting angle change of a powered wheelchair, because tilting angle change is essentially one axis angular rotation following the axis between a wheelchair seat and its base. This app can use the embedded accelerometer data (the 3 axis value related to the gravity detected by the accelerometer chip) to calculate the initial space vector ($\overrightarrow{V_1} = (x_1, y_1, z_1)$) when starting the app. If the smartphone rotates to another position which leads to another space vector ($\overrightarrow{V_2} = (x_2, y_2, z_2)$), this app will calculate the angle between the two space vectors by the following formula.

$$\cos\theta = \frac{\overrightarrow{V_1} \cdot \overrightarrow{V_2}}{|\overrightarrow{V_1}||\overrightarrow{V_2}|}$$

Procedure

In this study, we chose four different initial positions for the smartphone to test the validity of the phone's ability to detecting the single axis rotation. The four initial positions are defined as follows (Figure 44). As can be seen, the rotation angle (row, pitch and yaw) of the last two initial positions are decided by random numbers. The feature of using a space vector means that the rotation angle changes can be calculated by two space vectors, no matter what the initial position is. Also, in real-life application, we can not assume that when users use their smartphones as instructions to perform an effective pressure relief with a sufficient tilting anlge, they will put the smartphone in exactly the same position each time. Each initial position was checked by a standard goniometer. The inclinometer is at the same position among the four different positions trials, which is parallel to the armrest.

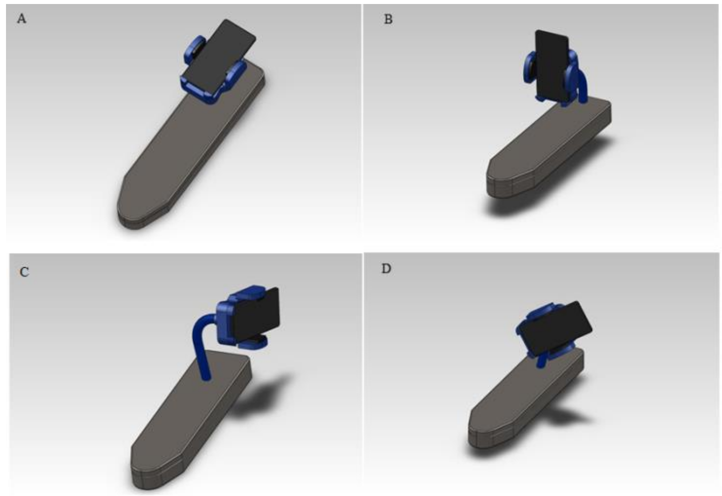


Figure 44. Four initial positions tested in this study. A. The smartphone faces up and is pararell the armrest. B. The smartphone faces backward and is pararell the armrest. C. The smartphone rotates to a random position. (row: 82; pitch: 11; yaw: 56.) D. Another random position. (Row: 49; Pitch: 25; Yaw: 86.)

During each trial, the powered wheelchair first lowered down to the minimum tilting angle. At this point, the inclinometer was calibrated to zero degrees; at the same time, our app started to run, so the app could catch this minimum tilting angle as the initial space vector. Next, the tilting angle of the powered wheelchair began to increase gradually with 5 degree intervals from zero to 45 degrees shown by the inclinometer as the reference degrees. (i.e., 0, 5 ,10, 15, 20, 25, 30, 35, 40, 45). The angular changes shown in our app were recorded at these 10 reference degrees to perform the validity test.

Statistics

The Pearson correlation coefficient was calculated between the value of angular change from the smartphone and the reference angle from the inclinometer in each trial. Also, the pooled data from four trials was calculated using the Pearson correlation coefficient as a overall validity index. The significant value was set at $p < 0.05$. All statistical analyses were performed using SPSS v20 (IBM, Armonk, NY).

Results

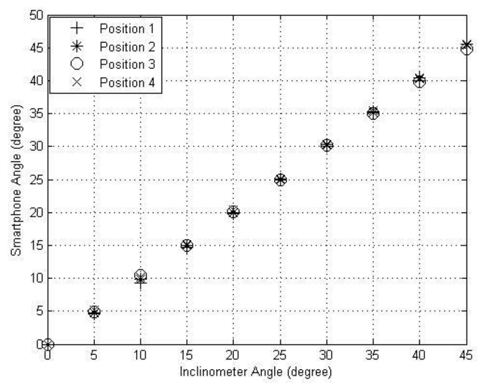


Figure 45. Scatter plot for all 40 pooled data points among 4 position.

Figure 45 shows the scatter plot between the values of smartphone angle and inclinometer angle for pooled data from four positions. Each measurement was performed within approximately 3 to 5 seconds. The Pearson correlation values for the four positions are all significant: $rs > 0.99$, $ps < .001$, $Rs^2 > 0.99$. (Table 37)

Table 38. The Pearson correlation coefficience for each position trial and pooled data.

	Pearson's R	R^2	*p*
Position 1	0.9998	0.9998	<.01
Position 2	0.9999	1.0000	<.01
Position 3	0.9999	0.9999	<.01
Position 4	0.9999	0.9999	<.01
Pooled	0.9998	0.9998	<.01

APPENDIX C

QUESTIONNAIRE FOR EVALUATING THE USABILITY OF SMARTPHONE VIRTUAL SEATING COACH

General Impression of the Virtual Seating Coach (VSC)

Each item below describes how you would see and interact with the VSC. Please put an X in the appropriate box to show how easy you feel while using the VSC.

Data Visualization	Very easy	Easy	Neutral	Difficult	Very difficult
View the seating angle information on the screen clearly					
Understand the seating angle information					
View the stats chart (pressure relief and safety warning number) on the screen clearly					
Understand the stats chart (pressure relief and safety warning number)					
Coaching Instruction	Very easy	Easy	Neutral	Difficult	Very difficult
Enter the coaching screen through clicking the warning message					
Understand the instruction in the warning message to adjust your					

wheelchair					
Enter the pressure relief screen through clicking the reminder alert					
Understand the instruction in the reminder message to perform pressure relief					

Which features do you like the most (check all that apply)?

☐ The seating angle information showed on the application

☐ Brief summary about the pressure relief performance and the number of safety warning

☐ The coaching instruction for pressure relief and safety warning

☐ The automatic reminder of pressure relief

☐ Customized setting for clients (If you are a clinician)

☐ Other, please specify __________________

What would be the potential problem to use thus device?

☐ The small display of a smartphone might not show the information clearly

☐ The location for the smartphone cradle might interfere with transfers or other daily living

☐ The wires connecting the accelerometers might interfere with transfers or other daily living

☐ The accelerometers might be broken

☐ Other, please specify __________________

How do you rate the usefulness of the application delivered by a cell phone?

a. Extremely useful
b. Very useful
c. Moderately useful
d. Slightly useful
e. Not useful

On a scale of 1-5, 1 being totally disagree and 5 being totally agree, please circle the number to rate your answer for each question:.

Question	Totally Disagree		Neutral		Totally Agree
It was easy to learn how to use this system	1	2	3	4	5
It was easy and simple to use this system	1	2	3	4	5
It was easy to obtain what I need	1	2	3	4	5
The interface of this system is pleasant	1	2	3	4	5
I like the interface of this system	1	2	3	4	5
The organization of information was clear	1	2	3	4	5
It was easy to navigate where to find what I need	1	2	3	4	5
Whenever I made a mistake using the system, I could recover easily and quickly	1	2	3	4	5
The system gave error messages that clearly told me how to fix problems	1	2	3	4	5
This system has all the functions and capabilities I expect it to have	1	2	3	4	5
Overall, I am satisfied with the quality of service/information being provided via this system	1	2	3	4	5

Would you use the application on your smartphone if this application becomes available?

a. Definitely would.
b. Probably would.
c. Not sure.
d. Probably not.
e. Definitely not.

Would you suggest your friend(s) whom you think may need it to use it if this application becomes available?

a. Definitely would.
b. Probably would.
c. Not sure.

d. Probably not.
e. Definitely not.

(For clinician only) Would you introduce your clients to use this application for powered seat function usage?

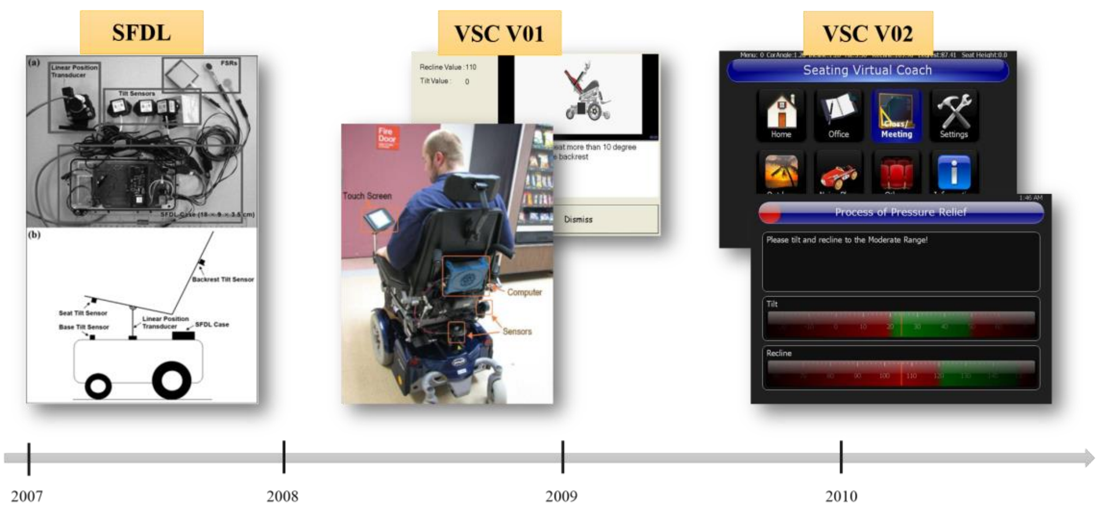
a. Definitely would.
b. Probably would.
c. Not sure.
d. Probably not.
e. Definitely not.

What are your concerns about using or developing this device?

Please provide any suggestions for developing or design this Virtual Seating Coach application.

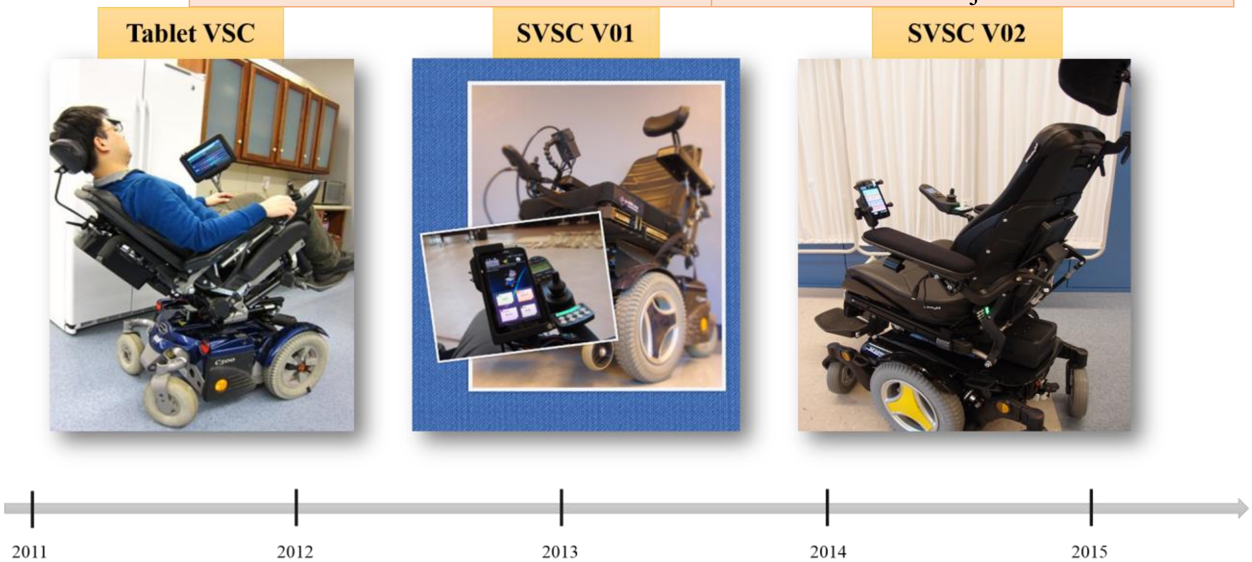
APPENDIX D

THE HISTORY OF THE VIRTUAL SEATING COACH DEVELOPMENT



	Features	Contributions
SFDL	• A data logger to record the usage of tilt, recline, seat elevation, and wheelchair occupancy. • Able to record the usage of PSFs in the users' community environment.	• Subject testing, it revealed that users adjusted their PSFs in small ranges. [17] • Subjects did not perform repositioning exercises as frequently as they needed. [17]
VSC V01	• Mounting encoders on wheelchairs to detect PSF usage. • An onboard computer generated repositioning exercise reminders and safety reminders.	• A survey study [68] on users' preference on displaying reminders found that users' preference to the reminder modes depended on their individual needs and their different contexts.
VSC V02	• New clear and attractive interface were designed. • Different reminder modes for users to	• Start to provide visual feedback to adjust users' PSFs, such as angle meters indicating the target angle that

	select.	users' need to adjust their PSFs.



	Features	**Contributions**
Tablet VSC	• Using a tablet for displaying information. • Separating the tablet from the electronic box.	• The electronic box and the tablet were independent, making the system easy to maintain. • The compliance rate increased around 33% after the intervention of the tablet VSC. [1]
SVSC V01	• Using accelerometers to detect seating angles and using hook and loop fasteners to mount the accelerometers on wheelchairs. • Using smartphones to display information. • Integrating the electronic box into a phone cradle.	• The system simplified the sensor installation process. • The system was able to apply it to different types of wheelchairs. • The dimension of the system decreased significantly.
SVSC V02	• Accessing PSF data from the built-in actuators on Permobil wheelchairs via Bluetooth communication. • Using cloud computing for data storage and data visualization.	• The patent has been filed and Permobil licensed it. • The system became wireless. • The web service allows the review of users' PSF usage in real-time and change of the coach parameters. • The compliance rate was 44% after the intervention of the SVSC.

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