USING WEARABLE SENSORS FOR PHYSICAL ACTIVITY MEASUREMENT AND PROMOTION IN MANUAL WHEELCHAIR USERS

by

Kalai Tsang

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This dissertation was presented

by

Kalai Tsang

It was defended on

July 27, 2018

and approved by

Rory A. Cooper, PhD, Distinguished Professor, Rehabilitation Science and Technology

Brad E. Dicianno, MD, Associate Professor, Physical Medicine and Rehabilitation

Theresa M. Crytzer, DPT, ATP, Assistant Professor, Rehabilitation Science and Technology

James H. Rimmer, PhD, Professor, School of Health Professions at University of Alabama at Birmingham

Dissertation Director: Dan Ding, PhD, Associate Professor, Rehabilitation Science and Technology

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Regular participation in physical activity (PA) is vital to good health. Despite numerous reported physical, physiological, and psychological benefits associated with regular PA for people with disabilities, many of them still lead a sedentary lifestyle, especially those who use manual wheelchairs as their primary means of mobility. Therefore, this research aims to provide tools to accurately measure and promote PA participation in manual wheelchair users (MWUs). In the first study, we established a PA compendium for MWUs with various diagnoses based on various daily and leisure PA performed by a total of 90 MWUs in the lab and home environments. The improved compendium allowed MWUs and/or clinicians to accurately determine the energy cost of various PA and develop a strategy to maintain energy balance. In the second study, we developed a set of custom algorithms for objectively predicting energy expenditure of MWUs and classifying time spent at different intensity levels during different PA using the commercial sensor, ActiGraph GT3X+, which was worn at the dominant upper arm and wrist. Algorithms were developed and validated using PA data from 45 MWUs in Pittsburgh, PA and Birmingham, AL. To achieve the overall goal of providing tools to measure and promote PA, the custom algorithms were made available for use through a smartphone app, *WheelFit*. In the third study, we conducted focus groups with MWUs and rehabilitation professionals who worked with MWUs to determine app

content, features and functions that were most relevant, attractive, and which appropriately addressed the needs and desires of MWUs in a PA measurement and promotion app. As a result of the focus group inputs, we developed a functional prototype of *WheelFit v1.0* including the following features: 1) goal setting; 2) real-time self-monitoring of daily PA; 3) progress tracking; 4) a workout library; 5) exercise reminder to trigger more PA; and 6) preliminary action planning to motivate users to perform target behavior. In the last study, we tested the usability of *WheelFit v1.0* in 5 MWUs which showed that MWUs were generally satisfied with the app and were enthusiastic about using it to adopt and maintain an active lifestyle.

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1.0 INTRODUCTION

Regular participation in physical activity (PA) is vital to good health [1]. According to *Healthy People 2020*, adults who are physically able to, should engage in at least 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity aerobic activities, and muscle-strengthening activities on 2 or more days per week [2, 3]. However, more than 80% of adults in the United States do not engage in PA at recommended levels [4], especially those who have mobility disabilities. There are currently 3.6 million wheelchair users in the United States, and 2.8 million of them are manual wheelchair users (MWUs) [5, 6]. More than half (57%) of adults with mobility disabilities, including MWUs, get no aerobic PA and lead a sedentary lifestyle due to various physical, personal, and environmental barriers such as decreased muscle mass, the lack of self-awareness of being physically inactive, and the lack of accessible equipment and gym in the community [7-10]. Consequently, this population is three times more likely to develop chronic diseases such as obesity, diabetes, and cardiovascular diseases than people without disabilities [7, 11]. Preventative measures such as promoting regular PA participation and an active lifestyle are some of the best ways to reduce the incidence of chronic diseases in this population [12].

Promoting healthy lifestyles in MWUs is challenging, mainly because most of them have lost the continuity between being a patient and an exercise participant [13]. Two types of MWUs face similar obstacles in PA participation – the one that acquired their disability in adulthood and the other that had a pediatric onset condition. For those with acquired conditions, since the US healthcare system reduced the length of stay of inpatient rehabilitation from a median of 20 to 12 days between 1994 and 2001 [14], these individuals often have received insufficient physical therapy and wheelchair skills trainings. People such as those with acquired traumatic brain injuries sometimes do not even receive formal inpatient rehabilitation after trauma [15]. Some MWUs with acquired injuries may leave hospital without achieving the necessary functional gains to live independently and productively [16, 17]. To address this problem, medical professionals often prescribe outpatient therapy or recommend exercise programs to MWUs and expect them to continue the intervention independently at home or in the community. Unfortunately, the community is underprepared to support MWUs' health and wellness needs [18, 19], such as lack of social support [20] and inaccessible gyms [20, 21]. For those who have pediatric onset conditions, their outpatient therapy often ends when they become adults. Many of them do not have the necessary community support to continue the transition into becoming active PA participants. As a result, MWUs' recreation and fitness participation are often compromised. Without any supervision or accountability measure, even those who have access to home- or community-based exercise interventions, it is very common that MWUs drop out of these programs, eventually leading towards a sedentary lifestyle [22]. These MWUs fail to transition from "patients" to "PA participants" [16].

A new framework – transformative exercise framework – was proposed to guide people with disabilities such as MWUs to transition from a rehabilitation *patient* to a lifetime PA *participant* [16]. The framework (Figure 1) has three overarching goals – restore, improve, prevent – spanning over 4 focus areas including 1) rehabilitation, 2) condition-specific exercise, 3) fitness, and 4) lifetime PA participant [16]. For people who have acquired a disability such as those injured from traumatic events, this process begins immediately after initial trauma. However, for people who have pediatric onset conditions, this process starts very early in life and spans a long period of their lifetime as individual grows and changes. During rehabilitation, the primary goal is to restore physical function after acquired injury and/or prevent the onset of conditions, or symptoms, associated with a disability or diagnosis. At this phase, MWUs recover body function and/or independence in activities of daily living and learn how to use manual wheelchairs and other assistive technology within inpatient or outpatient settings. During condition-specific exercise, the goal is to continue and build upon a pre-established plan in rehabilitation to improve body functions with a specific focus, e.g., gain muscle strength or improve balance. MWUs usually aren't hospitalized at this phase; however, they should have an environment, e.g., outpatient clinics or specialty fitness facilities, that allows them to comfortably perform more focused exercise under the supervision of therapist and/or specialty fitness trainer such as a certified Inclusive Fitness Trainer accredited by the American College of Sports Medicine [16]. During fitness, the goal is to independently continue PA to improve body functions, especially the cardiorespiratory and musculoskeletal systems, and prevent secondary health conditions such as deconditioning and spasticity. The exercise programs become more generic and include a variety of activities ranging from aerobic, muscle strength, endurance, power, body composition, to flexibility. At this phase, MWUs may learn to self-manage their exercise program at the community gyms. Guidance and/or prescription of appropriate exercises from certified personal trainers at this phase can be helpful but is not required. Offering a variety of activities at this phase is critical to reduce boredom or burnout to keep MWUs adherent to the exercise program. During the last phase, i.e., lifetime PA participant, the goal is to prevent chronic diseases such as diabetes and obesity that are related to sedentary lifestyle by regular PA participation. MWUs now become a lifetime PA participant who emphasizes group dynamics, e.g., joining an exercise class to build social cohesion with other members of the class, and skills that are required for recreational activities or adapted sports. Depending on life situations, MWUs may go through this process multiple times in their lifetime. For example, an MWU who is already a lifetime PA participant could return to rehabilitation or condition-specific exercise phase because he/she gets injured during a wheelchair basketball game or has a new health condition. This framework aims to guide MWUs transition from being rehabilitation patients to lifetime PA participants at any time during their lifespan.

To implement the transformative exercise framework to facilitate lifetime PA, measuring and promoting PA in MWUs is extremely crucial. Information about the duration/frequency of the prescribed exercise and the amount of PA performed by MWUs in relation to the change of body function and health outcome is important to capture during the first 2 phases (i.e., rehabilitation and condition-specific exercise) as it can help therapists develop personalized exercise program and evaluate the effectiveness of the program. Promoting PA, on the other hand, is more crucial in the later phases (fitness and lifetime PA participant) as it encourages self-management and keeps MWUs engaged and adherent to the PA/exercise programs. Tools that can measure and promote PA in MWUs are needed for this framework.

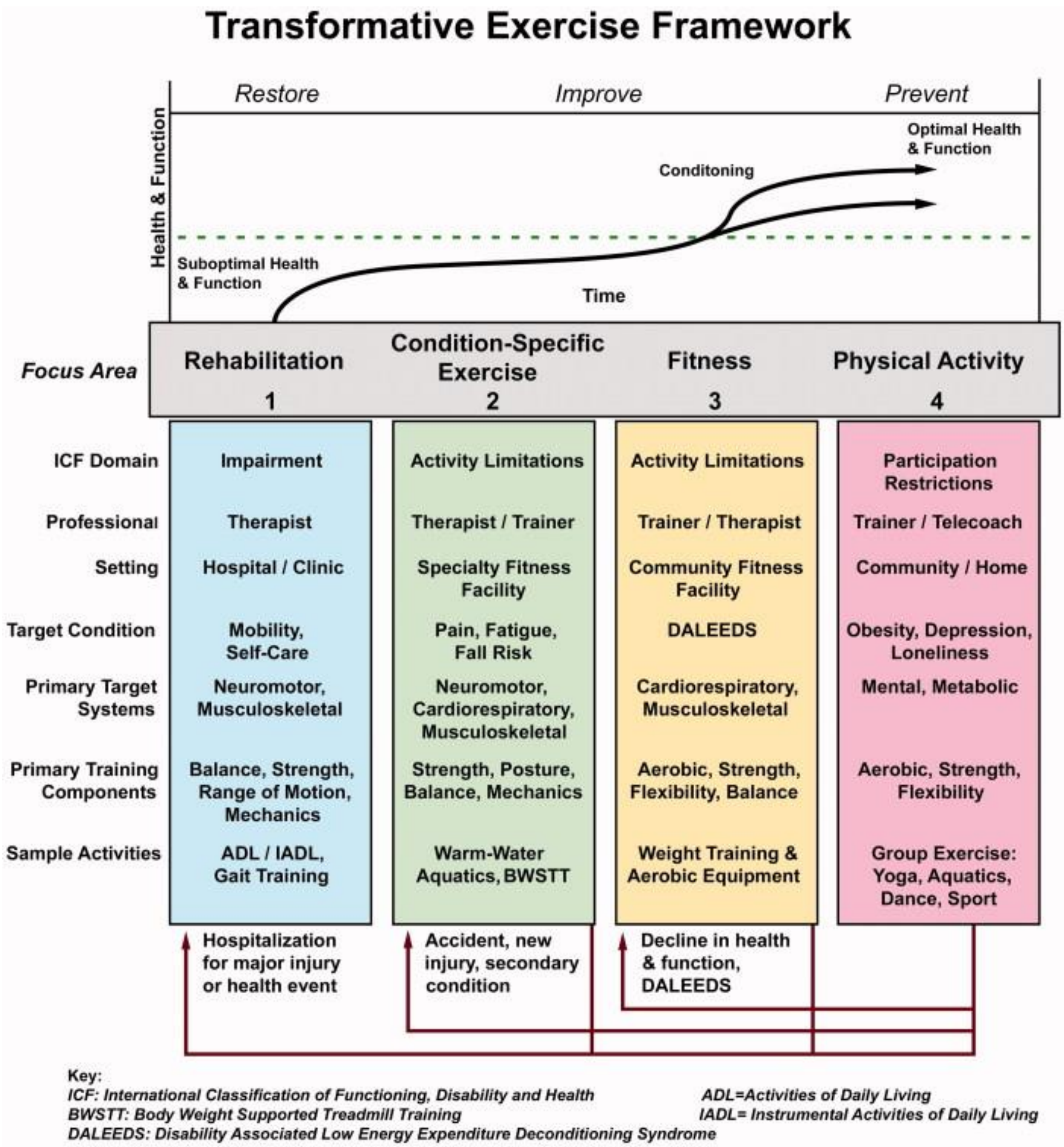


Figure 1. Transformative exercise framework has three goals, *restore*, *improve* and *prevent*, and four focus areas: rehabilitation, condition-specific exercise, fitness, and physical activity (PA) which aim to bridge the gap and help MWUs transition from being a rehabilitation *patient* to a lifetime PA *participant* [16]

1.1 CURRENT METHODS FOR MEASURING PHYSICAL ACTIVITY IN MANUAL WHEELCHAIR USERS

PA can be measured by different dimensions including type, amount, intensity, duration, and frequency. For MWUs, usual types of activities include wheelchair propulsion and mostly upper limb involved activities of daily living. PA amount could be quantified by the distance traveled and number of propulsions. PA intensity could be quantified through energy expenditure (EE), oxygen consumption (VO2), and metabolic equivalent of tasks (MET). PA duration could be quantified as the length of time for certain activities or at certain levels of intensity. PA frequency is typically expressed in sessions, episodes, or bouts per day or per week. Different measurement tools can be used to measure one or more dimensions of free-living PA in the community over a longer period of time (1-week or more) including doubly labeled water, survey-based tools, and sensor-based tools.

1.1.1 Doubly labeled water

Doubly labeled water (DLW) is one of the commonly used indirect calorimetry methods to obtain gold standard measurement of energy expenditure (EE) for long-term monitoring. It requires an individual to drink a dose of stable isotopes of water, $^{2}H_2{}^{18}O$, and provide urine or saliva specimens over the monitoring period for analysis. The theory behind this is that the two isotopes, deuterium (^{2}H) and oxygen-18 (^{18}O), in the dose of stable isotopes of water will be eliminated from the body as water, and combination of water and carbon dioxide, respectively (Figure 2). The carbon dioxide production can then be calculated by subtracting the elimination of deuterium from oxygen-18 [23]. Since the carbon dioxide production is the result of carbohydrate, fat, and protein oxidation, it is considered as an index of EE [23]. The Weir equation is used to determine EE using measured values for the respiratory quotient (RQ), the rate of carbon dioxide production (rCO_2), and the urinary nitrogen production (UN): EE = 3.941 (rCO2 / RQ) + 1.106 (rCO_2) - 2.17 (UN) [24].

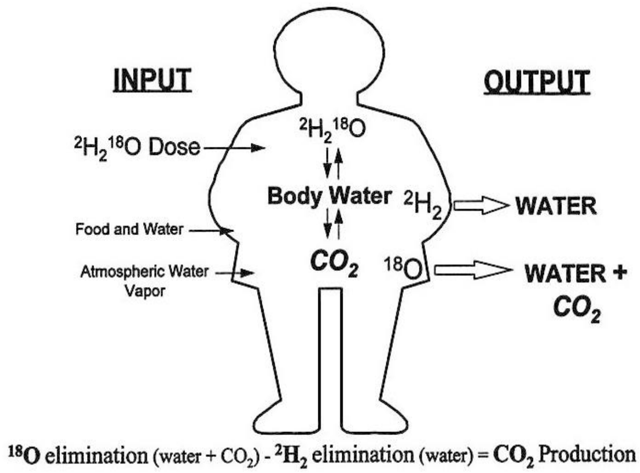


Figure 2. The theory of DLW

There are two typical DLW protocols, two-point sampling and multi-point sampling. The two-point sampling protocol begins with the collection of baseline urine or saliva specimens, followed by oral administration of a dose of $^2H_2{}^{18}O$. Saliva samples are obtained 2 to 4 hours after the dose for calculating dilution space ratios (i.e., the ratio of the rates of decreasing the concentration of ^2H and ^{18}O in body) [25-27], and a urine sample is collected in the following morning. Multiple specimens are collected at the initial time point in case of loss or contamination of specimens (Figure 3). For example, if the saliva samples after 2 to 4 hours are invalid, the urine sample on the following morning can be used [28]. Multiple urine specimens are collected at the end of monitoring period, i.e., the second last day and the last day, for the same reason. The overall timeline of specimen collection of a two-point sampling protocol is shown in Figure 3. For a typical adult, the optimal monitoring period for one dose of $^2H_2{}^{18}O$ ranges from 10 to 21 days depending on how active the person is (very active people have faster water turnover) [29-31].

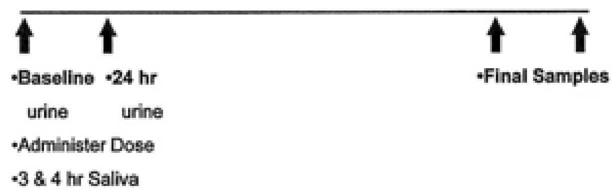


Figure 3. The overall timeline of specimen collection of a two-point sampling DLW protocol [28]

1.1.2 Survey-based tools

Survey-based tools are inexpensive to administer and pragmatic for large-scale long-term monitoring. They are suitable to track duration and intensity of PA and estimate EE in MWUs for applications like understanding the impacts of community-based health promotion programs, tracking participants' compliance to long-term interventions, and determining the dose-response relationships between PA and health benefits or chronic illnesses. Despite their practicality in large-scale applications, survey-based tools are subject to recall bias, and are insensitive to daily PA changes because they are designed for monitoring a period of time (usually 3- to 7-day).

The Physical Activity Recall Assessment for People with Spinal Cord Injury (PARA-SCI) and the Physical Activity Scale for Individuals with Physical Disabilities (PASIPD) are two surveys designed and validated for tracking PA in MWUs. The PARA-SCI is used for tracking three categories of PA, i.e., lifestyle, leisure-time, and cumulative activities, in MWUs with SCI over a 3-day period [32, 33]. The PASIPD assesses 5 distinct types of PA, 1) home repair, lawn and garden work, 2) housework, 3) vigorous sport and recreation, 4) moderate sport and recreation, and 5) occupation and transportation, in people with physical disabilities over a 7-day period [34]. Both surveys include questions that directly measure duration and intensity levels of PA, e.g., “how many minutes engaged in moderate intensity leisure-time physical activity”. This information combined with a compendium of PA can then be used to estimate EE in MWUs; however, the most up-to-date compendium of PA was limited to structured wheelchair-related activities such as propulsions at specified speeds on treadmill and was mostly applicable to MWUs with SCI [35]. For tracking duration and intensity levels of PA, studies reported that the PARA-SCI has intraclass correlation coefficients (ICC) ranged from 0.45 (for moderate intensity leisure PA) to 0.91 (for heavy intensity leisure PA) [32, 33, 36]; while the PASIPD has a test-retest reliability Spearman correlation of 0.77 [34, 37]. The Pearson correlation between the PARA-SCI estimates of time spent at mild, moderate, and heavy intensity PA and the criterion portable metabolic cart measures of intensity of PA ranged from 0.63 to 0.88 [32, 33, 36], while the Spearman’s ρ between the PASIPD estimates of the duration of PA and the validated accelerometer-based activity monitor estimates ranged from 0.28 to 0.31 [38]. The standard error of measurement (SEM) and the minimal detectable change (MDC) of the PARA-SCI of different activity categories were determined to examine its sensitivity to changes (Table 1) [39]. While the survey is sufficient to detect the MDC, the MDC for some of the activity categories are quite large. For example, a minimal change of 100 min of cumulative moderate intensity activity over a 3-day period (i.e., at least 33 mins/day in 3 consecutive days) is required to be captured by PARA-SCI, implying its limited sensitivity to small daily PA changes. The SEM and MDC of the PASIPD were not established, but it is expected that PASIPD will be less sensitive to PA changes than PARA-SCI as it monitors a 7-day period which makes recalling PA accurately more difficult. For estimating EE, the correlation between estimated PA EE by PARA-SCI and the doubly labeled water (DLW) was 0.71 with an estimation error of 6% for total EE and 18% for PAEE over a 3-day period, while that between PASIPD and the DLW was 0.36 with an estimation error of 1% for total EE and 3% in PA EE over a 7-day period [40].

Table 1. Results of SEM and MDC of PARA-SCI [39]

PARA-SCI measure and Intensity Level	SEM (min)	MDC (min)
Cumulative - Total	64.7	179.4
Cumulative - Mild	63.5	176.1
Cumulative - Moderate	36.3	100.6
Cumulative - Heavy	13.6	37.8
Leisure Time Activity - Total	31.7	87.9
Leisure Time Activity - Mild	15.3	42.3
Leisure Time Activity - Moderate	24.8	68.7
Leisure Time Activity - Heavy	8.5	23.5
Lifestyle Activity - Total	65.0	180.1
Lifestyle Activity - Mild	54.3	150.6
Lifestyle Activity - Moderate	29.5	81.7
Lifestyle Activity - Heavy	9.8	27.2

Both surveys are designed and validated for tracking PA duration and intensity in MWUs. The PARA-SCI shows high validity and reliability but is designed and validated among MWUs with SCI, while the PASIPD shows fair validity and reliability but is designed and validated for MWUs with any diagnoses. Both instruments are intended for large-scale long-term monitoring, but they have limited sensitivity to PA changes and are subjected to recall bias as they rely on individuals' memories. Furthermore, both surveys require frequent administrations (PARA-SCI: every 3-day; PASIPD: every 7-day) for long-term monitoring, which may cause inconvenience to some people, resulting in potential data loss in the long run. Given the recall bias, limited sensitivity, and administration difficulties with survey use, survey-based tools may be suitable for research purposes but may not be suitable for consumers to support self-management.

1.1.3 Sensor-based tools

Sensor-based tools show great capability to objectively quantify real-time PA in MWUs in terms of EE, duration, intensity of PA, wheelchair movements (e.g., distance traveled, wheel rotations and speed), and user movements (i.e., propulsion frequency, number of propulsions and types of PA performed). This wide range of information provided by sensor-based tools have prompted their use in various research and clinical applications such as PA monitoring/surveillance and lifestyle coaching (e.g., increasing EE and/or time spent at moderate intensity PA) [41].

We published a systematic review in 2016 for examining the validity of sensor-based tools for quantifying PA in MWUs. The information below is an excerpt from the review paper. Full details can be found in the published article [42]. There are three types of wearable monitors that were designed and/or validated for measuring PA in MWUs – commercial monitors, commercial monitors with custom algorithms, and custom monitors. Among all commercially available monitors, the two most commonly used types are accelerometer and multisensor-based devices. Accelerometer-based devices detect spatial changes in one, two, or three directions; while multisensor-based devices detect spatial changes as well as physiological responses (e.g. heart rate, near-body temperature, and skin conductance) to bodily movement.

Commercial monitors

While there is a plethora of monitors for the general population to measure PA, there is only one commercial monitor in the market, i.e., the Apple watch (Apple, Inc., CA), that can provide relevant information to MWUs including the number of propulsions, distance traveled, and EE on a daily basis. However, its performance has not been validated since its release in fall 2016. Other commercial devices such as Panobike (Topeak, Inc., MA), SensorTag (Texas Instrument, Inc., TX), and activPAL trio (PAL Technologies Ltd, UK) are not designed for MWUs, but preliminary testing has shown that they could be used for tracking the amount of PA in terms of distance and speed travelled by MWUs, as well as EE. User-testing with various sampling frequencies (Table 2) and benchtop-testing with various traveling speeds (Table 3) were carried out at HERL to examine the abilities of Panobike and SensorTag at estimating distance traveled. Both sensors showed relative errors from 0.6% to 17.5% when compared to the actual distances (Table 2 and 3). The activPAL trio (PAL Technologies Ltd, UK) was evaluated for tracking number of wheel revolutions and angle of rotations by another research team [43]. It was found that the absolute error for the number of wheel revolutions was 0.59% with an ICC (2,1) of 1.00, and the Bland-Altman 95% limits of agreement ranged from -0.029 to 0.032 revolution when compared to the actual measurements [43]. In addition, the ICC (2,1) for the absolute angle of rotations was 0.999 with the Bland-Altman 95% limits of agreement ranged from -7.56^{o} to 7.55^{o} [43]. Although commercial monitors such as Panobike, SensorTag, and actiPAL trio are not designed for MWUs, they are ready-to-use and show good accuracy, reliability, and agreement when compared to the criterion measures, making them valid tools for assessing wheelchair movements such as distance traveled, number of wheel revolutions, and angle of rotations. However, these commercial monitors lack the ability to track other PA dimensions.

Table 2. The estimation errors of SensorTag at different sampling rate (Hz) on a 22.2ft path

Frequency (Hz)	Distance measured (ft)	Mean Absolute Error %
30	22.487	1.291 +/- 0.98 %
25	22.494	1.324 +/- 0.304 %
20	22.601	1.806 +/- 0.228 %
15	22.619	1.886 +/- 0.495 %
10	22.394	0.873 +/- 0.504 %
5	21.872	1.479 +/- 0.753 %
1	19.100	13.964 +/- 3.881 %

Table 3. The percent difference between actual distance and measured distance by Panobike at different speed (rpm) using a Computer Numeric Control (CNC) lathe

Speed (rpm)	Actual distance (ft)	Measured distance (ft)	% error
5	157.08	169.64	8.00
10	314.16	259.03	17.55
15	471.24	458.67	2.67
20	628.32	634.60	1.00
40	1256.64	1263.92	0.58
60	1884.96	1897.52	0.67
80	2513.27	2532.12	0.75

Commercial monitors with custom algorithms

Since limited commercial monitors are designed and validated for MWUs, some researchers have adapted the commercial monitors designed for ambulatory population (e.g., Sensewear and ActiGraph devices) to MWUs and developed custom algorithms to estimate different PA dimensions among MWUs including EE, time spent at different intensity levels, and types of PA performed. The accelerometer-based commercial monitors with custom algorithms have relative and absolute errors of EE prediction ranging from -41.0% to 50.2% and from 1.65% to 81.6%, respectively, when compared to the criterion of portable metabolic cart or the DLW [42]. The combined accelerator and heart rate monitor, ActiHeart (CamNtech, Inc.), was evaluated for estimating PAEE in MWUs. Results showed the mean absolute errors of estimated EE were 16.8±15.8% using individual calibration [44]. For estimating time spent at sedentary, light, moderate, and vigorous intensity levels, the accelerometer-based monitors with custom algorithms showed relative errors ranging from -5.4% to 8.6% [45]. For identifying types of PA, the accelerometer-based monitors with custom algorithms showed accuracies ranging from 89.4% to 93.5% while classifying 5 types of PA (sedentary, transfers, housework, locomotion, and moderate PA) [46], from 94.8% to 96.3% while classifying 4 types of PA (resting, deskwork, propulsion, and arm ergometry exercise) [47], and had a sensitivity of 88.3% with a specificity of 83.3% for classifying 2 types of PA (self-propelled wheelchair driving and other activities) [48].

<u>Custom monitors and algorithms</u>

Custom monitors were usually gyroscope-based monitors used for measuring wheelchair activities. In the past, researchers could not access the commercial devices to download their raw data. They were also not allowed to update firmware of the devices for specific research; therefore, custom monitors were created so that researchers were able to revise firmware to provide real-time feedback and other needs for research studies. Researchers have designed and validated custom monitors for MWUs to track additional dimensions of PA, including distance traveled, speed, number of propulsions, and types of PA performed. For distance traveled, the custom gyroscope-based monitors made by Hiremath et al. (2013) showed that the relative and absolute estimation errors ranged from 0.2% to 1.4%, respectively [49]. For speed, the custom monitors made by Hiremath et al. (2013) showed that the absolute estimation errors ranged from 0.03% to 2.2% [49]. For the number of propulsions, the monitor made by Ojeda et al. (2014) showed the absolute errors ranged from 8.0% to 13.4% and ICC ranged from 0.984 to 0.994 [50]. For distinguishing the types of PA performed by MWUs, studies found that the monitors made by Ding et al. (2011), and Hiremath et al. (2015) showed accuracies ranged from 64.2% to 96.0% for detecting 3 types of PA (self-propulsion, being pushed in wheelchair, and sedentary activities) [51, 52].

Measuring PA in MWUs using sensors is considered an “extremely complex” task because the mobility-limiting conditions change the nature of PA itself: how major muscles are used, the amount of EE required, and what types of activities are done [53, 54]. Wheelchair users usually have varying amounts of active muscle mass due to underlying pathology that results in variability of ways of moving [54]. Motion sensors have been shown to be sensitive to detect changes in movements (including involuntary movements such as muscle spasms) [54] and capable of removing noise (such as constant vibration caused by vehicles). However, motion sensors were unable to factor in wheelchair design, terrain, and users' wheelchair skills which contribute to the EE variation during the same PA. For example, an individual using the same propulsion technique going uphill would spend more energy than going on leveled ground. This increases the difficulty in providing accurate EE prediction in wheelchair users.

1.2 CURRENT METHODS FOR PROMOTING PHYSICAL ACTIVITY IN MANUAL WHEELCHAIR USERS

PA promotion among MWUs typically rely on traditional in-person or telephone-based behavior change interventions with trained rehabilitation professionals. While there are large numbers of studies found on investigating the benefits of health and wellness promotion interventions in the ambulatory populations, only a few similar studies were found for the MWUs population. Nooijen et al. investigated a behavior change intervention for promoting active lifestyle in adults with subacute SCI. This randomized controlled trial (RCT) included a control group where individuals received regular rehabilitation after discharge, and an experimental group where individuals received an additional 13 sessions of behavior intervention delivered by a coach after discharge. Results showed that individuals in the experimental group demonstrated increases in wheeled PA 6 months after discharge and the last 12 months after discharge [55]. Latimer et al. evaluated the efficacy of an 8-week implementation intention intervention for promoting PA among individuals with SCI. Results showed that participants who received the intervention (i.e., formulate a plan to include three 30-min bouts of moderate-to-vigorous PA per week) followed through with their PA intentions, and engaged in more PA than participants in the control group [56]. In addition, Arbour-Nicitopoulos et al. evaluated the effectiveness of a PA telephone service for 53 adults with SCI. It was found that 70% of participants followed through with the 6-month intervention, and an increased percentage of participants who were regularly active at baseline (35%) versus 4 months (48%) and 6 months (52%) into the intervention [57]. Froehlich-Grobe has an ongoing project which examines the usability, feasibility, and effectiveness of an Internet-based intervention (WOWii) in promoting exercise and improved fitness for those with spinal cord injury (SCI) over 16-week [58]. To our knowledge, results of this project have not yet been published. Although the limited literature showed promising results implementing behavior change interventions in MWUs, traditional interventions can be challenging to implement in MWUs given cost and resource limitations in this population [7-10].

Due to the proliferation of sensing technology, the use of mobile health (mHealth) applications along with fitness wearables have become popular for the general population. Significant research efforts have been implemented to examine the potential of apps and wearables to increase PA and ultimately improve health outcomes in various ambulatory populations ranging from the general populations (adolescents, young and older adults) to people with chronic health conditions (e.g., cancers and obesity) [59-62]. A systematic review of 26 studies found that individuals who used fitness apps and wearables showed an average of 2000 more steps taken per day, 0.38 decrease in BMI, 3.8 mmHg decrease in systolic blood pressure, and 0.3 mmHg decrease in diastolic blood pressure when compared to the baseline [63]. Another systematic review and meta-analysis of 12 studies showed the use of fitness and weight loss mobile apps was associated with significant changes in body weight (-1.04 kg) and body mass index (-0.43 kg/m^2) when compared to control groups [64].

Unfortunately, research in mHealth and tele-based health and wellness promotion programs is quite limited in people with disabilities including MWUs [65]. Lai et al. conducted an 8-week pre/post tele-exercise intervention that includes the use of upper body ergometry, tablet, and physiological monitor among 4 MWUs with SCI, where participants could schedule their training sessions with a remote professional trainer (3 times per week). The results showed the tele-exercise intervention had increased minutes of moderate exercise (from 24.3 min from week 1 to 74.8 min at week 4) over the study period [66]. Applications among MWUs using fitness apps along with wearables on PA promotion were not found. Studies that examined the use of apps to encourage PA behavior changes in MWUs were also nonexistent. This may be due to the lack of smartphone apps and wearables that are tailored to specifically meet the needs of this population and provide them relevant information to facilitate behavior change.

1.3 ADDRESSING THE GAP IN PHYSICAL ACTIVITY MEASUREMENT AND PROMOTION IN MANUAL WHEELCHAIR USERS

There are over 97,000 health and medical apps available in the app store [64]. Most of these apps focus on general health and physical fitness by facilitating self-monitoring of various health behaviors and vitals in ambulatory populations using wearable sensors [67-69]. Unfortunately, there are only three existing commercially available fitness/health apps that facilitate and promote healthy and active lifestyles in MWUs. There is an immediate need for valid and affordable tools to measure and promote PA in MWUs. Quantifying and promoting PA is very important in the global context of increasing rates of non-communicable chronic diseases related to physical inactivity [70]. A large number of clinical and epidemiologic studies have been conducted to determine the relationships between PA, health, and diseases in the general population using wearable sensors [71]. A systematic review on health benefits of PA in the able-bodied population found that every increase of 500 kcal in EE per week was associated with a 6% decreased incidence of type 2 diabetes, and that regular PA (1000 kcal in EE per week) was associated with a 20% – 30% reduction in all-cause mortality [72]. Promoting PA is the key to reducing the risk of MWUs from developing chronic diseases related to physical inactivity. Therefore, this dissertation study aims to provide tools to objectively and accurately measure PA and promote active lifestyle in MWUs. Such tools would allow users to adjust their behaviors accordingly based on self-monitored PA to develop and maintain a healthy and active lifestyle. Such tools would also allow researchers/clinicians to develop health and wellness program to identify physical inactivity in MWUs, develop clinical interventions to facilitate energy balance and healthy behaviors, track adherence to the PA interventions, and determine the effectiveness of health promotion programs [73].

1.4 DISSERTATION STRUCTURE

The following is a brief description of the dissertation structure. Chapter 2 presents the development of a compendium based on MWUs with various diagnoses. The compendium consists of a list of PA and their associated intensities, which assists researchers and clinicians in coding and quantifying PAs reported through survey-based tools such as PASIPD and PARA-SCI surveys. Chapter 3 details the development and evaluation of new algorithms for estimating EE and classifying time spent at sedentary, light, and moderate intensity levels in MWUs based on commercial wearable sensors which improved the performance of available sensor-based tools in

MWUs. The applicability of the new algorithms on other accelerometer-based sensors is also discussed. Chapter 4 describes the process and methodology we adopted to collect pertinent information regarding the design and development of a mHealth mobile app to measure and promote PA in MWUs. Chapter 5 presents the prototype mHealth app *WheelFit v1.0* and the preliminary findings of its usability over a 1-week testing trial. Chapter 6 discusses the limitations of the presented work, future work, and conclusion of this dissertation research.

2.0 THE COMPENDUM OF PHYSICAL ACTIVITY FOR MANUAL WHEELCHAIR USERS

2.1 INTRODUCTION

Assessing physical activity (PA) in manual wheelchair users (MWUs) becomes crucial for developing appropriate intervention strategies to promote physical health. The development of these strategies relies on the ability of health professionals to accurately identify physical inactivity, track adherences to the PA interventions, and determine the effectiveness of health promotion programs [73]. However, measuring PA in wheelchair users is considered “extremely complex” because the mobility-limiting conditions change the nature of PA itself: how major muscles are used, the amount of energy expenditure (EE) required, and what types of activities are done [53, 54]. Wheelchair users usually have varying amounts of active muscle mass due to underlying pathology that results in variability of ways of moving [54]. While there are many ways for assessing PA, one of the popular ways is to use self-reported instruments such as diary and surveys [33, 34].

Self-reported instruments are inexpensive to administer and pragmatic for large scale long-term monitoring. These instruments are often combined with a compendium of PA to track the frequency, duration, EE, and intensity of activities during the monitoring period. The compendium is basically a comprehensive list of PA and their associated MET values. It was traditionally used to facilitate the coding of self-reported behaviors obtained from PA questionnaires, records, surveys [74], and to promote comparison of coded PA levels across observational studies [75]. More recently, its use was expanded to include estimating the EE of individual PA for exercise and weight management programs [76] and quantifying the energy cost of PA. There are many uses of the compendium in research, clinical, community settings to inform others about the health benefits of regular PA and about ways they can become physically active [75]. For example, Matthews et al. used the compendium to identify daily activity patterns among adults enrolled in a yearlong study of seasonal variations in PA and blood cholesterol levels [77]. Results showed increases in household and leisure-time PA during summer months and increases in occupational activities in the winter [77]. Ainsworth et al. examined the moderate and vigorous intensity of PA patterns of 141 African American and Native American women enrolled in the cross-cultural activity participation study. Results showed that nearly 2-hour/day were spent in moderate intensity activities such as household chores, walking for exercise, caring for children, lawn and garden activities; less than 5-min/day was spent in vigorous intensity of PA [78]. While the compendium of PA was widely used in various research and community-based studies to quantify PA in ambulatory populations, there is limited literature in this area for MWUs.

In the past decades, researchers acknowledged the need of measuring the energy cost in MWUs during different PAs. Collins et al. developed a compendium for 27 activities by conducting a larger scale study with 170 MWUs with SCI in various locations including laboratory, hospital rooms, and natural environments, e.g., city park and local stores [79]. Later, Conger et al. combined data from 11 published PA studies (including studies conducted by Collins et al.) and created a compendium for wheelchair-related activities with a total of 365 MWUs (about 95% of them were diagnosed with SCI) [35]. Since the compendium developed focused primarily on people with SCI and activities performed in a controlled manner, it had limited applicability in real life. A compendium based on MWUs with various diagnoses and activities performed in more realistic settings is needed. Therefore, the objective of this study was to compile a compendium of

PA to estimate the energy cost of 29 common PA that MWUs with various diagnoses perform on a regular basis.

2.2 METHODS

This study was approved by the Institutional Review Board at the University of Pittsburgh and the University of Alabama at Birmingham.

Individuals were recruited from both Pittsburgh, PA and Birmingham, AL areas, and were enrolled in the study if they: 1) were between 18 and 65 years old who lived in a community; 2) used manual wheelchairs as their primary mode of mobility and could propel independently; and 3) were at least one-year post-injury and medically stable. Individuals were excluded if they were unable to tolerate sitting for three hours, had active pelvic or thigh wounds, had medical conditions that were contraindications to exercise, or were pregnant (based on self-report). The purpose of the study was explained to eligible participants and written consent was obtained prior to their participation.

2.2.1 Instrumentation

The open-circuit, indirect calorimetry COSMED K4b2 metabolic cart (COSMED USA Inc., IL) is a portable device that collects and analyzes gas samples, given off by an individual during respiration, and allows for breath-by-breath EE calculation during different PA [70]. Using the device requires the participants to wear a mask over their nose and mouth, and the analyzer on their chest. The analyzer measures the oxygen intake (VO2) and the carbon dioxide produced (VCO2) with each breath [80]. It then multiplies the VO2 (L/min) by the caloric equivalent of VO2 (kcal/L) that is based on the respiratory exchange ratio (RER) (i.e., VCO2/VO2) to calculate the EE (kcal/min) [81, 82]. The outputs of the K4b2 include the timestamp, measured VO2 and VCO2, and calculated EE.

2.2.2 Procedure

The study was divided into two sessions (i.e., lab and home) and conducted at four different locations. The lab sessions took place at the Human Engineering Research Lab at the University of Pittsburgh in Pittsburgh, PA and the Human Performance Lab at Lakeshore Foundation in Birmingham, AL. The home sessions took place in the participants' home in Pittsburgh, PA and in a residential apartment on the Lakeshore Foundation campus in Birmingham, AL.

Lab session

All participants completed a demographic questionnaire that included age, gender, type of injury, experience using a manual wheelchair, and dietary and exercise habits. Weight was measured to the nearest 0.5 kg using a portable 6500 Wheelchair Scale (DETECTO Scale Company, CO), and height was self-reported in feet and inches. After strapping the instruments on, participants were asked to sit still in their own wheelchair for 30 min to obtain resting EE. They were then asked to select and perform at least 6 activities from the following list: 1) propelling wheelchair on a flat tile surface at self-selected normal speed, 2) at self-selected fast speed, and 3) at self-selected slow speed; 4) propelling wheelchair at self-selected normal speed around a track, 5) on a low pile carpeted surface, 6) on a sidewalk, and 7) up and down a ramp; 8) playing wheelchair basketball; 9) exercising with a Theraband; 10) weight lifting; and 11) doing arm ergometry exercise at self-selected normal speed/resistance, 12) at self-selected high speed/resistance, and 13) at self-selected low speed/resistance.

Home session

All participants were invited to the home session, which was scheduled within 3 months of their lab sessions. Participants were asked to wear the same instruments as in the lab sessions. After sitting quietly in their wheelchair for 10 min to obtain resting EE, they were then requested to perform at least 5 free-living activities continuously without a break for 1.5 hours. Activities included 1) watching TV, 2) washing dishes, 3) folding clothes/bedsheets, 4) cleaning the house, 5) reading, 6) using computer, 7) playing games, 8) propelling around the neighborhood, 9) stretching exercise, 10) chair aerobic exercise, and 11) strength exercise. Instructional videos were provided for the stretching, chair aerobic and resistance exercises.

2.2.3 Data Analysis

To construct the compendium, we used data from two studies – study described here and a previous PA study conducted by Hiremath et al. in 2012 [83]. The previous PA study had similar study protocol, but included MWUs with SCI only, involved different PA, and took place at 3 different locations: Human Engineering Research Lab, the 2012 National Veterans Wheelchair Game (NVWG), and participants' homes. Details of previous PA study protocol can be found elsewhere [83].

We combined data from two studies and extracted the K4b2 data for each participant. The breath-by-breath data was downloaded from the K4b2 using the COSMED K4b2 software and converted into a 1-min interval using MATLAB R2016a (Mathwork, Inc., MA). The data collected during breaks was identified and excluded. For the data collected during each activity, only the steady-state data was extracted and used for analysis. A steady-state is defined as VO2 and VCO2 measured by the K4b2 changing 10% or less within 5 consecutive minutes [84, 85]. When this was not achieved, the duration was reduced to 4 consecutive minutes [86-88]. Data was discarded if the duration was less than 4 consecutive minutes.

Final data was analyzed using MATLAB and SPSS (SPSS Inc., IL). Descriptive analysis was performed to characterize the study participants and determine the average energy cost during different activities. Results are presented as mean ± standard deviation (SD). Data was later divided into two groups based on participants' diagnoses – SCI and other diagnoses (Other). Since data was not normally distributed, a non-parametric test (Mann-Whitney U) was used to determine if there were significant differences ($p<0.05$) in oxygen intake between groups of diagnoses. Box plots were also constructed to visualize the distribution of the oxygen intake between MWUs with and without SCI during the same activities.

2.3 RESULTS

A total of 49 participants from Pittsburgh, PA and Birmingham, AL were recruited to complete our study. After screening, data from 1 participant was excluded from the analysis due to K4b2 malfunction. We combined data from 48 participants with 42 participants in the previous PA study conducted by Hiremath et al. in 2012 [83]. There was a total of 90 MWUs (73 male; 17 female) with 3 overlapping participants, performing 29 different activities. Majority of the participants (79%) had a diagnosis of SCI, followed by spina bifida (9%), cerebral palsy (2%), amputation (2%), and others (8%; arthrogryposis, multiple sclerosis, paralysis [participant was unsure about his actual diagnosis], poliomyelitis, traumatic brain injury, and transverse myelitis). Details of the participants can be found in Table 4.

Table 4. Demographics of all participants used to construct the compendium of PA

	All	SCI	Other
Number of subjects (n)	90	71	19
Age (yr)	39.9 ± 12.5	41.3 ± 12.6	34.7 ± 10.9
Gender			
Male	73	62	11
Female	17	9	8
Weight (kg)	76.6 ± 20.1	79.5 ± 19.2	65.7 ± 20.2
Height (cm)	172.3 ± 15.0	176.8 ± 11.1	155.7 ± 16.3
BMI	25.8 ± 6.6	25.4 ± 5.7	27.3 ± 9.2
Wheelchair use (yr)	14.3 ± 9.8	13.4 ± 9.3	18.0 ± 11.1
Type of diagnosis			
Spinal cord injury	71	49 (paraplegic); 18 (tetraplegic); 4 (not reported)	
Spina bifida	8		8
Cerebral palsy	2		2
Amputation	2		2
Others	7		7

The number of MWUs who performed each activity, the total time (min) they spent on each activity, the average EE (kcal/min), the VO2 (mL/min), the VO2/kg (mL/min/kg), the metabolic equivalent of task (MET) and SCI-adjusted MET (MET-SCI) of each activity are shown in Table 5. The MET was computed by dividing the VO2/kg by the caloric equivalent of 3.5 mL/min/kg [74], and the MET-SCI was computed by dividing the VO2/kg by 2.7 mL/min/kg for people with SCI [79]. Both MET and MET-SCI computed for all participants because although the MET-SCI has been widely accepted as a more accurate representation of the intensity of activities performed by MWUs with SCI [79], it remained unclear whether MWUs with other diagnoses should adopt MET or MET-SCI [35].

We split the data into two groups based on participants' diagnoses, SCI (i.e., acquired SCI) and Other (e.g., multiple sclerosis, cerebral palsy, and pediatric onset spinal cord diseases such as spina bifida and transverse myelitis), and compared the oxygen intake (VO2/kg) between these groups for each activity. Out of the 23 activities performed by both SCI and Other groups, results showed there were significant differences in VO2/kg between the two groups in 15 of the activities ($p<0.05$). The distribution of age and weight in both groups for each of those activities with significant different oxygen intake were comparable. MWUs with SCI tended to have lower VO2/kg than MWUs with other diagnoses, meaning they expended less energy than those without SCI while performing the same task. Figure 4 illustrates the distribution of oxygen intake between MWUs with and without SCI during a few PA. Separate compendiums for MWUs with and without SCI may be needed for accurate PA tracking.

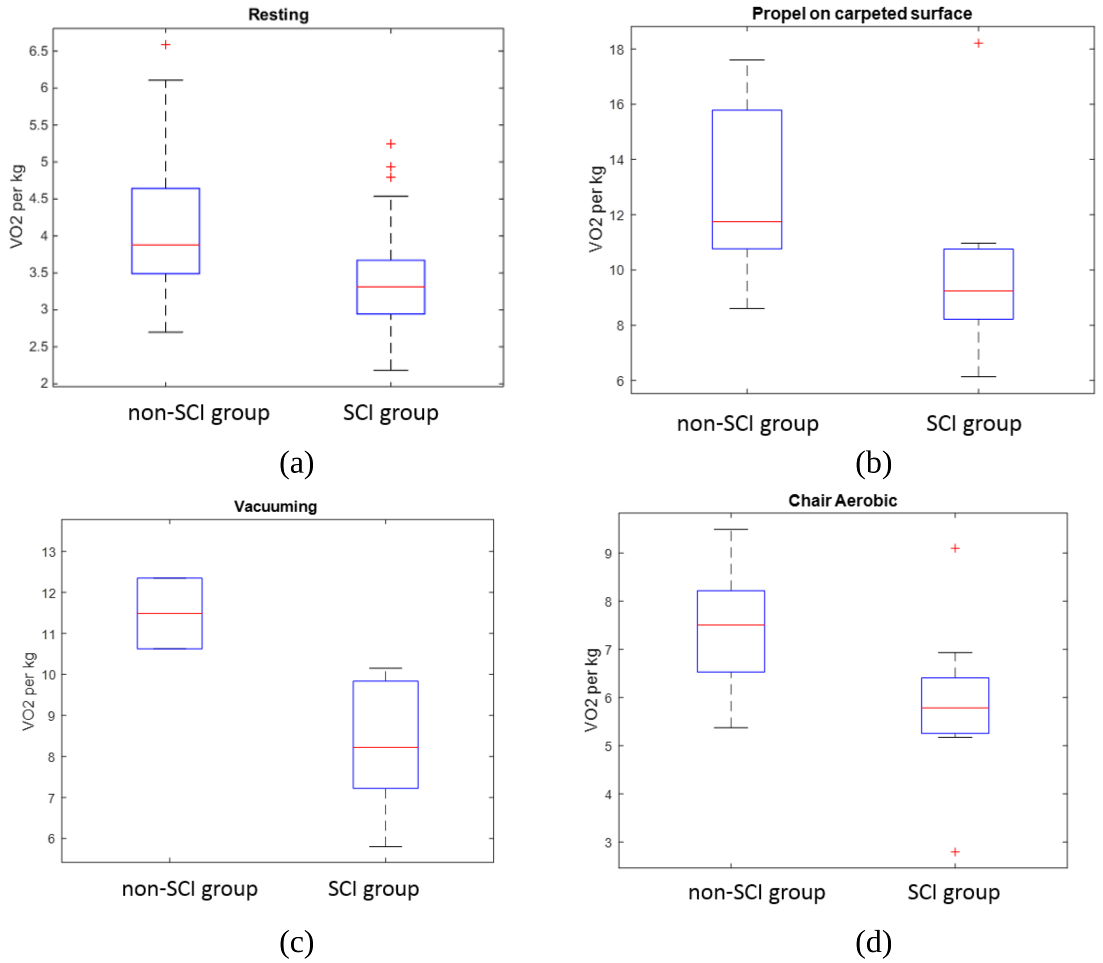


Figure 4. The distribution of oxygen intake (VO2/kg) of MWUs with and without SCI during (a) resting (seated), (b) propulsion over a carpeted surface, (c) vacuuming, and (d) chair aerobic

Table 5. The compendium of physical activity for manual wheelchair users

Description	Subjects (n)	Total time (min)	EE (kcal/min)	VO2 (mL/min)	VO2/kg (mL/min/kg)	MET	MET-SCI
Resting (seated)							
All	59	821	1.27 ± 0.29	266 ± 62	3.65 ± 0.90	1.04	1.35
Other	18	323	1.21 ± 0.25	252 ± 53	**4.19 ± 1.14†**	1.20	1.55
SCI	41	498	1.30 ± 0.31	272 ± 65	3.41 ± 0.66	0.97	1.26
Watching TV							
All	28	167	1.30 ± 0.31	270 ± 64	3.79 ± 1.08	1.08	1.40
Other	11	76	1.36 ± 0.40	284 ± 84	**4.35 ± 1.26***	1.24	1.61
SCI	17	91	1.26 ± 0.24	262 ± 49	3.43 ± 0.79	0.98	1.27

Table 5 (continued)

Reading							
All	32	211	1.35 ± 0.35	284 ± 72	4.00 ± 1.07	1.14	1.48
Other	14	98	1.29 ± 0.34	271 ± 70	**4.19 ± 1.21***	1.20	1.55
SCI	18	113	1.40 ± 0.36	294 ± 73	3.85 ± 0.96	1.10	1.43
Deskwork - paperwork/computer							
All	17	103	1.28 ± 0.34	266 ± 68	3.76 ± 0.73	1.07	1.39
Other	2	13	1.30 ± 0.05	275 ± 11	**5.09 ± 1.11†**	1.45	1.88
SCI	15	90	1.27 ± 0.36	265 ± 73	3.58 ± 0.48	1.02	1.33
Being pushed on a flat surface							
All	2	9	1.54 ± 0.03	327 ± 10	3.79 ± 0.18	1.08	1.40
SCI	2	9	1.54 ± 0.03	327 ± 10	3.79 ± 0.18	1.08	1.40
Being pushed up/down a ramp							
All	2	8	1.36 ± 0.10	512 ± 237	3.94 ± 0.94	1.13	1.46
SCI	2	8	1.36 ± 0.10	512 ± 237	3.94 ± 0.94	1.13	1.46
Cleaning the house							
All	8	48	2.46 ± 1.05	514 ± 219	6.44 ± 2.00	1.84	2.38
Other	1	5	2.52 ± 0	527 ± 0	5.53 ± 0	1.58	2.05
SCI	7	43	2.45 ± 1.13	277 ± 32	6.57 ± 2.13	1.88	2.43
Folding laundry							
All	36	171	2.29 ± 0.64	475 ± 131	6.77 ± 2.03	1.93	2.51
Other	7	29	2.10 ± 0.76	438 ± 154	**8.75 ± 2.78***	2.50	3.24
SCI	29	142	2.34 ± 0.61	484 ± 126	6.29 ± 1.51	1.80	2.33
Cooking							
All	3	19	2.47 ± 0.55	513 ± 97	7.25 ± 0.53	2.07	2.68
Other	1	10	2.29 ± 0	490 ± 0	7.20 ± 0	2.06	2.67
SCI	2	9	2.56 ± 0.74	524 ± 135	7.27 ± 0.74	2.08	2.69
Washing dishes							
All	9	65	2.71 ± 0.85	572 ± 182	7.41 ± 1.97	2.12	2.74
Other	5	30	2.57 ± 0.99	540 ± 213	7.48 ± 2.09	2.14	2.77
SCI	4	35	2.89 ± 0.72	612 ± 155	7.31 ± 2.12	2.09	2.71
Vacuuming							
All	8	56	3.48 ± 1.08	722 ± 216	9.70 ± 3.18	2.77	3.59
Other	2	10	3.74 ± 0.42	781 ± 83	**14.09 ± 2.47***	4.03	5.22
SCI	6	46	3.39 ± 1.25	702 ± 249	8.24 ± 1.62	2.35	3.05
Propulsion on a flat surface @ 2±0.5 ft/s							
All	9	36	2.74 ± 1.17	554 ± 223	7.14 ± 1.78	2.04	2.65
Other	4	20	2.65 ± 1.53	550 ± 312	8.06 ± 1.62	2.30	2.99
SCI	5	16	2.81 ± 0.98	557 ± 163	6.40 ± 1.68	1.83	2.37
Propulsion on a flat surface @ 4±0.5 ft/s							
All	35	163	3.74 ± 1.40	764 ± 274	10.07 ± 3.63	2.88	3.73
Other	8	41	3.56 ± 1.43	720 ± 265	10.67 ± 3.30	3.05	3.95
SCI	27	122	3.79 ± 1.42	776 ± 280	9.90 ± 3.76	2.83	3.67
Propulsion on a flat surface @ 6±0.5 ft/s							
All	13	54	5.18 ± 1.44	1045 ± 282	13.84 ± 3.29	3.95	5.13
Other	4	13	5.07 ± 1.90	1018 ± 355	14.93 ± 4.18	4.27	5.53
SCI	9	41	5.23 ± 1.33	1057 ± 267	13.36 ± 2.96	3.82	4.95
Propulsion on a racing track							
All	10	65	3.11 ± 0.97	637 ± 196	9.65 ± 2.78	2.76	3.57
Other	5	30	2.71 ± 0.73	549 ± 135	**10.64 ± 3.17***	3.04	3.94
SCI	5	35	3.50 ± 1.10	726 ± 221	8.66 ± 2.21	2.47	3.21

Table 5 (continued)

Sidewalk propulsion							
All	17	126	3.45 ± 1.02	721 ± 215	10.95 ± 2.74	3.13	4.06
Other	5	37	3.16 ± 0.80	665 ± 172	**12.39 ± 1.95†**	3.54	4.59
SCI	12	89	3.57 ± 1.11	745 ± 233	10.35 ± 2.86	2.96	3.83
Carpet propulsion							
All	16	99	3.83 ± 1.67	796 ± 342	11.23 ± 3.52	3.21	4.16
Other	7	49	3.72 ± 1.17	774 ± 249	**12.71 ± 3.33***	3.63	4.71
SCI	9	50	3.91 ± 2.05	813 ± 415	10.09 ± 3.39	2.88	3.74
Neighborhood propulsion							
All	7	37	4.01 ± 1.81	828 ± 362	11.55 ± 4.35	3.30	4.28
Other	3	20	4.91 ± 2.02	1012 ± 396	14.50 ± 3.99	4.14	5.37
SCI	4	17	3.34 ± 1.55	690 ± 315	9.35 ± 3.46	2.67	3.46
Propulsion up/down a ramp							
All	23	135	4.64 ± 1.74	945 ± 350	12.44 ± 4.31	3.55	4.61
Other	4	25	5.41 ± 2.29	1100 ± 451	**16.92 ± 2.80***	4.83	6.27
SCI	19	110	4.47 ± 1.63	912 ± 331	11.50 ± 4.01	3.28	4.26
Arm ergometry exercise @ 20 W							
All	5	31	3.72 ± 1.13	761 ± 218	10.52 ± 1.48	3.01	3.90
Other	2	14	3.09 ± 0.68	653 ± 115	11.13 ± 1.63	3.18	4.12
SCI	3	17	4.14 ± 1.30	833 ± 263	10.11 ± 1.57	2.89	3.75
Arm ergometry exercise @ 40 W							
All	23	173	5.08 ± 0.82	1043 ± 168	13.28 ± 2.83	3.79	4.92
Other	8	62	5.25 ± 0.96	1071 ± 198	**14.79 ± 2.48***	4.23	5.48
SCI	15	111	4.99 ± 0.75	1027 ± 155	12.48 ± 2.75	3.57	4.62
Arm ergometry exercise @ 60 W							
All	2	13	7.87 ± 1.26	1551 ± 216	19.18 ± 1.44	5.48	7.10
Other	2	13	7.87 ± 1.26	1551 ± 216	19.18 ± 1.44	5.48	7.10
Theraband exercise							
All	16	89	2.22 ± 0.91	456 ± 183	6.52 ± 2.70	1.86	2.41
Other	2	10	1.76 ± 0.35	362 ± 67	**8.37 ± 3.47***	2.39	3.10
SCI	14	79	2.28 ± 0.95	469 ± 192	6.25 ± 2.63	1.79	2.32
Chair aerobic exercise							
All	17	84	2.05 ± 0.64	426 ± 131	6.58 ± 1.69	1.88	2.44
Other	8	39	1.85 ± 0.54	385 ± 107	**7.42 ± 1.34***	2.12	2.75
SCI	9	45	2.23 ± 0.69	463 ± 146	5.83 ± 1.67	1.67	2.16
Stretching exercise							
All	13	65	2.68 ± 0.72	559 ± 150	7.75 ± 1.21	2.21	2.87
Other	8	42	2.66 ± 0.87	558 ± 179	**7.96 ± 1.02***	2.27	2.95
SCI	5	23	2.72 ± 0.45	561 ± 106	7.42 ± 1.54	2.12	2.75
Resistance exercise							
All	2	9	2.73 ± 1.35	563 ± 263	7.87 ± 1.04	2.25	2.91
Other	2	9	2.73 ± 1.35	563 ± 263	7.87 ± 1.04	2.25	2.91
Weight lifting							
All	5	30	4.50 ± 2.75	886 ± 517	12.74 ± 5.81	3.64	4.72
Other	2	13	2.39 ± 0.64	494 ± 131	**9.11 ± 1.60***	2.60	3.37
SCI	3	17	5.91 ± 2.73	1147 ± 520	15.16 ± 6.65	4.33	5.62
Playing darts							
All	2	11	2.97 ± 0.07	631 ± 23	8.20 ± 2.89	2.34	3.04
SCI	2	11	2.97 ± 0.07	631 ± 23	8.20 ± 2.89	2.34	3.04

Table 5 (continued)

Wheelchair basketball							
All	16	92	4.97 ± 1.13	1027 ± 233	14.46 ± 3.36	4.13	5.35
Other	5	29	4.67 ± 1.14	961 ± 239	15.64 ± 3.45	4.47	5.79
SCI	11	63	5.11 ± 1.15	1057 ± 236	13.92 ± 3.35	3.98	5.16

Other: People who were not diagnosed with acquired spinal cord injury
SCI: People who were diagnosed with acquired spinal cord injury (C2 – L5)
*Difference in oxygen uptake (mL/min/kg) between Other and SCI, $p<0.05$
†Difference in oxygen uptake (mL/min/kg) between Other and SCI, $p<0.001$

2.4 DISCUSSION

The purpose of this study was to construct a realistic compendium of PA for estimating the energy cost of activities MWUs performed on a regular basis. This is one of the first studies to measure energy cost in MWUs with various diagnoses during free-living activities. To further increase the generalizability of the results, we asked study participants to perform each of the selected activities in their own way. For example, some people performed weight lifting in their wheelchairs while others transferred themselves to different surfaces, i.e., floor and/or bench. In addition, we asked participants to use their own tools and instruments to complete the selected tasks. For example, participants use different brands and styles of vacuum cleaners for vacuuming their carpeted, tile, or wood floor. Some participants used cloth or paper towels to wipe countertops when others used brush to scrub the surface while cleaning the house. The variability of how participants performed the same task was reflected in the relatively large standard deviation in VO2/kg (mL/min/kg) in each activity. Furthermore, to mimic real-life scenarios, participants were asked to perform selected activities continuously without break. However, this might introduce carryover effect where the EE from the previous activity passed onto the current activity resulting in possible EE overestimation for activities immediately followed. Further investigation might be needed to see if this potential carryover effect was eliminated while extracting steady-state data.

We initially separated the study participants into two groups based on their diagnoses – SCI and Other. Results have shown that MWUs without SCI tended to consume more oxygen (i.e., expended more energy) than MWUs with SCI while performing most of the PA included in this study. For those activities, we closely examined personal characteristics such as age and weight to analyze if they contributed to the varying amounts of oxygen consumption seen between SCI and Other groups while performing the same activity. We selected activities that were performed by relatively equal number of MWUs with and without SCI, such as watching TV (SCI: n=17; Other: n=11), reading (SCI: n=18; Other: n=14), propulsion on a racing track (SCI: n=5; Other: n=5), and propulsion over carpeted surface (SCI: n=9; Other: n=7). Although MWUs with and without SCI consumed significantly different amount of oxygen, the distribution of age and weight in both groups for each of those activities was comparable. This implied that personal characteristics were unlikely to cause the difference in oxygen consumption. Instead, this difference might be due to the unique anatomical and physiological changes in MWUs with SCI such as reduced fat-free mass and decreased sympathetic nervous system activity [79, 89, 90 91-93]. While we did not have VO2/kg data for resting (in supine position), the significantly higher VO2/kg observed in MWUs without SCI during seated resting and watching TV when compared to those with SCI implied that 1 MET may not be equivalent to 2.7 mL/min/kg for MWUs without SCI; it may be something higher. Further studies need to be conducted to determine how resting EE differs between diagnoses.

We further divided MWUs with SCI into two sub-groups based on their self-reported level of injury (four individuals who did not report their level of injuries were excluded for this analysis), tetraplegic (C8 or above) and paraplegic (T1 or below) and examined if there was any difference in oxygen intake between two groups. Results showed that there was no significant difference in VO2/kg between tetraplegic and paraplegic groups, which was consistent with results from studies by Collins et al., Conger et al., and Lee et al. [35, 79, 89].

The compendium is a useful tool for quantifying PA in MWUs using self-reported instruments. We compared our compendium with an earlier compendium for MWUs developed by Conger et al. in 2011 [35] which consists of combined results of PA studies from the past decades (including studies by Collins et al. and Lee et al.) focused on structured PA performed mainly by MWUs with SCI. Conger et al. reported a (unadjusted) MET of 1.1 for sitting or watching TV, 2.7 for vacuuming, 3.2 for basketball (shooting baskets), 3.8 for propelling wheelchair on sidewalk, 3.9 for propelling up a ramp, and 5.1 for arm ergometry exercise (60W) [35]. Our results were slightly different (MET difference ranged from 0.03 to 0.93; none of these differences differed to an extent where it crossed intensity levels), probably because these activities were performed in an uncontrolled manner in our study, whereas Conger et al. gathered PA studies that mostly involved structured activities, e.g., wheelchair dynamometer at certain resistance, propulsion on an oval track at certain speeds, and arm ergometry exercises at certain resistance, in the lab settings or gym [35] (Table 2). Since our compendium included a wide range of free-living PA performed by MWUs with various diagnoses, it should be used as a supplement to the compendium developed by Conger et al. We recommend researchers and health professionals to use the MET-SCI in our compendium for MWUs with SCI when estimating the EE as it has been validated and widely accepted for this population. Since our results showed evidence of MWUs without SCI might have a higher resting MET, we advise readers to use our compendium to estimate EE in MWUs without SCI with caution.

Limitations

Even though we put effort in recruiting MWUs with various diagnoses to participate in our multi-site PA study, 60% of participants (29 out of 48) had a diagnosis of SCI. To increase the sample size, we combined data from a previous PA study targeted MWUs with SCI (*n*=42) which resulted in 79% (71 out of 90) of total participants having SCI. Although we increased the amount of data of MWUs performing free-living activities, we also increased the amount of MWUs with SCI which made our compendium less applicable for MWUs without SCI. Future studies should consider stratified sampling over simple random sampling to gather a pool of MWUs reflecting the actual MWUs population.

In this study, individuals were split into two groups (SCI and Other) and into two levels of injury (tetraplegic and paraplegic) for secondary analysis. Individuals who reported that they had acquired SCI were grouped into SCI while others including those who had multiple sclerosis, cerebral palsy, and pediatric onset spinal cord diseases such as spina bifida and transverse myelitis were grouped into Other. Due to this classification, people in SCI group and some in Other group (especially those with pediatric onset spinal cord diseases) might have similar functional abilities and experience similar anatomical and physiological changes including decreased sympathetic nervous system activity and decreased muscle mass. This implies that the difference observed in oxygen consumption between the two groups during the same task may be due to factors other than these changes. Future research should investigate on ways to better classify them into groups, e.g., grouping individuals with spinal cord related conditions in one group and having the rest in another group, to determine the potential causes of different oxygen consumption during the same task. Future investigation should also consider using a larger sample size for each group to confirm the observed difference in oxygen consumption between two groups is not due to chance. In addition, we separated people in the SCI group into two levels of injury based on self-reported information. While most of them knew their level of SCI, they might not know their functional levels which might cause mischaracterization. This may explain why there was insignificant difference in oxygen consumption between the tetraplegic and paraplegic group during the same task. A more objective evaluation of the actual level of functional ability of study participants is recommended for future study such as by having a clinician assess functional ability for each study participant through performing an ASIA Impairment Scale (AIS) exam.

2.5 CONCLUSIONS

We constructed a compendium of PA for MWUs based on a wide range of free-living activities which can be used as a tool for estimating EE and standardizing the assignment of intensities in PA surveys for wheelchair users. This compendium will help enhance the comparability of results across studies using self-report instruments and facilitate clinical and epidemiologic studies in this population. Based on the results of our study, additional research on the equivalent value of 1 MET for MWUs without SCI is needed to expand the applicability of the compendium.

3.0 QUANTIFYING PHYSICAL ACTIVITY OF MANUAL WHEELCHAIR USERS USING ACTIGRAPH GT3X+ MONITOR

3.1 INTRODUCTION

Quantifying physical activity (PA) becomes an essential part of the whole-of-day approach to PA participation, particularly in tracking the time spent in activities at different intensity levels. The intensity level is typically classified by the metabolic equivalent (MET), which is defined as the multiples of energy cost (kcal/kg/h) above an individual sitting quietly [94, 95]. Wearable activity monitors are widely used to objectively quantify daily PA [96-99]. One of the most common types of monitors is accelerometer-based devices. This type of monitor measures raw acceleration in 1, 2, or 3 directions, which is then processed by manufacturers' algorithms to provide meaningful outputs such as estimated energy expenditure (EE) and time spent at different intensity levels of PA. These manufacturers' algorithms, however, were designed to analyze movement patterns of ambulatory populations and may have limited accuracy in manual wheelchair users (MWUs). Tsang et al. (2016) investigated the validity of off-the-shelf monitors in estimating EE of MWUs with various diagnoses [42]. The review found a large error in the EE predicted by monitors using manufacturers' algorithms when compared to indirect calorimetry measured with a metabolic cart or doubly labeled water. The relative error ranged from -62.5% to -48.1%, indicating an overestimation of EE during wheelchair related activities [42]. Researchers in the field began to develop custom algorithms based on the off-the-shelf devices to improve the EE estimation performance. Some of the custom algorithms developed were based on commercial devices that had proprietary outputs such as activity counts instead of raw signals; therefore, the custom algorithms based on such outputs could only be used for that specific device [83, 100, 101].

Studies also started to evaluate wearable monitors in tracking time spent at different intensity levels in ambulatory populations. It was found that while most devices gave accurate estimates during sedentary activities, they were highly variant when measuring light, moderate or vigorous intensity PA [102, 103]. Similar studies in MWUs were very limited. Veerubhotla et al. examined the ability of ActiGraph GT9X Link (ActiGraph, Inc.) to estimate activity intensity for MWUs based on a variety of lifestyle activities and exercises [104]. Cut-off points for sedentary, light, and moderate intensity levels were derived, and results showed an accuracy of 93.4% to quantify sedentary behavior [104]. Although the accuracy was high, the cut-off points were not applicable to other devices since they were derived from vector magnitude counts, a proprietary output that was specific to GT9X Link.

In this study, we developed two custom EE prediction and two PA intensity classification models based on raw data collected by ActiGraph GT3X+ monitors worn at the upper arm and wrist, and assessed the ability of these models in predicting EE and tracking time spent in activities at different intensity levels among MWUs.

3.2 METHODS

This study was approved by the Institutional Review Board at the University of Pittsburgh and the University of Alabama at Birmingham.

Individuals were recruited from both Pittsburgh, PA and Birmingham, AL areas, and were enrolled in the study if they: 1) were between 18 and 65 years old who lived in a community; 2) used manual wheelchairs as their primary mode of mobility and could propel independently; and 3) were at least one-year post-injury and medically stable. Individuals were excluded if they were unable to tolerate sitting for 3 hours, had active pelvic or thigh wounds, had medical conditions that were contraindications to exercise, or were pregnant (based on self-report). The purpose of the study was explained to eligible individuals and written consent was obtained prior to their participation.

3.2.1 Instrumentation

The K4b2 portable metabolic cart was calibrated for each participant following the manufacturer's instructions. The EE measured by the K4b2 served as the criterion measure for all analyses. The K4b2 was attached to the chest and a facial mask was placed around the nose and mouth while performing activities. The ActiGraph GT3X+ is an off-the-shelf activity monitor that contains a tri-axial accelerometer, inclinometer, and ambient light sensor. Each participant wore one ActiGraph device over the triceps and one on the wrist of the dominant arm, respectively. The two ActiGraph devices and K4b2 were time synchronized during the testing trials.

3.2.2 Procedure

The study was divided into two sessions (i.e., lab and home) and conducted at four different locations. The lab sessions took place at the Human Engineering Research Lab in Pittsburgh, PA and at Lakeshore Foundation in Birmingham, AL. The home sessions took place in the participants' home in Pittsburgh, PA and onsite housing at Lakeshore Foundation in Birmingham, AL.

Lab session

All participants completed a demographic questionnaire that included age, gender, type of injury, experience using a manual wheelchair, and dietary and exercise habits. Weight was measured to the nearest 0.5 kg using a portable 6500 Wheelchair Scale [c], and height was self-reported in feet and inches. After strapping the instruments on, participants were asked to sit still in their own wheelchair for 30 min to obtain resting EE. They were then asked to select and perform at least 6 activities from the following list: 1) propelling wheelchair on a flat tile surface at self-selected normal speed, 2) at self-selected fast speed, and 3) at self-selected slow speed; 4) propelling wheelchair at self-selected normal speed around a track, 5) on a low pile carpeted surface, 6) on a sidewalk, and 7) up and down a ramp; 8) playing wheelchair basketball; 9) exercising with a Theraband; 10) weight lifting; 11) doing arm ergometry exercise at self-selected normal speed/resistance, 12) at self-selected high speed/resistance, and 13) at self-selected low speed/resistance; 14) stop-and-go (propelling wheelchair for a distance and stopping for a short break at random).

Home session

All participants were invited to the home session, which was scheduled within 3 months of their lab sessions. Participants were asked to wear the same instruments as in the lab sessions. After sitting quietly in their wheelchair for 10 min to obtain resting EE, they were then requested to perform at least 5 free-living activities continuously without a break for 1.5 hours. Activities included 1) watching TV, 2) washing dishes, 3) folding clothes/bedsheets, 4) cleaning the house, 5) reading, 6) using computer, 7) playing games, 8) propelling around the neighborhood, 9) stretching exercise, 10) chair aerobic exercise, and 11) resistance exercise. Instructional videos were provided for the stretching, chair aerobic and resistance exercises.

3.2.3 Data Analysis

The raw acceleration data from the AG was sampled and downloaded at 30 Hz using the ActiLife software (version 4), and then was filtered using a 2nd order lowpass elliptic filter with 3 dB of passband ripple, 200 dB of stopband attenuation, a lower passband frequency of 0.25 Hz, and a higher passband frequency of 2.5 Hz in MATLAB (R2016b). We computed the vector magnitude (VM) by taking the square root of the sum of squares of the filtered accelerations in x, y, and z directions, and used it to represent the amount of arm or wrist movement. The processed AG data such as EE, and MET were downloaded at 15s-epoch. Both AG and K4b2 data was later converted into 1-min intervals using MATLAB. Participants were stratified into two groups based on the body weight and gender. Eighty percent of the participants were in the training group and their data was used to build models for estimating energy cost and classifying time spent in different intensity levels. The remaining 20% of participants were in the testing group and their data was used to evaluate the models.

Custom algorithms for estimating energy cost

Two algorithms, one for the upper arm and one for the wrist of the dominant side, needed to be developed. A set of relevant features was first generated based on data from the ActiGraph and demographic questionnaire. A total of 149 features were obtained, including those directly collected, e.g., age, weight, and vector magnitude of acceleration, and those derived, e.g., $mass^{0.75}$ and $height^2 \times$ vector magnitude of acceleration. The derived features might not have intuitive interpretations, but have good linear correlation with the criterion EE. For example, $mass^{0.75}$ is a better predictor of EE than mass, according to Kleiber's law [105]. A linear regression model with three predictors was chosen to predict EE. The goal here was to have computationally simple algorithms that could be easily implemented into a mobile platform and provide real-time feedback. More complicated algorithms may yield more accurate results but may not be able to meet the real-time needs. The wrapper method based on linear regression models along with a search strategy, i.e., the greedy method with forward selection, was used to select the optimal subset of three predictors by iteratively evaluating subsets of features based on the prediction performance. The procedure started with an empty feature subset and added one feature at a time in each round; this one feature was selected from the pool of all features that are not in the feature subset, and it was the feature that – when added – resulted in the best prediction performance. The performance was evaluated using the mean integrated squared error (MISE) between the estimated and criterion measures, and the leave-one-subject-out cross-validation was used in this feature selection process to avoid over-fitting.

Custom algorithms for classifying time spent into different intensity levels

To classify time spent in sedentary, light, or moderate intensity levels, we built two 2-step decision trees: one was based on the speed of the wheelchair and the amount of arm movement, and the other was based on the speed of the wheelchair and the amount of wrist movement. To establish the decision rules, we determined the wheelchair speed threshold that distinguish wheelchair-involved activities (e.g., wheelchair basketball) and wheelchair-not-involved activities (e.g., reading), and the arm or wrist movement thresholds for sedentary-to-light and light-to-moderate intensity levels of activities. Two methods were used to determine these thresholds. The first method was to define the wheelchair-not-involved activities as resting, watching TV, using a computer, and other stationary activities, and the wheelchair-involved activities as wheelchair propulsion, basketball, and other locomotive activities. The wheelchair speed data of these activities from all participants in the training group was gathered, and the wheelchair speed that separated the wheelchair-not-involved and wheelchair-involved activities was used as the threshold, i.e., 1 ft/s.

A second method – bisection method – was used to establish the arm or wrist movement thresholds for sedentary-to-light and light-to-moderate intensity. To begin, we needed to determine the range of arm or wrist VM values that would contain the optimal VM values. The optimal VM value is defined as the value (while used as the threshold) that gave the smallest absolute percent error while classifying the time spent in sedentary and light intensity level. To find the range of VM values, we identified activities in the training data that was classified as sedentary based on MET measurement from the K4b2, and used the minimum and maximum arm or wrist VM values as the range. The bisection algorithm then used the minimum and maximum VM values as the initial two guesses for the threshold to classify sedentary and light intensity activities. The absolute percent error of the estimated total time spent in sedentary and light intensity was computed. The algorithm then determined the next guess for the threshold by finding the midpoint between the previous two guesses. Then, the absolute percent error was computed. This iterative process continued until one of these two conditions was met: 1) the new guess for the threshold had less than 1-unit difference in magnitude than the current guess, or 2) the absolute percent error of the estimated time spent in sedentary and light intensity levels had less than 0.01% decrease than the previous error. The same process was repeated to determine the optimal VM value as the threshold for light-to-moderate intensity level.

Statistical analysis

We evaluated the custom models for estimating EE and decision trees for classifying time spent at different intensity levels using the data from the testing group. Data is presented as mean ± SD. Statistical analysis was performed to examine the ability of the custom models to predict EE (kcal/min) and total EE (tEE in kcal) over the study period. The mean percent error (MPE), mean absolute percent error (MAPE), and the intraclass correlation coefficient (ICC) of two-way mixed model with absolute agreement were calculated. The Bland-Altman plots were also constructed to examine the agreement of the predicted EE and the criterion EE. To examine the classification performance of the decision trees, the MAPE were computed. Confusion matrices were constructed. Sensitivity, specificity, precision, and accuracy were also calculated.

3.3 RESULTS

A total of 49 participants were recruited and completed our study. Data from 4 of the participants was excluded due to lost data and data abnormality. Detailed demographics of all participants can be found in Table 6. Overall, each participant performed a total of 179.3±10.3 min of activities in the lab and home trials. Participants spent, on average, 41% of the time in sedentary, 38% in light, and 21% in moderate intensity activities.

Table 6. Demographics of participants in training and testing groups

	Training	Testing
Number of subjects (n)	36	9
Age (yr)	39.8 ± 12.5	36.2 ± 11.1
Gender		
Male	29	6
Female	7	3
Weight (kg)	73.6 ± 19.2	82.6 ± 22.3
Height (cm)	170.1 ± 13.2	175.8 ± 16.8
BMI	25.3 ± 5.4	26.9 ± 7.1
Wheelchair use (yr)	16.9 ± 10.6	12.4 ± 11.8
Type of injury/diagnosis		
Spinal cord injury	22	6
Spina bifida	7	1
Cerebral Palsy	1	1
Multiple Sclerosis	1	0
Others	5	1

Equation 1. Custom upper arm model for estimating energy expenditure**:**

EE = 0.462812848596821 + 0.000004289646354*BMR1xVM + 0.000606930434196*BMR2 + (-0.002423011727630*VM)

Equation 2. Custom wrist model for estimating energy expenditure**:**

EE = -0.006197602220975 + 0.000000088463104*BMR2xVM + 0.000823693371782*BMR1 + 0.000577607827818*X

Note: *BMR1xVM: basal metabolic rate by World Health Organization multiplies vector magnitude of the accelerations; BMR2: basal metabolic rate by Mifflin et al. (1990); VM: vector magnitude of the accelerations; BMR2xVM: basal metabolic rate by Mifflin et al. (1990) times vector magnitude of the accelerations; X: acceleration in x direction, i.e., vertical axis of the monitor.*

In general, both custom models (Equation 1 and 2) showed higher accuracy in EE and tEE compared to the default models. Table 7 shows a detailed summary of the MPEs, MAPEs, and ICC (2,1) of the estimated EE by default and custom upper arm and wrist models. The Bland-Altman plots show that the estimated EE by the custom models had stronger agreement with the criterion than the estimated EE by the default models (Figure 5).

Table 7. The mean percent error (MPE), mean absolute percent error (MAPE), and intraclass correlation coefficient (ICC) of estimated EE (kcal/min) by default and custom upper arm and wrist models compared to the criterion

	MPE mean±sd	**MAPE mean±sd**	**ICC (2,1) mean [95% confidence interval]**
Default			
Upper arm	-40.13±56.80%	125.61±48.81%	0.53 [0.45, 0.60]
Wrist	-18.16±35.53%	83.17±20.39%	0.72 [0.69, 0.75]
Custom			
Upper arm	-8.93±10.19%	26.97±9.34%	0.89 [0.88, 0.90]
Wrist	-9.04±15.78%	31.48±6.69%	0.84 [0.83, 0.86]

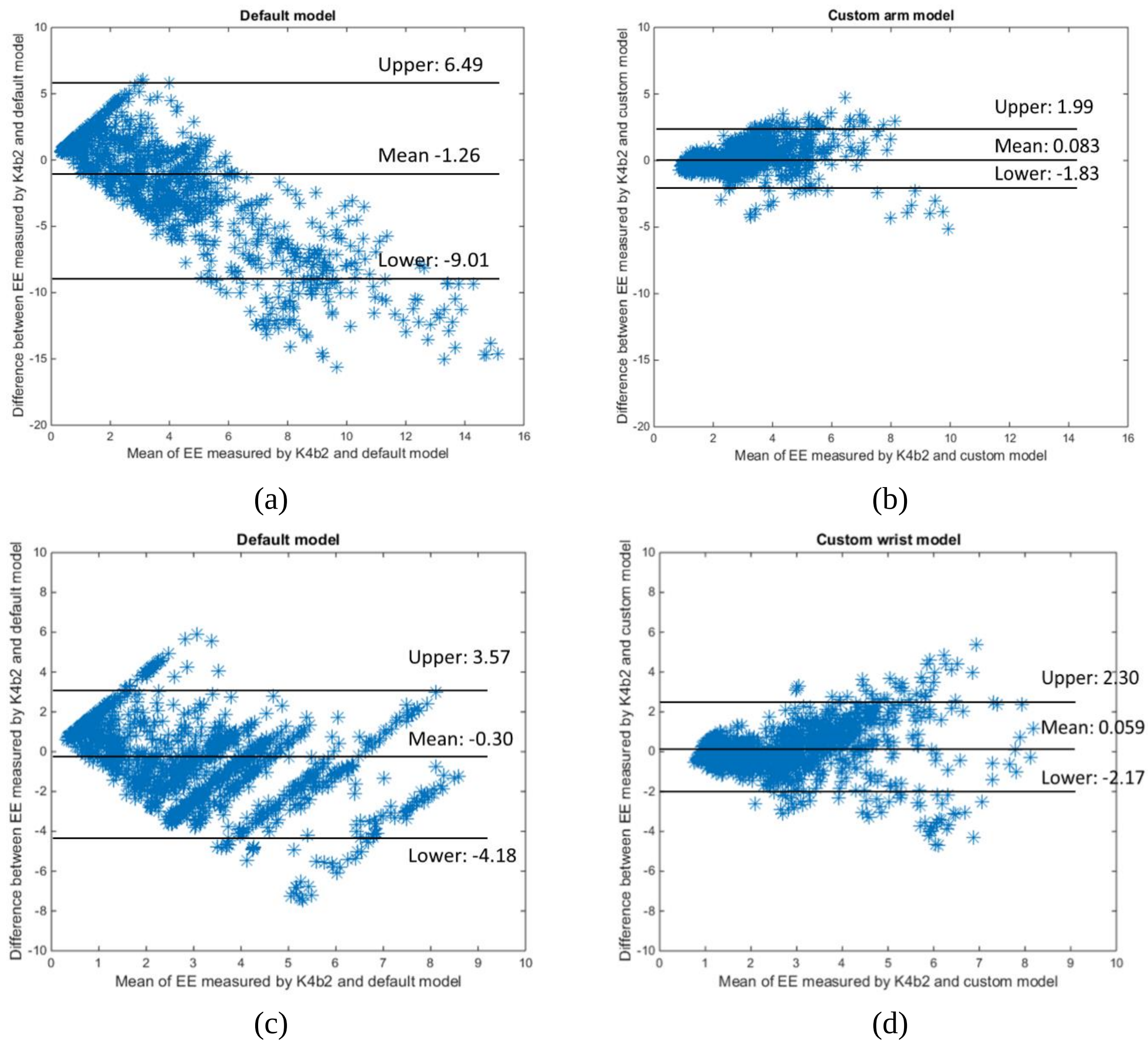


Figure 5. The Bland-Altman plots of default ActiGraph model (a) and custom model (b) at the upper arm, and default (c) and custom models (d) at the wrist

The MPEs between the estimated and criterion tEE over the study period (~3 hours) at the upper arm were 1.64±9.32% (MAPE: 7.43±5.19%) for the custom model, and -45.73±48.23% (MAPE: 54.54±36.28%) for the default model. At the wrist, the MPEs were -0.16±16.64% (MAPE: 12.01±10.57%) for the custom model, and -12.43±23.64% (MAPE: 20.89±15.39%) for the default model.

Two decision trees, one based on AG worn at the upper arm (Figure 6) and one based on AG worn at the wrist (Figure 7), were developed. For the classification performance of the decision trees, the MAPEs between the estimated and measured time spent in sedentary, light, and moderate intensity levels were computed. At the upper arm, the MAPEs were 9.6±8.9%, 12.8±7.0%, and 41.3±85.7%, respectively for the decision tree, and were 19.7±19.7%, 74.5±18.6%, and 93.3±42.2% respectively for the AG default MET outputs (Table 8). At the wrist, the MAPEs were 9.3±10.4%, 16.4±13.6%, and 13.5±8.9%, respectively for the decision tree, and were 21.7±17.7%, 94.4±83.3%, and 129.5±61.9% for using the AG default MET outputs (Table 9).

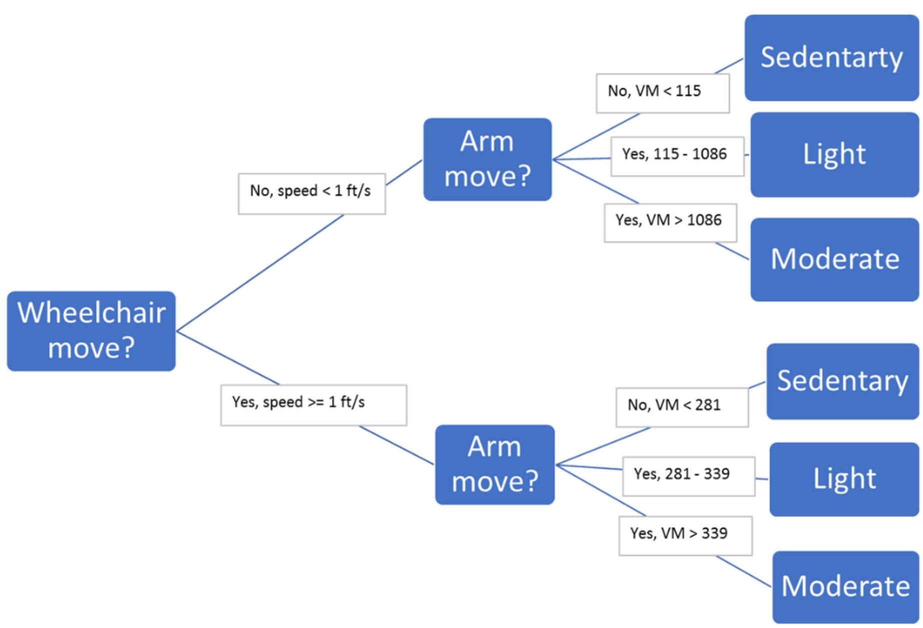


Figure 6. The decision tree showing wheelchair speed and dominant upper arm movement thresholds for classifying time spent at sedentary, light, and moderate intensity levels

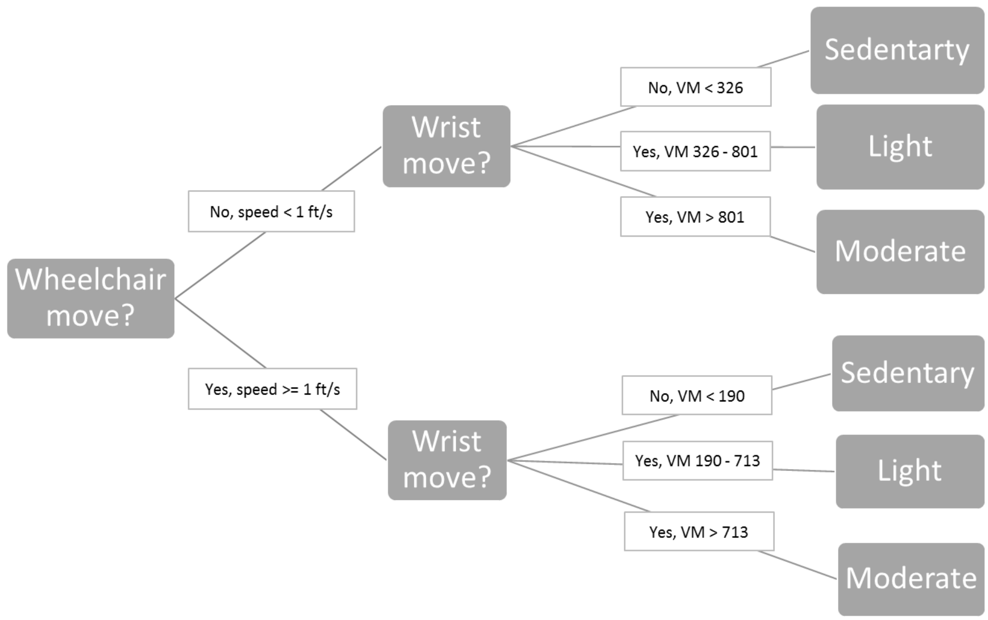


Figure 7. The decision tree showing wheelchair speed and dominant wrist movement thresholds for classifying time spent at sedentary, light, and moderate intensity levels

Table 8. The measured time spent (min) at sedentary, light, and moderate intensity level by the K4b2 (Gold Standard), and the estimated time spent (min) by the default MET output from the ActiGraph device (Default Arm) and the decision tree based on the wheel and dominant upper arm movements (Custom Arm). The absolute percent error (%) of the estimated time spent were also computed

		Gold Standard			Default Arm			Custom Arm		
ID	Diagnosis	Sedentary	Light	Moderate	Sedentary	Light	Moderate	Sedentary	Light	Moderate
4	SCI C5 complete	78	69	35	103 (32.1%)	20 (71%)	59 (68.6%)	87 (11.5%)	75 (8.7%)	20 (42.9%)
6	SCI C2 incomplete	56	80	40	81 (44.6%)	12 (85%)	83 (107.5%)	73 (30.3%)	63 (21.3%)	40 (05)
8	Cerebral palsy	73	61	40	72 (1.4%)	18 (70.5%)	84 (110%)	74 (1.4%)	70 (14.7%)	30 (25%)
19	Polymyositis	31	66	0	41 (32.3%)	9 (86.4%)	47 (INF)	32 (3.2%)	63 (4.5%)	2 (INF)
31	* SCI T6	66	58	48	75 (13.6%)	10 (82.7%)	87 (81.3%)	65 (1.5%)	66 (13.8%)	41 (14.5%)
101	* SCI T8-9	32	13	51	32 (0%)	17 (30.8%)	47 (7.8%)	36 (12.5%)	48 (269.2%)	12 (76.5%)
108	* SCI T6-7	52	77	46	77 (48.1%)	4 (94.8%)	94 (104.3%)	57 (9.6%)	75 (2.6%)	43 (6.5%)
115	Spina Bifida	102	48	29	107 (4.9%)	9 (81.3%)	63 (117.2%)	97 (4.9%)	58 (20.8%)	24 (17.2%)
117	† SCI incomplete	72	62	28	72 (0%)	20 (67.7%)	70 (150%)	64 (11.1%)	72 (16.1%)	26 (7.1%)
Overall (%)					**19.7 ± 19.7%**	**74.5 ± 18.6%**	**93.3 ± 42.2%**	**9.6 ± 8.9%**	**41.3 ± 85.7%**	**23.7 ± 25.1%**

*The completeness of injury was not reported.
†The level of injury was not reported.

Table 9. The measured time spent (min) at sedentary, light, and moderate intensity level by the K4b2 (Gold Standard), and the estimated time spent (min) by the default MET output from the ActiGraph device (Default Wrist) and the decision tree based on the wheel and wrist movements (Custom Wrist). The absolute percent error (%) of the estimated time spent were also computed

		Gold Standard			Default Wrist			Custom Wrist		
ID	Diagnosis	Sedentary	Light	Moderate	Sedentary	Light	Moderate	Sedentary	Light	Moderate
4	SCI C5 complete	78	69	35	77 (1.28%)	15 (78.3%)	90 (157.1%)	88 (12.8%)	52 (24.6%)	42 (20%)
6	SCI C2 incomplete	56	80	40	68 (21.4%)	36 (55.0%)	72 (80.0%)	75 (33.9%)	69 (13.7%)	32 (20%)
8	Cerebral palsy	73	61	40	59 (19.2%)	105 (72.1%)	10 (75.0%)	74 (1.4%)	59 (3.3%)	41 (2.5%)
19	Polymyositis	31	66	0	12 (61.3%)	26 (60.6%)	59 (INF)	29 (6.5%)	68 (3.0%)	0 (0%)
31	* SCI T6	66	58	48	54 (18.2%)	21 (63.8%)	97 (102.1%)	75 (13.6%)	52 (10.3%)	45 (6.3%)
101	* SCI T8-9	32	13	51	28 (12.5%)	54 (315.4%)	14 (72.5%)	32 (0%)	7 (46.1%)	57 (11.8%)
108	* SCI T6-7	52	77	46	49 (5.8%)	20 (74.0%)	106 (130.4%)	54 (3.8%)	82 (6.5%)	39 (15.2%)
115	Spina Bifida	102	48	29	81 (20.6%)	21 (56.3%)	77 (165.5%)	105 (2.9%)	39 (18.7%)	35 (20.7%)
117	† SCI incomplete	72	62	28	47 (34.7%)	16 (74.2%)	99 (253.6%)	66 (8.3%)	75 (21.0%)	21 (25.0%)
Overall (%)					**21.7 ± 17.7%**	**94.4 ± 83.3%**	**129.5 ± 61.9%**	**9.3 ± 10.4%**	**16.4 ± 13.6%**	**13.5 ± 8.9%**

*The completeness of injury was not reported.
†The level of injury was not reported.

Confusion matrices were also constructed to show the overall performance of classifying each minute spent at sedentary, light, and moderate intensity levels using the decision trees and the AG default MET outputs. At the upper arm, the sensitivity was 0.52 – 0.87, the specificity was 0.77 – 0.93, the precision was 0.63 – 0.87, and accuracy was 0.74 – 0.89 while using the decision tree (Table 10b). On the other hand, the sensitivity, specificity, precision and accuracy for the AG default outputs were 0.17 – 0.94, 0.72 – 0.94, 0.44 – 0.81, and 0.66 – 0.88, respectively (Table 10a). At the wrist, the sensitivity was 0.67 – 0.91, the specificity was 0.84 – 0.93, the precision was 0.71 – 0.84, and accuracy was 0.77 – 0.88 while using the decision tree (Table 11b). The sensitivity, specificity, precision and accuracy for using the AG default MET outputs were 0.19 – 0.80, 0.63 – 0.95, 0.37 – 0.92, and 0.61 – 0.88, respectively (Table 11a).

Table 10. A confusion matrix of classifying time spent in sedentary, light, and moderate intensity levels among all participants in the testing group using the default outputs (a) and the decision tree (b) for the dominant upper arm, as well as the overall sensitivity, specificity, precision, and accuracy

(a) Default Upper Arm								
		Actual						
		Sedentary	Light	Moderate	Sensitivity	Specificity	Precision	Accuracy
Predicted	Sedentary	660	242	24	0.94	0.83	0.81	0.88
	Light	29	104	28	0.17	0.94	0.65	0.66
	Moderate	13	356	286	0.87	0.72	0.44	0.75

(b) Custom Upper Arm								
		Actual						
		Sedentary	Light	Moderate	Sensitivity	Specificity	Precision	Accuracy
Predicted	Sedentary	612	89	5	0.87	0.90	0.87	0.89
	Light	90	418	152	0.70	0.77	0.63	0.74
	Moderate	0	94	171	0.52	0.93	0.65	0.85

Table 11. A confusion matrix of classifying time spent in sedentary, light, and moderate intensity levels among all participants in the testing group using the AG default outputs (a) and the decision tree (b) for the dominant wrist, as well as the overall sensitivity, specificity, precision, and accuracy

(a) Default Wrist								
		Actual						
		Sedentary	Light	Moderate	Sensitivity	Specificity	Precision	Accuracy
Predicted	Sedentary	559	48	0	0.80	0.95	0.92	0.88
	Light	98	115	46	0.19	0.86	0.44	0.61
	Moderate	45	438	282	0.86	0.63	0.37	0.68

(b) Custom Wrist								
		Actual						
		Sedentary	Light	Moderate	Sensitivity	Specificity	Precision	Accuracy
Predicted	Sedentary	637	114	6	0.91	0.87	0.84	0.89
	Light	63	404	103	0.67	0.84	0.71	0.78
	Moderate	2	83	219	0.67	0.93	0.72	0.88

3.4 DISCUSSION

Similar custom EE models development and evaluation studies could be found easily in the existing literature; however, these studies only determined the models' ability to predict EE 1) while performing limited and structured PAs in the controlled lab environment or 2) for MWUs with a specific diagnosis, e.g., spinal cord injury, only [83, 100, 106-108]. This study provided a more comprehensive evaluation of the custom models by including MWUs with various diagnoses and allowing participants to choose various PAs they perform on a daily, or regular, basis under both structured (i.e., gym) and unstructured (i.e., home) environment to mimic real world settings.

Valid EE measurement is fundamental in tracking daily PA participation in MWUs as it assists clinicians to make recommendations, establish strategies to promote energy balance, and motivate MWUs to engage in regular PA [42, 109]. Both custom models showed higher accuracy in estimating the energy cost of PA performed by MWUs compared to the default outputs. The large errors of the default AG model suggested that it was not suitable for MWUs. Similar results were also found with other off-the-shelf monitors, suggesting that these commercial devices were not valid or reliable for MWUs to use [42]. After correction, the custom upper arm and wrist models showed reasonable accuracy (about 10% MPE, 28% MAPE) and they were comparable to results with ambulatory studies (about 7% MPE) [110]. While looking at the tEE over time, the estimation errors were smaller (about 2% MPE, 10% MAPE) than that of EE (kcal/min) due to the cancellations of under- and over-estimation of EE during different activities. These results were similar to that in ambulatory populations (about 12% MAPE) [111, 112]. Therefore, both custom models could potentially be used to not only track energy cost of individual activity, but also measure tEE across a prolonged period.

When examining the estimation accuracy of the custom models in depth (Table 7), we noticed that there was some variability between types of activity. We therefore clustered each activity into three groups: 1) little to no wheelchair/limb movements involved such as watching TV; 2) only limb movements involved such as washing dishes; 3) wheelchair/limb movements involved such as basketball. Both custom models showed higher errors and variances for activities in group 2 compared to groups 1 and 3, especially for chair aerobics, stretching, and weight lifting. Since both custom models assumed limb movements (accelerations) were directly proportional to EE, the custom models overestimated chair aerobics and stretching, both of which involved extensive limb movements but require less physical exertion; while underestimated weight lifting which involved great physical exertion but little limb movements. The accuracy of the custom models was influenced by the types of activity performed. In other words, if an MWU performed mostly activities in group 1 or 3 throughout the day, the estimated EE and tEE would be more accurate than if he/she performed mainly activities in group 2.

Custom models for classifying time spent into different intensity levels

This was one of the first studies that assessed the performance of the custom models based on commercial monitors in tracking time spent at different intensity levels in MWUs. Tracking time spent at different intensity levels was crucial. It not only helps MWUs and/or clinicians identify physical inactivity due to prolonged sedentary time and/or insufficient exercise, and set appropriate fitness goals, but also allows clinicians/researchers to track adherence to, and examine the effectiveness of, interventions that are designed to reduce sedentary time and/or increase activity level [42, 60, 71, 109, 113, 114]. The default AG, however, was not appropriate for tracking intensity levels in MWUs given its large errors. The custom models also had some issues in this classification. Relatively higher MAPEs (Table 8 and 9) and lower sensitivity/specificity (Table 10b and 11b) in time spent at light and moderate intensity levels were observed while using the decision trees. This was likely due to misclassification during arm ergometry exercises, chair aerobics, or other PAs that involved limb movements that were disproportionate to physical exertion. Participants who performed arm ergometry exercises at high resistance, for example, usually had slower limb movement but with higher physical exertion; while at low resistance, they had faster limb movement but with lower physical exertion. This became more obvious in subject 101 who performed mostly PAs (i.e., arm ergometry exercises at 3 different resistances, theraband exercise, chair aerobic, and propulsion up/down a ramp) that involved limb movement that were disproportionate to physical exertion. This caused the decision trees to misclassify the time spent at light and moderate intensity levels. After we combined the light and moderate intensity levels into non-sedentary level, the MAPEs using decision trees reduced to 9.6±8.9% and 5.8±4.4% for sedentary and non-sedentary levels at the upper arm, and 9.3±10.4% and 5.6±5.1% for sedentary and non-sedentary levels respectively at the wrist.

Limitations

One of the limitations of our study was selection bias. Our study sample was overrepresented by individuals with SCI (64.4%) and underrepresented by females (22.2%). Inclusion of MWUs with different gender and diagnoses is important for generalizing our findings to any population group that uses a manual wheelchair [115]. Future studies with stratified sampling will be needed to recruit a representative sample of MWUs. Another limitation was the small sample size in the test data set. The advantage of having a test data set is that it provides unseen data for evaluating the custom models. However, only 9 participants were in the test group. Increasing the sample size in the test group would increase the generalizability of the results.

The custom models also had some limitations. First, accelerometer-based wearables were limited to track activities that only involve limb movements that were proportionate to physical exertion. Their performance was subpar for activities that involved more limb movements but less physical exertion, or vice versa. A new model that could characterize resistance and non-resistance activities might help improve the prediction accuracy. Second, since the custom models were developed using a tri-axial accelerometer-based device worn at the upper arm and wrist, the models were only applicable to the same type of commercial monitors worn at the same locations. Third, the performance of the custom models for tracking time spent at different intensity levels should be interpreted with caution, as only 21% of the activity data for developing the custom models were collected at moderate and vigorous intensity levels. Due to the voluntary nature of the study, participants tended to select sedentary/light activities to avoid exhaustion. Future studies should expand the selections of moderate/vigorous intensity activities. Another potential cause of the skewed data was the inability of participants reaching moderate/vigorous intensity levels. In this study, we used the MET values for different intensity levels defined for the general population, which might not be suitable for MWUs. Studies found that 1-MET for people with SCI was approximately 0.77-METs [79] to 0.88-METs [116] for ambulatory populations. A more appropriate MET definition of different PA intensity levels for MWUs with various diagnoses would be needed to track PA behaviors in this population.

3.5 CONCLUSIONS

In this study, we developed and evaluated two custom EE prediction models for MWUs based on a ActiGraph GT3X+ monitor worn on the upper arm and wrist. Both models showed improved overall accuracy in estimating EE with comparable performance to the wearable monitors for ambulatory populations. The intensity classification models (decision trees) showed promising results in tracking sedentary and non-sedentary (i.e., light and moderate intensity) behaviors, with limited ability to accurately classify light and moderate intensity PAs that involved limb movements that were disproportionate to physical exertion.

4.0 HOW TO DESIGN A MHEALTH APPLICATION TO PROMOTE PHYSICAL ACTIVITY IN MANUAL WHEELCHAIR USERS: A FOCUS GROUP STUDY

4.1 INTRODUCTION

Physical inactivity is one of the biggest health concerns in the modern world [117]. More than 80% of adults in the United States do not engage in physical activity (PA) at recommended levels [4], especially those who have mobility disabilities. There are currently 3.6 million wheelchair users in the United States, and 2.8 million of them are manual wheelchair users (MWUs) [5, 6]. More than half (57%) of adults with mobility disabilities, including MWUs, do not engage in aerobic PA and lead a sedentary lifestyle due to various physical, personal, and environmental barriers such as decreased muscle mass, lack of self-awareness of being physically inactive, and lack of accessible equipment and gyms in the community [7-10]. Consequently, this population is three times more likely to develop chronic diseases than people without disabilities [7, 11]. According to a report from the Centers for Disease Control and Prevention, approximately 86% of total healthcare expenditure in the United States is used to treat the chronic diseases that are associated with physical inactivity such as obesity, type 2 diabetes, cardiovascular diseases, and some cancers [118, 119]. Effective strategies to promote regular PA participation in this population are desperately needed [120-122].

With the proliferation of mobile devices, technology-based health interventions have become increasingly popular to provide patient education, support, and healthcare services [123]. Mobile device ownership and use has been rising rapidly over the years. A 2017 report showed that 77% of Americans now own a smartphone which is more than a double from 35% in 2015 [124]. The utility of mobile devices has been further expanded by the use of apps and their capability to connect to wearable technology such as smart watches [125]. From 2007 to 2013, Apple reached 50 billion app downloads while Google reached 48 billion [68]. Health apps have become a part of this fast growing market, with over 97,000 health and medical apps available in the app store [64]. Most of these apps focused on general health and physical fitness by facilitating self-monitoring of various health behaviors and vitals using wearable sensors [67-69]. Previous research suggested that mobile apps may be beneficial in facilitating behavioral changes [59, 64, 68, 126].

A 2015 systematic review summarized and evaluated the existing literature on using mobile health apps to assist ambulatory populations in changing their behaviors [68]. Based on the findings on 24 interventional studies, it was found that the core behavioral components of these apps included self-monitoring, cues to action and feedback, and social support [68]. In addition, among all the features found in PA apps, users were most satisfied with the accountability of the app and emphasis on exercise and additional feedback [127]. The systematic review later referenced other PA studies which showed real-time smartphone display and feedback significantly increased users' motivation to engage in PA [128, 129]. In addition to the overall user acceptability of using mobile apps to facilitate behavioral changes, the efficacy of the mobile health apps in increasing PA levels and reducing sedentary time in ambulatory populations was also illustrated [68, 130-132]. In the study conducted by King et al., participants showed 188.6±289.3 minutes/week increase in weekly minutes of moderate-to-vigorous PA and 29.1±84.5 minutes/day decrease in TV viewing time using a mobile app with features such as goal setting, informational tips, and real-time feedback on PA progress over the 8-week intervention period when compared to the baseline [130]. A randomized controlled trial conducted by Mattila et al. showed that intervention participants, who received face-to-face intervention supported by a custom mobile app along with a scale, pedometer and heart rate monitor to self-monitor weight, heart rate, and daily PA, decreased weight by 1.2 kg and decreased waist circumference by 1.4 cm over a year versus controlled group participants, who received standard healthcare without health app support, increased weight by 0.6 kg and increased waist circumference by 0.7 cm [131]. The use of a mobile app seems promising in facilitating PA participation.

While there are several fitness/health apps available for the ambulatory populations, there's an extremely limited amount of similar health apps available for MWUs. Three existing commercially available fitness/health apps that facilitate and promote healthy and active lifestyles in MWUs are *SCI-Ex*, *Wheelchair Calorimeter*, and *Apple Health*. *SCI-Ex* is a health education app designed by the Shepherd Center (Atlanta, Georgia) specifically for teaching people with spinal cord injury (SCI) to achieve and maintain an active lifestyle by showing and describing exercises in instructional videos (available in both iOS and Android). *Wheelchair Calorimeter* is an activity tracking app designed by Craig Chaillie for determining calories burned by a MWU during outdoor exercises using GPS (only available in iOS). Lastly, *Apple Health* tracks PA by measuring wheelchair push counts and estimating calories based on the measurement (used with Apple Watch; only available in iOS). None of these apps were examined in research studies, and the accuracy of the latter two are unknown. *SCI-Ex* had the most downloads (~1000 in Google Play; ~20 in App store) among three apps, with a rating of 3.5 out of 5 (among 8 ratings) in Google Play and a rating of 1 out of 5 in App store (among 1 rating). Most of the complaints were about the app crashes and some wanted to see more exercise videos. *Wheelchair Calorimeter* had a rating of 4.3 out of 5 (among 7 ratings) in App store, but no user review was found. *Apple health* was a default app on Apple products which made it hard to track its usage with the wheelchair push accessible version. To gather any unaddressed needs and preferences in PA tracking and promotion apps for MWUs, we conducted several focus groups to gather input from MWUs and rehabilitation professionals to determine the content, features, and functions in a PA promotion app that were most relevant, attractive, and appropriate in addressing the needs and desires of MWUs.

4.2 METHODS

The study was approved by the Institutional Review Board at the University of Pittsburgh.

Participants

We conducted 5 focus groups (3 for MWUs and 2 for rehabilitation professionals) in Pittsburgh, Pennsylvania between October 2017 and February 2018. We recruited participants for the focus groups through flyers sent to community clinics such as the Center for Assistive Technology (CAT), local support groups such as the SCI Peer Support Group hosted by the University of Pittsburgh Medical Center, and local non-profit organizations such as Transitional Paths to Independent Living. MWUs were recruited if they 1) were at least 18 years old, 2) used a manual wheelchair as their primary means of mobility; and 3) had experience using a smartphone. MWUs were excluded if they 1) were unable to tolerate sitting for at least 2 hours; and 2) had a history of cardiovascular diseases. Rehabilitation professionals were recruited if they 1) were at least 18 years old, 2) had at least 1 year of experience working with MWUs; and 3) had experience evaluating, suggesting, or prescribing PA and/or adapted exercise to MWUs.

Procedures

For the MWUs' focus groups, we asked participants to fill out a questionnaire that asked about demographic information (e.g., age, gender, diagnoses, and time of injury), wheelchair information (e.g., brand and model), physical health and fitness, and barriers to PA. They were also asked to answer the Exercise Self-Efficacy Scale (ESES), a 10-item survey (4-point Likert) designed to evaluate the confidence of people with disabilities regarding their ability to carry out regular PA and exercise (Appendix A) [133]. The scale ranges from 10 to 40 with the higher score indicating greater confidence one has in carrying out regular PA and exercise. After the questionnaire, we began the discussion portion of the study. The discussion was semi-structured and led by a research assistant who followed a list of pre-determined questions written by the research team (Appendix B). We started by asking their experience with PA participation and the associated challenges they encountered. Then, we asked participants about their perceptions of their own physical health, and if they used or tried any fitness/health apps to help them stay active. We further asked them what they liked and/or disliked and their expectations of those fitness/health apps. Then, we introduced the wireframes (non-functional prototype) of a custom PA promotion app to participants. The app wireframes were created by the research team using a free wire framing tool (marvelapp.com), and the design was based on extensive research on literature related to mobile health apps for promoting behavioral changes and our previous work on validating wearable devices among MWUs [134, 135]. The wireframes displayed simulated information, design elements, and user interactions, which were used to facilitate discussions on preferred features and functions of a mobile health app for PA promotion.

For the rehabilitation professionals' focus groups, we started by asking participants to fill out a questionnaire that asked about demographic information (e.g., age, gender, occupation), years of experience working with MWUs, and experience in prescribing, suggesting, and evaluating adaptive physical activities. The format of the focus group discussion was similar to that of MWUs' focus groups, except that we asked the rehabilitation professionals what they perceived as the main barriers of PA participation for MWUs, how they helped MWUs overcome these barriers, and if they suggested any fitness/health apps to MWUs to help them stay active

(Appendix C). After that, we showed the same app wireframe used in the MWUs' focus group to the rehabilitation professionals and asked for feedback on the relevance and appropriateness of the app content for MWUs. All focus group sessions were digitally recorded, and later transcribed and de-identified for analysis.

Data analysis

Descriptive statistic was used to analyze the data collected from the questionnaires. Content analysis was used to identify and categorize any common trends in the transcripts. A team of two research associates independently coded the focus group data. Data was first read word by word by each coder. Codes were first derived by selecting the exact word in text that captured the key thoughts of the focus group participants. The selected words became the initial codes. Afterwards, one of the coders combined the two lists of initial codes into one list of final codes by grouping the synonyms. If the codes related to the same transcription quote from the two coders did not match, two coders would reexamine the transcription and the initial codes until a consensus was reached. Final codes were then grouped into categories based on how they were related. The emergent categories were used to organize and group codes into meaningful clusters.

4.3 RESULTS

There were 24 participants (MWUs, n=11; rehabilitation professional, n=13) in 5 focus groups. Among the 11 MWUs, most of them were diagnosed with spinal cord injury (54.5%), followed by cerebral palsy (27.3%) and multiple sclerosis (9.1%). One participant had multiple diagnoses including tethered cord and Ehlers-Danlos syndrome. The majority of the MWUs (63.6%) had less than 10 years of experience using a manual wheelchair. About half of MWUs considered themselves as athletes (54.5%), and most participants (72.7%) rated their own physical health as "Good" or better. In addition, over 80% of them reported that they engaged in PA and/or exercises at least 1 time/week. The average ESES score was 29.6 ± 4.7, indicating the participants had moderate confidence in carrying out regular PA and exercise. This might be due to the reported barriers they encountered in PA participation. Details of the demographic characteristics of MWUs participated in the focus groups can be found in Table 12. Findings on barriers to PA participation extracted from the interviews are included in a later section.

Table 12. Demographic characteristics of MWUs that participated in the focus groups

Characteristics	MWUs, n (%)
Age (in years)	33.7 ± 12.1
Gender	
Female	4 (36.4%)
Male	7 (63.6%)
Education	
High school diploma	6 (54.4%)
Associate degree	1 (9.1%)
College degree	4 (36.4%)
Employment	
Yes	7 (63.6%)
Full-time (40 hour/week or more)	*4 (57.1%)*
Part-time (less than 40 hour/week)	*3 (42.8%)*
No	4 (36.4%)
Diagnoses	
Spinal cord injury	6 (54.5%)
Tetraplegic (C7 or above)	*4 (66.7%)*
Paraplegic (T1 or below)	*2 (33.3%)*
Multiple sclerosis	1 (9.1%)
Cerebral palsy	3 (27.3%)
Multiple diagnoses	1 (9.1%)
Experience of using a manual wheelchair (in years)	
<5	3 (27.3%)
5 – 10	4 (36.4%)
11 – 20	2 (18.2%)
21 – 30	1 (9.1%)
>30	1 (9.1%)

Table 12 (continued)

Do you have any secondary health conditions?	
No	4 (36.4%)
High blood pressure	1 (9.1%)
Fainting or dizziness	2 (18.2%)
Diabetes	1 (9.1%)
Shortness of breath at rest or with mild exertion	1 (9.1%)
Unusual fatigue or shortness of breath with usual activities	2 (18.2%)
Are you an athlete?	
Yes	6 (54.5%)
No	5 (45.5%)
How do you rate your fitness level?	
Excellent	0 (0%)
Very good	2 (18.2%)
Good	6 (54.5%)
Fair	3 (27.3%)
Poor	0 (0%)
Do you exercise regularly?	
Yes	3 (27.3%)
Occasionally (1 to 2 times/week)	6 (54.5%)
Not at all	2 (18.2%)
Have you experienced any of these barriers when participating in physical activity/exercise? *Note: each participant could report multiple barriers in each category.*	
Personal (e.g., no time, no energy, lack of motivation, need assistance, lack of company, feel exhausted, lack skills, feel pain/discomfort, activities are not adaptable, not no mood for activities, not able to pre-schedule activities for the week)	26 (32.9%)
Economic (e.g., cost of gym membership, exercise equipment, transportation, fewer economic resources)	16 (20.2%)
Equipment related (e.g., not adaptable, not wheelchair accessible, no space for equipment, lack equipment in my house)	15 (19.0%)
Information (e.g., fitness center employees are not trained on how to adapt programs for MWUs, difficult to find facilities/programs that are suitable to them)	22 (27.8%)
Exercise self-efficacy scale Note: This exercise self-efficacy scale was developed by Kroll et al. (2007) for people with spinal cord injury.	29.6 ± 4.7

Among the 13 rehabilitation professionals, 5 of them were occupational therapists, 4 of them were physical therapists, and 4 were in other occupations (1: social worker, 1: assistive technology specialist, 1: independent living specialist, and 1: advocate). They all had experience working with MWUs, and about half of them (6 out of 13) had over 10 years of experience. Over 90% of them educated their MWUs clients on the health benefits associated with regular PA and/or risks from lack of PA at least half of the time during work. And 77% of them suggest, prescribe, and/or evaluate PA and adapted exercises as part of their job. Based on their observations, about 85% of rehabilitation professionals did not think MWUs engage in enough PA and/or exercises due to the barriers they thought MWUs encounter. More details on the demographic characteristics of rehabilitation professionals in our focus groups can be found in Table 13. Full findings on the barriers to PA participation in MWUs during interviews are included in a later section.

Table 13. Demographic characteristics of rehabilitation professionals that participated in the focus groups

Characteristics	Rehabilitation professional, n (%)
Age (in years)	38.8 ± 12.2
Gender	
Female	9 (69.2%)
Male	4 (30.8%)
Occupation	
Occupational therapists	5 (38.4%)
Physical therapists	4 (30.8%)
Others	4 (30.8%)
Experience of working with MWUs (in years)	
<1	2 (15.4%)
1 – 3	3 (23.1%)
4 – 6	2 (15.4%)
6 – 10	0 (0%)
>10	6 (46.1%)

Table 13 (continued)

How often do you educate MWUs on the health benefits/risks associated with regular or lack of PA?	
Never	0 (0%)
Sometimes	1 (7.7%)
About half of the time	5 (38.4%)
Most of the time	4 (30.8%)
Always	3 (23.1%)
How often do you suggest, prescribe, and evaluate PA and/or adapted exercises to MWUs?	
Never	0 (0%)
Sometimes	3 (23.1%)
About half of the time	2 (15.4%)
Most of the time	4 (30.8%)
Always	4 (30.8%)
Do you think your MWUs clients engage in enough PA?	
Yes	2 (15.4%)
No	11 (84.6%)
What are the main reasons you think they don't engage in enough physical activity? *Note: each participant could report multiple barriers in each category.*	
Personal (e.g., no time, no energy, lack of motivation, need assistance, lack of company, feel exhausted, lack skills, feel pain/discomfort, activities are not adaptable, not no mood for activities, not able to pre-schedule activities for the week)	18 (60%)
Economic (e.g., cost of gym membership, exercise equipment, transportation, fewer economic resources)	2 (6.6%)
Equipment related (e.g., not adaptable, not wheelchair accessible, no space for equipment, lack equipment in my house)	5 (16.7%)
Information (e.g., fitness center employees are not trained on how to adapt programs for MWUs, difficult to find facilities/programs that are suitable to them)	5 (16.7%)

We organized the themes that emerged from the focus groups into 4 main categories, aligning with the general structure of the interview: 1) barriers to PA; 2) previous experience in

PA participation and using fitness/health apps; 3) impression of the app wireframes we developed; and 4) suggestions for improving the app. Sub-themes emerged in each of the main categories. Table 14 shows the 4 main themes and the sub-themes related to each of them.

Table 14. Themes which emerged as a result of the focus groups consisting of 24 participants

Theme	Description
Barriers to physical activity	
Personal	The attitude towards fitness, motivation, time, fatigue, energy, need assistance, and fear of injury
Knowledge	Information about regular physical activities, types of exercise, duration of exercise, adaptive equipment, and safety related to exercise.
Resource	Transportation, exercise equipment, support networks (friends, care givers, family)
Environmental	The accessibility of the community, gym, and other facilities for physical activities and exercises.
Previous experience	
Physical activity/exercise	Physical activity and/or exercise participation by MWUs
Knowledge on regular PA	Information about what PA/exercise to perform, the duration of exercise, how to perform them correctly, and resources for MWUs to stay active
Fitness/health app	Experience using or recommending fitness trackers and/or health app that provides physical activity tracking or promotion to users
Impression of app wireframes	
Design	Impression on the icons, color scheme, font size, terminology, and layout of the wireframes
Content	Feedback on the educational materials, resources
Features/functions	Comments on the features, including but not limited to: 1) goal setting and action planning, 2) progress tracking, 3) adaptive exercise library, and 4) fitness tips, and how they work.
Overall	Impression of what the app could offer as a whole.

Table 14 (continued)

Suggestions for improvement	
Design	Suggestions and desire for the icons, color scheme, font size, terminology, and layout for the actual app
Content	Information that were desired to have but not included in the wireframes
Features/functions	Suggestions for refining and adding features to better suit the need of a wide range of MWUs
Safety	Suggestions for minimizing potential safety issues related to using the app without supervision.

Barriers to physical activity

Both MWUs and rehabilitation professionals acknowledged that there were barriers to participating in regular PA. They both mentioned personal barriers, e.g., lack of energy, lack of motivation, fear of getting hurt, and lack of time, as the biggest barriers (Table 13 and 14).

> *"…when you are fatigued, how do you spend 30 minutes to exercise? Because you are tired, so you don't have energy to do anything else in your life." – MWU, female, 61*
>
> *"I really relate to that. I feel like if I exercise, that's the thing I did that day. And that means I didn't do my laundry, and I didn't do the dishes…" – MWU, female, 22*
>
> *"They had no motivation and no desire [in doing any physical activity] …and they don't believe they can engage in physical activity…" – Occupational therapist, female, 44*
>
> *"They are fear of [getting] injured…" – Occupational therapist, female, 27*

Information barriers were identified as the second biggest challenge MWUs face in PA participation. MWUs often do not know about what they could and should do physically. Rehabilitation professionals also did not have relevant information to provide their clients:

> *"A lot of the information that I have, as far as when to exercise, how often you exercise, what exercise to do, were right after my injury when I was a lot weaker… so I don't know*

now, in the body [10 years post injury] that I am in right now, how much I should be doing…" – MWU, female, 27

"I don't want to hurt myself… [because] with the shoulder injury, in a manual chair, you're, you're out… so, it's just finding that balance between safely exercising and then not hurting yourself." – MWU, male, 29

"…they [MWUs] lack the knowledge on types of exercise to do that is safe, lack of knowledge on accessible fitness centers…" – Occupational therapist, female, 28

"…that's the struggle of PTs in general. We see them in our gym, but then, when they are done with us, what does the community offer to allow them to follow up? Perhaps YMCA? …I don't have the information [community fitness center or program] to send them [MWUs]…" – Physical therapist, female, 56

Other barriers included resources, environments, and limited body functions:

"I can't get anywhere except to the car, and I don't have my own car, so, not being able to drive, and not being able to get to where the bus stop is kinda limits me. I live in a hilly area, so I can't just really go out in my chair. I could go one block before the hills get too steep. Or I can go downhill, and not being able to get back." – MWU, female, 22

"…I asked them [front desk employee at a local fitness center] about their accessibility on their equipment. And they see you in the chair, and they just think that everybody in a chair has the same ability…He [fitness center staff] said 'oh yeah, we have a guy comes in here and just pops right on the machines…' I can't just pop in because I don't have full hand functions." – MWU, male, 27

Previous experience in PA participation and using fitness/health apps

Most MWUs mentioned that they learned about the types of PA and adaptive exercises online and during their therapy sessions with their occupational and/or physical therapists. They were all aware of the PA guidelines and said that they knew they should engage in aerobic exercises for about 30 min/day. However, they didn't seem to know the types of PA/exercise they should be engaging in and how they can divide their workouts into multiple shorter sessions.

"I just have 5 and 10 lbs kettle bells at my house… I know I should be doing [exercise, referring to weight lifting here] at least half hour every night…" – MWU, male, 29

"I did have a physical therapist for a little bit who gave me exercises, but I didn't really think they address what I needed… I got a lot of information in general online like everyone else…" – MWU, female, 61

"I didn't know you can just exercise for a short period of time like 5 or 10 mins at a time, and spread the 30 min over the day…" – MWU, male, 27 (3 other MWUs agreed)

None of the rehabilitation professionals suggested any fitness/health apps to their clients. Some of the MWUs had experience using fitness/health apps to track their PA levels and keep them active. They did not like the limited tracking ability (i.e., only cover some variables) in the apps. They also did not like that separate apps are needed for different purposes.

"I used the iWatch [now Apple watch]… It only tracks your pushes and calories. The version I have doesn't have GPS so it doesn't track distance." – MWU, female, 27

"I used Fitbit… I love the heart rate thing… I don't know how it estimates the amount of calories cause it doesn't detect your pushes… you just put the time you did it… there's a big difference between going around the mall and going uphill over bumpy sidewalks. I feel like there's a huge amount of difference in terms of calories, but the app doesn't know that." – MWU, female, 22

"I tried to use the Shephard app [has only adaptive exercise videos]. Their fitness is…uhh… you have to have the equipment in order to do it. If I don't have the access to the gym, I am not gonna use the video." – MWU, male, 27

Impression of the app wireframes

After asking MWUs about their experiences using fitness/health apps, we showed the wireframes of our custom app and gathered their initial impressions. All MWUs expressed that they liked the overall design and the features/functions of the app, especially the adapted exercise library and progress tracking feature. Most of them adored the exercise reminder feature while a few preferred other ways of reminding them to exercise.

> *"I'm impressed. Seriously, I'm impressed. I think it will get people more active because of what it offers…" – MWU, male, 31*
>
> *"It really gives me a lot of information to know what I need and how to reach a little bit further." – MWU, female, 45*
>
> *"I really like being able to look at the progress over time." – MWU, male, 30*
>
> *"…and the fact that you have a library of exercise is really a big thing too. Having someone who look like me, act like me, is a huge advancement. I will use that." – MWU, male, 39*
>
> *"I like the idea of carving out a chunk of time to focus on fitness [using exercise reminder]." – MWU, male, 41*

Rehabilitation professionals also highly praised the adapted exercise library.

> *"That's cool. I like that idea [exercise library]. Even for someone leaving rehab, it will be nice to pick a bunch of exercises that they are allowed to do at home…" – Occupational therapist, female, 27 (4 other occupational/physical therapists agreed)*

Some MWUs pointed out how they did not like some elements of the design such as color palette and the terminology used in the app content shown in the wireframes.

> *"I will say the picture for the resources has very little contrast. With the light background, you might want to change the font to a darker color or something to make it easier to read." – MWU, female, 45*
>
> *"… 'workout' is preferable. You agree? Because no one wants a 'routine'… It sounds very clinical." – MWU, male, 32*

Suggestions for improvement

Both MWUs and rehabilitation professionals provided constructive feedbacks on how to improve the app. Feedbacks from MWUs mainly focused on the app design, user interface, and privacy.

> *"It would be great to see the smart watch battery on here [app]…" – MWU, male, 22*

Lots of the comments surrounded the accessibility of the app. Some MWUs do not have hand dexterity, so navigating the app proved to be challenging if the content was too dense or the buttons were too small or too close together. Other MWUs mentioned that cognitive disabilities were quite common among them; therefore, keeping the content short and simple would be ideal.

> *"I think somebody who has visual impairment might have a little bit hard time to see this page. They [images and words] can be a little bigger, and the color contrast… maybe brighter." – MWUs, female, 32*
>
> *"If you have to scroll [down the page], there are too many choices… If they fit on one screen, it's more accessible." – MWU, male, 29; MWU, male, 22*

Privacy was a concern to the users; MWUs mentioned having the autonomy to choose what to do with their own health data was very important.

> *"…and having the ability to clear that data, to take out that day, seems counter to your effort [of monitoring physical activity], but it's very important matter of personal privacy." – MWU, female, 45*
>
> *"…I don't want this [data] used against me in the future. Like oh, you have been so active in the past week, guess you don't need the caregivers…" – MWU, male,*

Participants gave feedback on the existing features and suggestions to improve it or modify it.

> *"I don't schedule things [won't use exercise reminder] … maybe just sending me an email saying you haven't logged into the app for a while, where are you? That's much more agreeable." – MWU, female, 45*

Additionally, they suggested having functions/features such as social networking and gamification to improve user engagement and app retention which were not included in the wireframes.

> *"Our [rugby] team would use a networking function… Like, if I saw my buddy already pushed half a mile and at the top of the 'leader chart', I would be like, oh okay, I better start doing something… You can set up a little group of friends and challenge each other, not like anyone can see it." – MWU, male, 29*
>
> *"I do like the thought of connecting with friends and being able to share it [progress] through social media." – MWU, male, 30*

Both MWUs and rehabilitation professionals provided constructive feedback on how to improve the app. Feedbacks from MWUs mainly focused on the app design, user interface, and privacy; while feedbacks from rehabilitation professionals emphasized on the app content such as types of adaptive exercises and safety.

> *"It would be great to see the smart watch battery on here [app]…" – MWU, male, 22*
>
> *"If you have to scroll, there are too many choices… If they fit on one screen, it's more accessible." – MWU, male, 29*

Rehabilitation professionals suggested a list of adaptive exercises and alternative movements to accommodate users of a wide range of abilities.

> *"What about internal and external rotation [exercise]? What about scapula elevation and shoulder scaption? You can have them do push up from their chairs." – Occupational therapist, female, 25*

It was suggested that the app should have a warning message to remind users that clearance from doctors is needed to engage in exercise to ensure safety.

> *"…on your library home page, [I would] put like a disclaimer saying that make sure you are clear for physical activity." – Physical therapist, female, 57*

4.4 DISCUSSION

Studies evaluating what app features/functions were most important and needed to promote behavior change and increased PA in ambulatory populations were easily found. A review of 15 studies using smartphone apps for increasing PA concluded that automatic tracking of PA such as step counts and calories burned and tracking of progress toward PA goals were most important to users [136]. Another review study examined 64 apps to promote PA among adults stated that self-monitoring, feedback on performance, and goal-setting were used most frequently [126]. However, a recent review pointed out that while such strategies pertaining to self-management and self-efficacy for physical activity have been successfully incorporated into interventions for chronic diseases, have rarely been done for neurologic rehabilitation. The review also stated that strategies such as goal setting, feedback about performance, tailored instruction, and ongoing personal or social support are important for this population, and mobile health and tele-rehabilitation technologies offer new ways to support self-management and self-efficacy by monitoring activity from wearable devices and instrumented exercise devices to allow real-world feedback, goal setting, and instructions [137]. After consolidating all the information from the focus group discussions, the following features/functions were identified as desirable and should be incorporated when developing a PA promotion app for MWUs. Many of these features/functions were quite similar to what is currently available and found useful by the general population [126, 136, 137]. However, some of them were unique to MWUs, e.g., workout library that instructs users how to perform adapted exercises and safety information related to PA and exercises.

Goal setting – motivations that keep you going

Both MWUs and rehabilitation professionals noted that personal barriers such as lack of motivation was the biggest barrier to regular PA participation in MWUs during the focus group interviews. This matched the finding from other research studies [7-10]. Goal setting has shown promise in promoting PA behavior change among adults [138]. Previous studies showed that goals could be used as a self-management technique and could motivate individuals who had a low degree of motivation to a task and increase their performance [139-142]. Focus group participants also seemed to recognize the importance of having a target to work towards, and they appreciated that they could customize their goals any time based on their changing needs.

Progress tracking – visual feedbacks on how you performed

Self-monitoring and real-time feedback has been shown to effectively increase one's motivation in engaging PA [68, 128, 129, 143]. Many focus group participants mentioned the importance of being able to review one's progress periodically with respect to the goals. A study by Matilla et al. reported that app users most enjoyed progress tracking over time and having a record of personal progress and seeing development in long-term health outcomes [131]. This matched the findings from the focus group discussions where MWUs expressed that they would like to see their performance advance over time and thus be encouraged to continue.

Workout library – instructions on how to safely exercise

Informational barrier is one of the barriers to PA identified by both MWUs and rehabilitation professionals. For example, MWUs were not sure what exercises they could do with their current abilities, how long they should exercise, etc. In addition, many MWUs showed low confidence in exercising on their own because they feared getting injured if they exercised incorrectly. Visual aids such as pictures with descriptions or videos with narratives would be a good medium to explain how to exercise safely. Having MWUs instead of able-bodied persons to demonstrate how to exercise was preferred. During the focus groups, examples of instructional exercise videos (1-min long each) were shown to study participants. All of them appreciated that there were two MWUs as exercise trainers in the videos and that the contents of the videos was concise. They found the videos were easy to follow and they felt more confident to try them when they could simply follow along with the videos.

Action planning – call for actions

Previous studies showed that planning served to mediate between exercise intentions and maintenance of PA [142, 144, 145], and was associated with increase in PA [146]. Action planning allows MWUs to plan and schedule various leisure PA and exercise based on their physical capabilities and time availability. It also minimizes the time barrier by allowing users to put together a short workout that takes 10 minutes instead of 30 minutes, making it easier for the users to start a new behavior. Focus group participants thought this could keep them accountable in terms of adopting and maintaining a new behavior [147]. In addition, a study showed that users preferred apps that coached and motivated them through tailored messages to take actions towards personally set goals [148]. Prompts or notifications to suggest users what to do based on their current progress at the right time would make it easy for users to transition to the desired behavior [149].

Health and wellness information – knowledge is power

As mentioned repeatedly, information barrier inhibited MWUs from participating in PA. Not only MWUs lack the knowledge of what they could do, rehabilitation professionals also lack the knowledge of what resources the community could offer. Information related to health and wellness would empower users to determine what to do to stay healthy. Information related to local resources such as the community PA programs, local adaptive sports organizations, and social events would help users build a support network for maintaining PA participation [150, 151].

Social networking – you are not alone

Several MWUs study participants mentioned that they would like to have some sort of social networking feature where they share their progress and even compete with friends and sports teammates. A review also supported that sharing of PA accomplishments with others through social media was beneficial as it facilitated behavior change [148].

Safety – look out for yourself

Several rehabilitation professionals were concerned about the safety of using *WheelFit v1.0* to exercise without supervision. Reminding users to set up the chairs properly, such as removing armrests or parts that get in the way during exercise and making sure the chair is locked, would be useful. Dehydration and over-exertion during exercise can be life-threatening. Safety precautions should be emphasized in the video, e.g., having a warning message during break time to remind users to stay hydrated. Prompts and notifications to remind users to slow down and rest if 30 minutes of continuous moderate intensity of activities is detected. Moreover, controlling users' access to the types of exercise videos in the library based on their body functions can keep users from trying exercises beyond their abilities to prevent injury. For example, a person with tetraplegia with no triceps function may not have access to triceps related exercises to prevent potential injury.

Limitations

This study was limited to a single-site, small convenience sample. The results from these focus groups were not generalizable to all MWUs and/or rehabilitation professionals who work with MWUs. All study participants lived in Pittsburgh, PA; and therefore, the barriers to PA participation reported in this study might not be the same as those experienced by other MWUs, or observed by other rehabilitation professionals, who lived in geographically and culturally different areas. We used an app wireframe to facilitate discussions on what MWUs' preferences were in a health/fitness app for PA promotion. While the wireframe provided a general concept to help focus group participants to brainstorm ideas and thoughts, this might limit and/or influence their views on what the app would be in terms of the design, content, and features/functionality. Future research should include a short session where participates could brainstorm freely before seeing the app wireframe. As a precursor to the development of a mobile fitness app for PA measurement and promotion in MWUs, results of this study reported the features and functions that were desirable to help MWUs initiate and maintain an active lifestyle: 1) goal setting, 2) workout library, 3) action planning, 4) progress tracking, 5) health and wellness information, 6) social networking, and 7) safety. The focus group findings as well as the app features suggested in this study should be used to further guide mobile app development in this area.

4.5 CONCLUSION

Through the focus group discussions, barriers to PA in MWUs were identified. The needs and desires of MWUs in a PA promotion app were acknowledged after understanding their previous exercise habits and experience of using commercial fitness/health products/apps. Several features/functions derived from the focus group discussions were identified as desirable and should be incorporated when developing a PA promotion app for MWUs. The focus group findings as well as the app features in this study should be used to guide further mobile app development in this area.

5.0 DEVELOPMENT AND USABILITY OF A MHEALTH APP TO PROMOTE PHYSICAL ACTIVITY IN MANUAL WHEELCHAIR USERS: PRELIMINARY RESULTS

5.1 INTRODUCTION

There are approximately 2.8 million manual wheelchair users (MWUs) in the United States [5, 6], and over half (57%) of them still lead a sedentary lifestyle despite clear and consistent physical activity (PA) guidelines [7]. Traditional in-person interventions have been shown to be effective in promoting behavior change and increasing PA [55, 56, 152]; however, it can be challenging to implement in MWUs given cost and resource limitations in this population [7-10]. Effective ways to encourage MWUs to make healthy lifestyle choices and to self-manage are desired. Many smartphone apps and fitness wearables designed to increase PA are available [153]. Because of access to the personalized data on PA patterns and the ability to track, compare, and monitor behavior [154], smartphone apps and fitness wearables are well recognized for their potential for impacting cognition and emotions which then increase PA of their users and ultimately improve health outcomes [155-157]. Usual support provided in face-to-face intervention such as motivational messages, monitoring, and behavior change tools, e.g., goal setting, prompts, and feedback, can be modified for delivery via smartphone apps [158, 159]. Since it is technically simple to deliver smartphone apps and wearables interventions to large populations, these modalities have gained increasing attention and are frequently considered as a mean to increase PA; however, the effectiveness of this method remains unclear.

A systematic review by McCallum et al. explored the 111 evaluation studies for PA apps and wearables and suggested that in order to understand overall effectiveness, real-world engagement with, and response to, an intervention should be evaluated [153]. Several studies that assessed the effectiveness of smartphone apps and fitness wearables in increasing PA can be found. A study by Caulfield et al. was conducted to examine the impact of Fitbit One (Fitbit, Inc.) on PA in a population of chronic obstructive pulmonary disease (COPD) patients [160]. Study participants used Fitbit One over a period of 6-week where they monitored PA and received feedback from the device. Results showed that participants had an increase of 70 steps/hour on average over the study period [160]. Another intervention study by Chung et al. was performed to test gamification to facilitate support for healthy lifestyle changes in obese and healthy young adults. Study participants tracked activity and diet using Fitbits and Twitter for 2 months. Results showed that the gamification element "one-day challenges" were successful in increasing steps in both obese and healthy young adults [161]. Melton et al. performed a randomized controlled trial to examine the efficacy of the Jawbone UP platform for increasing PA and improving sleep in African American college women. Study participants in intervention groups received and used Jawbone UP for 8-week. Results showed no evidence that the Jawbone UP platform is efficacious at improving PA participation or sleep [162]. Although promising, mixed results were found on the benefits of PA interventions using smartphone apps and fitness wearables. Further research in the ambulatory populations is needed to draw conclusions.

When looking into the MWUs population, literature on using mobile technologies for PA interventions was nonexistent. Though, a few tele-based interventions for MWUs could be found. For example, Arbour-Nicitopoulos et al. evaluated the effectiveness of a PA telephone service for 53 Canadians with SCI for a 6-month intervention. Results showed there was an increase in the percentage of participants who were regularly active at baseline (35%) vs 4-month (48%) and 6-month (52%) [57]. On the other hand, Froehlich-Grobe has an ongoing project which examines the usability, feasibility, and effectiveness of an Internet-based intervention (WOWii) in promoting exercise and improved fitness for those with spinal cord injury (SCI) over 16-week. To our knowledge, results of this project have not yet been published. The severe shortage of the use of mobile technologies and technology-based health and wellness programs in MWUs may be due to the lack of appropriate smartphone applications and/or wearables that are tailored to the needs of this population and provide them relevant information to facilitate behavior change. As mentioned in Chapter 4, there are currently only three commercially available apps that were designed for MWUs to stay active, but none of them were evaluated by the end-users: 1) *SCI-Ex*, 2) *Wheelchiar Calorimeter*, and 3) *Apple Health*. The *SCI-Ex* is an educational app that shows users how-to videos of various exercises with adaptive equipment, while the *Wheelchair Calorimeter* and the *Apple Health* are activity tracking apps that inform users of their daily activity levels. More details of these three apps could be found in Chapter 4. While these three apps integrated some behavioral-change techniques, such as self-monitoring (*Wheelchair Calorimeter* and *Apple Health*) and cues to action (*SCI-Ex*), they are limited in terms of providing partially helpful information to MWUs. For example, *SCI-Ex* only provides educational materials to teach users how to exercises with or without equipment, but do not support self-monitoring of daily PA. On the other hand, *Wheelchair Calorimeter* and *Apple Health* both provide some degrees of PA monitoring, e.g., calories burnt and push counts, but do not provide other resources such as health and wellness information. According to previous studies on mHealth interventions, multi-component or multifocal approaches were recommended as they appeared to be more effective in enhancing internal perception about, and motivation to, exercise, as well as increasing knowledge of how and where to exercise than stand-alone interventions [163, 164]. To bridge the gap between what's available and what's needed, a new multi-component mHealth app, *WheelFit*, has been designed based on a common behavior model – Fogg Behavioral Model (FBM) – to encourage active lifestyle in MWUs.

5.2 METHODS

5.2.1 Design and development of *WheelFit*

WheelFit was designed based on FBM and relevant research evidence, and integrated inputs from end-users and professionals in a previous focus group study (Chapter 4). Previous research has shown that multi-component interventions appear to be more effective than stand-alone interventions [163]; thus, *WheelFit* was designed to have multiple components. The development of *WheelFit* was guided by the FBM, which has 3 key factors: motivation, ability, and triggers [165]. To perform a target behavior, one must be 1) sufficiently motivated, 2) have the ability to perform the behavior, and 3) be triggered to perform the behavior [165]. *WheelFit* addressed these factors by integrating multiple behavior change strategies.

I. Motivation: Based on the finding from the focus group study described in Chapter 4, lack of motivation was one of the major barriers to PA in MWUs. There are a few strategies that could help improve motivation: increasing knowledge, awareness, and understanding of PA [166]. Two strategies can be used: facilitate self-regulatory activities and user education. Self-regulatory activities such as goal setting [167], self-monitoring of behavior [168], and reviewing progress have been found to be useful in raising awareness about existing behavior and motivating people to be physically active. With the current advancements in miniature sensing technology and decreasing costs of these devices, smartphone app and accompanying wearables can be used to self-monitor PA behavior [169].

WheelFit (Figure 8) is designed to include two commercial wearable sensors (i.e., an Android smartwatch around the dominant wrist and the wheel monitor attached to the wheelchair spoke), an Android-based app. The smartwatch uses its embedded accelerometer to sense the upper limb motion and streams the accelerometer signals at 30 Hz to the app via Bluetooth. It has a battery life of 7 – 8 hours and can be fully charged in about 30 mins. No changes were made to its firmware. The wheel monitor is a commercial Internet of Things (IoT) device, i.e., SensorTag by Texas Instruments, Inc. Its firmware has been modified so that only the accelerometer and gyroscope are activated to detect movement, distances per minute are calculated onboard based on gyroscope signals and streamed to the app, and the sleep mode is implemented to save battery where the accelerometer detects wheelchair movement and activates the gyroscope to track wheel rotation. The wheel sensor battery last about 1 month with the revised firmware. Both the smartwatch and the wheel sensor are also programmed to collect movement data and save them in their onboard memory in case they disconnect from the smartphone or are out of range. Once the connection is established, the data can be pushed to the smartphone app.

The app provides real-time self-monitoring of calories burnt, active time, distance travelled, push count, and heart rate (Figure 9). The calories burned, and active time are derived through a set of custom algorithms described in Chapter 3. As these algorithms were based on the raw acceleration signals from a single commercial monitor (i.e., ActiGraph GT3X+), they were applicable to the smartwatch used in this study. A simple test was carried out where a research assistant wore both the smartwatch and the ActigGraph GT3X+ while performing some random movements. Results confirmed that the raw acceleration from the smartwatch and from the ActiGraph GT3X+ were comparable after matching the axes.

In addition to self-monitoring, informational approaches addressing health and fitness concerns were also found to be effective in motivating people to increase their PA levels [170, 171]. A fitness tip feature was implemented in *WheelFit* to provide credible information in four sections, i.e., Guidelines, Safety, Equipment, and Resources. Guidelines section includes recommendation of PA (types of exercise, their frequency, and intensity) from the Center for Diseases Control and Prevention (CDC), and health benefit/risk associated with regular or lack of regular PA. The safety section includes information related to taking precautions to prevent injury during exercise. The equipment section includes information about home-based exercise equipment such as Theraband and dumbbells. Alternatives or adaptation to equipment such as kettle bells or wrist weights (instead of dumbbells) and Theraband handles for easier grip were also suggested. The resources section includes information about local adaptive sports organization where users could reach out and try new sports. In summary, *WheelFit* is designed to target motivation through automatic self-monitoring with commercial wearable sensors, goal setting, progress tracking, and delivery of educational materials.

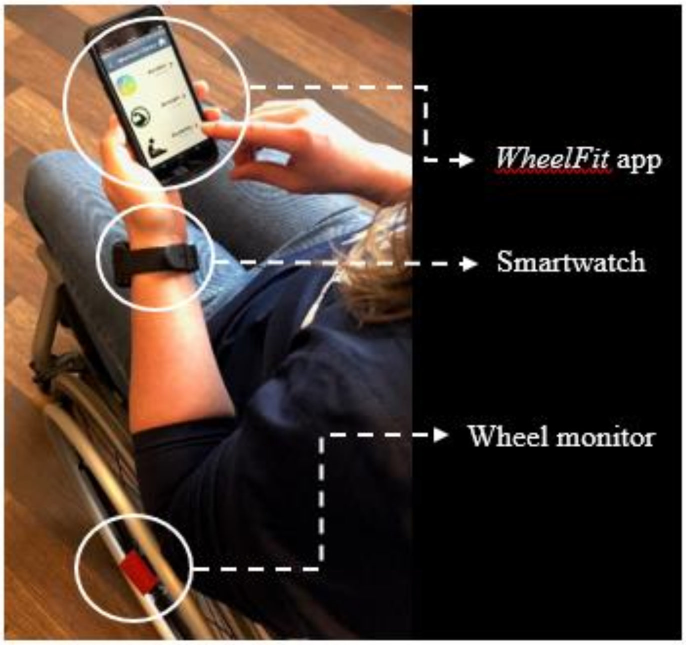


Figure 8. *WheelFit* consists of 3 components: 1) *WheelFit* app, 2) smartwatch, and 3) and the wheel monitor

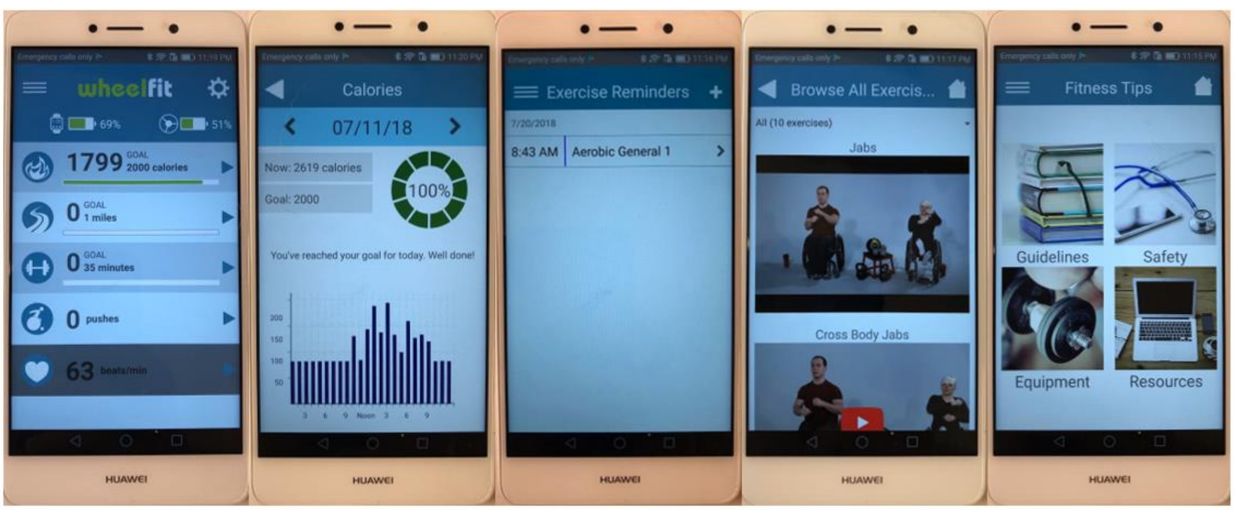


Figure 9. Screenshots of *WheelFit*. From left to right the images show: the home page, progress tracking (Daily Calories) page, exercise reminder page, workout library page, and fitness tips page

II. Ability: According to the FBM, making desired behavior easier to perform is simpler than training individuals to have new skills [165]. There are 6 elements to make desired behavior easier to perform: time, money, physical effort, brain cycles, social deviance, and non-routine [165]. If one's desired behavior is to allocate 30 min/day to exercise, but he/she does not have time or access to transportation or the gym, then this behavior becomes difficult to complete. Based on the results of the focus group study (Chapter 4), many MWUs reported a knowledge barrier about not knowing the kinds of exercises to do and that they could split the 30 min/day exercise into multiple shorter workout sessions Thus, *WheelFit* is designed to make PA participation easy for MWUs by providing an in-app adapted workout library that includes short exercise videos (about 1-min each), and thus allowing flexible planning that accommodates user schedule. These evidence-based exercises videos were created based on scientific literature and end-user inputs and reviewed by physical therapists from the Human Engineering Research Laboratories and the UPMC Mercy Hospital as well as ACSM certified personal trainer and exercise physiologist who have experience working with MWUs. The adapted library is designed to cover aerobic, shoulder strengthening, and flexibility exercises at both basic and advanced levels. For shoulder strengthening exercises, pain and no pain options are provided. In the first prototype of *WheelFit v1.0*, we have included 8 aerobic videos (basic level), 10 shoulder strengthening videos (pain and no pain options), and 7 flexibility videos (basic level). A disclaimer pops up when users access the workout library for the first time to ensure users have received clearance from their doctors to participate in exercises. Warnings about locking the chair in place and removing armrest/footrest to create enough clearance for movement during exercise were embedded in the exercise videos. In each exercise video, there are two trainers demonstrating the exercise. One of them shows the original form for the exercise, while the other shows the adapted movements for the same exercise to accommodate those with limited body functions.

To further facilitate user actions, we have also designed the action planning function where users go through a filter screen including the length, difficulty level, type of exercise, equipment (none, theraband, weights). Users will be asked at the end whether they are ready to exercise now or later. If users choose now, a custom workout will be created and played automatically; if users choose later, they will be directed to an exercise reminder page for scheduling. MWUs can create custom workouts based on their preferences using the short exercise videos in the library; they can then follow the video along and exercise from the comfort of their homes at any time. While we intend to provide a full range of customization to support action planning, *WheelFit v1.0* only provides custom workouts that were pre-made by study investigators due to the limited exercise videos that are currently available in the library.

III. Triggers: There are three types of triggers: sparks, facilitators, and signals [165]. A "spark" trigger works best with people who lack motivation as it is designed to motivate users to take action [165]. For example, a push notification showing the lack of progress towards the fitness goal for today or benefits of PA or risks of sedentary lifestyle from the fitness tips section may motivate MWUs to start working on their goal. A "facilitator" trigger works best with people who lack ability as it makes behavior easier [165]. An example would be prompting users with a short exercise video when prolonged sedentary period is detected. A "signal" trigger is best for people who have both motivation and ability as it simply reminds users of their desired behavior [165]. Participants from the focus group in Chapter 4 suggested to have push notification every morning with a fitness tip instead of requiring them to go find and read the articles themselves. This would be a more fun and convenient way to improve user engagement and adherence. While we intend to include different types of triggers, e.g., push notifications, in-app messages, and reminders to facilitate desired behavior under various circumstances in *WheelFit*, *WheelFit v1.0* only implemented a signal trigger in the form of reminders to help users adhere to the desired behavior.

In summary, *WheelFit v1.0* features include: 1) goal setting; 2) real-time self-monitoring of daily PA including calories burnt, distance traveled, active time, push counts, and push efficiency; 3) progress tracking which show users the behavioral trend and motivate them to engage in PA; 4) a workout library which included a good selection of home-based exercises that were appropriate to MWUs; 5) exercise reminder to trigger more PA; and 6) preliminary action planning to motivate users to perform target behavior. Push notifications under different circumstances were implemented to increase their ability to initiate and maintain an active lifestyle.

5.2.2 Usability of *WheelFit*

This study was approved by the Institutional Review Board at the University of Pittsburgh.

Participants

MWUs were recruited if they 1) were between 18- to 65-year-old, 2) were at least one-year post injury (if acquired) and medically stable, 3) used a manual wheelchair as their primary means of mobility, 4) lived in a community, and 5) had experience using a smartphone. MWUs were excluded if they 1) had any active pelvic or thigh wounds, 2) had contraindications to PA or exercises, and 3) were pregnant (based on self-report).

Procedure

Potential participants were contacted by a study investigator and were screened over the phone. Those who met the inclusion/exclusion criteria were invited to participate in this study. The study contained 2 lab visits and a 1-week long home trial. Participants were asked to use the *WheelFit* app and provide feedback to help improve the usability, relevance, and user experience.

Pre-home lab visit

During the first lab visit, a study investigator met with the participants and obtained written informed consent. Participants were then asked to complete a questionnaire pertaining to demographics (e.g., height, weight, age, and gender), wheelchair information (e.g., diameter of the wheel, the brand and model of the chair), and exercise/dietary habits. The stages of change of PA were also collected, where the five stages included stage 1 (pre-contemplation) during which an individual has not yet acknowledged that there is a problem with their PA behavior that needs to be changed, stage 2 (contemplation) during which the person acknowledges the existence of a problem but is not yet ready to make a change, stage 3 (preparation) during which the person is getting ready to change their PA behavior, stage 4 (decision/action) during which the person is undergoing a change in behavior, and stage 5 (maintenance) in which the person maintains an earlier implemented behavior change [172-174]. Depending on the stage a participant was at, their perceptions of *WheelFit v1.0* might differ. Lastly, the exercise self-efficacy was evaluated using the Exercise Self-Efficacy Scale (ESES) (Appendix A). The ESES is a 10-item questionnaire with a 4-point Likert scale to examine one's confidence to plan and carry out PA and/or exercise based on one's own volition [133]. The higher the ESES score (range from 10 to 40), the more confident one was towards PA participation.

The study investigator then briefly explained how to use the *WheelFit v1.0* app and its accompanying wearable sensors, i.e., the smartwatch and the wheel monitor (Figure 6), and attached the wheel monitor to the wheelchair wheel using two zip-ties, and asked participants to wear the smartwatch on the dominant wrist. Participants were given time to use the *WheelFit v1.0* app on their own until they felt comfortable using the app. They were then asked to fill out the pre-home trial questionnaire on their first impressions and initial interests of the app (Appendix F). This was to see user acceptance of the concept of *WheelFit v1.0* before they had extensive experience using the app. Next, participants were given 6 tasks to complete to ensure they knew how to use the app correctly prior to the 1-week home trial (Table 15). Each task required participants to obtain and enter specific data that would be used in a typical app task. The task was completed when the participants indicated that they finished the task successfully or when the participants gave up and requested help from the investigator. Their performance, i.e., the number of tasks performed successfully, and the time taken to complete each task, was documented for determining the technical effectiveness and relative user efficiency.

Table 15. Tasks for evaluating technical effectiveness of the app

Task	Description
1	Change the active time goal
2	Find out the distance traveled 3 days ago
3	Find out how much calories burnt today at 9am
4	Find an aerobic exercise video named “Uppercuts”
5	Set up a daily exercise reminder with one of the custom workouts in the library
6	Updating the profile with your personal information

Participants were given one of the two study smartphones (Huawei Mate 9 Lite and Samsung Galaxy S6) with the *WheelFit v1.0* app installed for the home trial. They were also instructed to set goals (e.g., calories, distance traveled, and active time) and use the app every day during the home trial. “Using the app” was defined as wearing the sensors and carrying the smartphone at all times during the day, using the app at least 3 times per day, and recharging the devices every night when necessary. The *WheelFit v1.0* app would have the PA updates/feedback enabled to guide the MWUs in relation to the goals they set for themselves. A logging function was included in the app to record participants' app usage activity such as the number of times the user visited the app and the pages. Investigators could access this information using the online portal with new updates every 10 minutes. Each participant was given a take-home package which included a wheel monitor, a smartwatch, a study smartphone, a "Devices setup guide" (Appendix D), and a "Troubleshooting guide" (Appendix E) at the end of the first visit.

<u>1-week home trial</u>

During the 1-week home trial, participants were asked to voice record any minor issues (e.g., app crash and lag) they experience during the trial using the phone's voice recorder app. Participants were instructed to contact the study investigator immediately in case of any major technical difficulties (e.g., app is not opening, sensors are not connecting to the app) experienced during the trial. A study investigator would provide any necessary assistance to resolve the problems. If the problems persisted, the home trial would be terminated, and participants would be given a choice to restart the home trial after the problems were resolved.

<u>Post-home lab visit</u>

At the end of the home trial, participants visit the lab to return the study materials including the sensors and the study smartphone. Participants were also asked to complete two post-home trial questionnaires (Appendix G) to evaluate 1) the overall functionality of the app and 2) its content and design. Lastly, a semi-structured interview was conducted to gather detailed feedback on user experience with *WheelFit*. The semi-structured interview was voice recorded and transcribed for analysis.

Data collection and analysis

According to the International standard ISO 9241-11, usability is defined as the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction [175, 176]. The usability of the *WheelFit* app was thus evaluated by measuring the effectiveness, efficiency, and user satisfaction. The usability testing plan proposed by Kushniruk et al. and Schneiderman were implemented [177, 178]. The plan consists of 3 stages: 1) technical effectiveness of the app, meaning whether users could successfully complete a given task, 2) relative user efficiency of the app, meaning how easy it was for users to navigate through the app, and 3) user satisfaction. In addition, user engagement (i.e., how frequently users interacted with the app and how much time they spent browsing through the app each time) was also evaluated as they were indicators of how likely users would sustain the use of the app and become committed [179].

Technical effectiveness

The technical effectiveness was determined using data collected in the first lab visit. It was computed by dividing the number of tasks completed successfully by the total number of tasks undertaken. In addition, the number of errors participants made was recorded. A major error was defined as an error resulting in an incorrect or incomplete task. A minor error was defined as an error resulting in browsing wrong pages during the process, but the task was still completed successfully at the end.

Relative user efficiency

The efficiency referred to the productivity, or the resources expended in relation to the accuracy and completeness with which users achieved the specific goals [175, 180]. It could be determined by dividing the number of tasks completed successfully during the first lab visit by the time taken to complete the task. The relative user efficiency score (RUS), which measured the average time a user took to complete a task in comparison with an expert user of the app [181], was also determined. A study investigator who had been testing the app during the app development process acted as our expert app user. The RUS equaled time taken to complete a task divided by the time taken by an expert app user to complete the same task.

User satisfaction

The user satisfaction referred to having confident and positive attitudes towards the use of a product in a specified context of use [175]. It was subjective in nature and needed to be assessed with self-report tools. Two self-report instruments, the System Usability Scale (SUS) completed in the first lab visit and the End-user Mobile App Rating Scale (uMARS) completed in the second lab visit, have been validated and widely used to assess users' internal beliefs, attitudes, and intentions towards technology [182-184]. The SUS is a 10-item questionnaire with a 5-point Likert scale that focuses on a global view of perceived usability or utility of a technology. It was used to examine the overall ease of use of the app. A SUS score of 80 (out of 100) or above meant people were impressed and would recommend it; and a score around 68 meant the app did okay and there was room for improvement. A score below 51 meant the app lack of usability and needed to be improved. The uMARS is a 27-item questionnaire that focuses on 6 areas of a health mobile app: 1) engagement (total score of 25), 2) functionality (total score of 20), 3) aesthetics (total score of 15), 4) information (total score of 20), 5) subjective quality (total score of 20), and 6) perceived impact (total score of 30) [183]. It was used to measure users' perceptions on how useful the app was in terms of increasing motivation and knowledge to participate in PA. The higher the score in each area, the better participants perceived the app in that area.

Furthermore, the qualitative data ascertained from the questionnaires and semi-structured interviews in the second lab visit were analyzed. Content analysis was used to identify and categorize any common trends or themes in the transcripts. Additionally, user engagement, e.g., the frequency of app visit and time spent on a specific page, during the 1-week home trial was evaluated using descriptive analysis to determine the features that interest participants the most/least.

5.3 RESULTS

Participant characteristics

This is an ongoing study with 4 MWUs completed the 1-week trial. All study participants were male and aged between 24 and 44 years old. Three of the participants were diagnosed with spinal cord injury (SCI) (at C5, T2, and T3) and one of them had spina bifida. Two of the participants already had a habit of exercising regularly, and they rated their own fitness level as good or excellent. According to the stages of change of PA, three of them were in stage 5 “Maintenance”, while the one was in stage 3 “Preparation”. Based on the Exercise Self-Efficacy Scale (ESES), they were relatively confident in engaging in regular PA (ESES: 32.2 ± 4.4 out of 40). More details on demographics of the study participants can be found in Table 16.

Table 16. Demographics of 4 MWUs who completed the 1-week trial

Characteristics	**MWUs, *n* (%)**
Gender	
Male	5 (100%)

Table 16 (continued).

Female	0 (0%)
Age, years (mean ± std)	33.2 ± 8.2
Weight, lbs (mean ± std)	180.0 ± 22.6
Height, in (mean ± std)	68.0 ± 3.8
Diagnosis	
Spinal cord injury	4 (80%)
Spina bifida	1 (20%)
Are you an athlete?	
Yes	3 (60%)
No	2 (40%)
Fitness level	
Good or above	4 (80%)
Fair or below	1 (20%)
Do you exercise regularly?	
Yes	3 (60%)
Occasionally	2 (40%)
No	0 (0%)
Are you employed?	
Yes	2 (40%)
No	3 (60%)
Do you follow a dietary plan?	
Yes	2 (40%)
No	3 (60%)
Stage of change of physical activity	
Stage 1: Pre-contemplation	0 (0%)
Stage 2: Contemplation	0 (0%)

Table 16 (continued).

Stage 3: Preparation	1 (20%)
Stage 4: Decision/Action	1 (20%)
Stage 5: Maintenance	3 (60%)
Exercise self-efficacy scale (mean ± std) Note: This exercise self-efficacy scale was developed by Kroll et al. (2007) for people with spinal cord injury.	32.2 ± 4.4

According to the data recorded in the *WheelFit v1.0* online portal, participants burnt an average of 2235.3 ± 264.2 kcal/day over the 1-week home trial (Table 17). This was reasonably higher than the basal metabolic rate of a man with the average age, height and weight of the four study participants using the Harris-Benedict equation, i.e., 1813 kcal/day [185]. They also traveled 0.75 ± 0.64 mile/day (ranged from 0.13 to 1.83 mile; one participant did not use his chair often because he walked when he was at home, and he spent a day sitting with the family at the hospital for an emergency event). Participants pushed 471.8 ± 339.2 times per day on average over the course of the study; spent 77.5 ± 10.9% at sedentary intensity level, 17.5 ± 7.0% at light intensity level, and 5.0 ± 4.0% at moderate intensity level. Participant 3 and 4 both used an add-on power assisted device such as SmartDrive to help them navigate tough terrains as they both need to get up/down hills on a daily basis. This explained why participant 3 pushed around the same amount as participant 2 but went some extra distance; and, participant 4 pushed less amount than participant 2 but covered a similar distance. All 4 participants were able to engage in at least 30 min/day of PA. More details on the summary of activities can be found in Table 17.

Table 17. Summary of activities during 1-week trial

	Subject 1	**Subject 2**	**Subject 3**	**Subject 4**	**Subject 5**
Number of days of app use (day)	4*	7	7	7	6
Total app use time (min/day)	1142.5	1405	1112.7	1037.7	384.7**
Average calories burnt (kcal/day)	1848.7	2588.2	2233.3	2205.4	2300.8
Average distance traveled (mile/day)	0.13	0.52	1.83	0.55	0.70
Average number of pushes (push/day)	84	705	640	128	802
Average time spent at sedentary intensity level (min/day, %)	962, 84.5%	1212.3, 86.1%	867.3, 77.9%	833.3, 80.3%	226.7, 58.9%
Average time spent at light intensity level (min/day, %)	143, 12.5%	155.7, 11.1%	207.1, 18.6%	169.7, 16.3%	111.2, 28.9%
Average time spent at moderate intensity level (min/day, %)	37.5, 3.3%	37, 2.6%	38.3, 3.4%	34.7, 3.3%	46.8, 12.2%

*Subject 1 missed 3 days due to family emergency.
**Subject 5 only used it during day time when he physically performed tasks.

User engagement

A logging function was included to track user engagement during the 1-week home trial. Data on the frequency of pages visited and time spent on a specific page were available in the online portal. On average, each participant visited 62.8 ± 28.6 app pages/day and spent 41.6 ± 20.6 min/day, meaning participants spent about 40 second every time they visited the app. About one third of the time (36.7 ± 5.5% total time), participants logged in and checked the home page for a quick overview of their performance. Besides the home page, the progress tracking pages were the most visited (34.9 ± 10.7%), followed by workout library (14.3 ± 6.6%), goal setting (5.9 ± 3.7%), exercise reminder (2.3 ± 0.5%), and fitness tips (1.2 ± 0.6%). More details can be found in Table 18.

Table 18. User engagement over 1-week home trial

	Subject 1	**Subject 2**	**Subject 3**	**Subject 4**	**Subject 5**
Total days in home trial	4*	7	7	7	6
Average app visit	19.2 min/day 52.8 visit/day	54.1 min/day 61.1 visit/day	37.4 min/day 54.1 visit/day	27.3 min/day 34.9 visit/day	70.2 min/day 111 visit/day
Home page	45.2% total min 30.8% total visit	67.6% total min 40.2% total visit	70.0% total min 35.9% total visit	60.9% total min 32.4% total visit	77.8% total min 44.1% total visit
Progress tracking	16.2% total min 33.6% total visit	26.2% total min 40.4% total visit	17.4% total min 45.9% total visit	5.9% total min 36.9% total visit	4.1% total min 17.6% total visit
Workout library	13.7% total min 9.5% total visit	1.6% total min 10.0% total visit	7.1% total min 9.2% total visit	30.5% total min 19.3% total visit	13.0% total min 23.4% total visit
Goal setting	8.5% total min 11.8% total visit	0.36% total min 2.1% total visit	1.1% total min 3.4% total visit	1.0% total min 6.5% total visit	1.4% total min 5.7% total visit
Fitness tips	0%	0.9% total min 0.9% total visit	0.01% total min 0.5% total visit	0.6% total min 2.0% total visit	1.0% total min 1.3% total visit
Exercise reminder	0%	0.6% total min 2.3% total visit	3.3% total min 3.0% total visit	0.7% total min 2.0% total visit	0.5% total min 1.9% total visit

*Subject 1 missed 3 days due to family emergency.

Technical effectiveness

Participants were able to complete all assigned tasks successfully without any assistance, and they commented how easy and intuitive it was to navigate through the app. There were no major errors recorded. Two minor errors from two participants (during task 1 and task 5) were recorded. These errors were caused by being confused of what the icons represent as new users of the app.

Relative user efficiency

The average time taken by study participants and an expert user to complete each task was computed and detailed in Table 19. The RUS was 1.7 ± 0.8 for task 1; 2.0 ± 0.5 for task 2; 1.8 ± 1.3 for task 3; 1.5 ± 0.6 for task 4; 1.3 ± 0.3 for task 5; and 1.7 ± 0.4 for task 6; meaning the study participants spent an average of 1.3 to 2.0 times longer than an expert user to complete each task.

Table 19. The overall impression, technical effectiveness, and relative user efficiency of *WheelFit*

	MWUs, *n* (%)		
Overall impression			
Very Impressed	2 (40%)		
Impressed	2 (40%)		
Somewhat impressed	1 (20%)		
Not impressed	0 (0%)		
What are you interested in tracking?			
Calories	4		
Distance traveled	3		
Active time	5		
Push counts	5		
Number of MWUs completed all tasks successfully	5 (100%)		
Time taken to complete the following task:	MWUs	Expert	RUS
Change the active time goal (s)	23.4 ± 11.3	13.7	1.7 ± 0.8
Find out the distance traveled 3 days ago (s)	16.9 ± 3.9	8.4	2.0 ± 0.5
Find out how much calories burnt today at 9am (s)	15.0 ± 10.7	8.4	1.8 ± 1.3
Find an aerobic exercise named “Uppercuts” (s)	21.1 ± 8.4	14.5	1.5 ± 0.6
Set up a daily exercise reminder (s)	41.7 ± 10.1	30.9	1.3 ± 0.3
Updating the profile with one’s personal information (s)	46.4 ± 10.8	27.4	1.7 ± 0.4

User satisfaction

The SUS score of 4 MWUs were 90, 57.5, 100, 87.5, and 92.5, respectively. Participants 1, 3, 4, and 5 thought the app was very easy to use, liked the app a lot, and said they would recommend it to their friends; participant 2 thought the app was okay. He had “neutral” responses for a few questions such as “I found the system unnecessarily complex”, “I thought the system was easy to use”, and “I think I would need the support of a technical person to be able to use this system”.

The mean uMARS app quality score was 17.9 ± 1.0 (out of 20), meaning participants thought the app was well made. The uMARS score for each of the 6 areas are detailed in Table 20. The perceived impact score was the lowest among the 6 areas, 21.2 ± 7.5 (out of 30). Participant 4 rated a total of 27 out of 30 for perceived impact; participants 2 and 3 each rated 24; participant 5 rated 23; and participant 1 rated a total of 8 out of 30 for this area. The high standard deviation implied that there were diverse opinions on the perceived impact of *WheelFit*.

Table 20. Results of the uMARS scores in 6 different app components: 1) engagement, 2) functionality, 3) aesthetics, 4) information, 5) app subjective quality, and 6) perceived impact.

Area of evaluation	**Score (mean ± std)**
App quality mean score (out of 20)	17.9 ± 1.0
I. Engagement (out of 25)	21.6 ± 2.1
II. Functionality (out of 20)	17.4 ± 1.7
III. Aesthetics (out of 15)	13.4 ± 1.1
IV. Information (out of 20)	19.0 ± 1.2
V. App subjective quality (out of 20)	14.4 ± 1.5
VI. Perceived Impact (out of 30)	21.2 ± 7.5

Overall impression

WheelFit is designed and developed to help MWUs who do not engage in regular PA or live a sedentary lifestyle to develop and maintain a healthy and active lifestyle through PA measurement and promotion. A convenience sample of 5 MWUs were recruited and they tested *WheelFit v1.0* for a week (4- to 7-day). The following is feedback gathered from users during the second lab visit (post 1-week home trial).

Overall, participant 2, 3, 4, and 5 were impressed with the app in general and shared how they used the app:

> *"I look up exercises I can do in the library that I don't know already." – Participant 2*
>
> *"I use it to check my push counts throughout the day and compare it with how much I normally push so that I know if I am stressing my shoulder too much." – Participant 3*

Participant 1 thought it was a great tool for lots of other MWUs to stay fit, but he personally didn't think that it was an ideal product for him. He explained that he was a professional athlete and a personal trainer. He knew the importance of having an active lifestyle, was very active already, and knew all the fitness and health information provided in the app. This explained why he rated "strongly disagree" for statements like "This app has increased my awareness of the importance of having an active lifestyle", or "This app has changed my attitudes toward more regular physical activity participation" in the uMARS.

In general, all 5 participants thought the progress tracking and workout library were the two of the most useful features, followed by the goal setting and fitness tips features, and lastly, the exercise reminder. This subjective rating of participants' perceived usefulness of the app features mirrored the logged frequency of the app page visited by participants (See User engagement section). In addition, all participants mentioned they were most interested in tracking their active time and push counts; four of them (participants 2, 3, 4, and 5) said they were interested in calories and distance traveled; participant 2 thought the exercise reminder would hold him accountable for daily exercise; and participant 3 was particularly impressed with the distance traveled and push counts measurement as he had yet to find any device could measure them well in MWUs. Furthermore, all participants agreed that push counts/efficiency were the most useful measurements, followed by distance traveled, calories burnt, and active time. They believed that distance traveled was the most accurate measure, followed by calories burned, push counts/efficiency, and active time. In terms of app quality, all participants thought *WheelFit v1.0* was most excellent in terms of functionality, aesthetics, and information.

There were also features that participants were not satisfied with. For example, participant 2 pointed out that *WheelFit v1.0* couldn't seem to detect he was working hard when he did strength training exercises at home. This could be due to the limitation of the custom algorithms not performing well in resistance related activities (See Chapter 4). Furthermore, all participants thought *WheelFit v1.0* needed improvement in user engagement. They thought the app wasn't fun to use and lacked interactive features. Some suggested providing personalized feedback on performance and creating your own workout might improve engagement.

> *"It will be nice if it knows I am lazy and then a message pops up on the watch to tell me to move."*

Comments that were brought up repeatedly by participants throughout app testing included 1) the Bluetooth disconnection between the smartwatch and the app (participants 1, 2, 3)

> *"I like a lot of it. The only thing I don't like is the watch disconnection problem. It's kind of annoying. Everything else works pretty good."*
>
> *"Fix the connection issue. It's annoying checking every now and then. It needs to give users confident that they [the watch and phone] will stay connected and track activity… it didn't record one of the workouts I did [because of the disconnection] at all…"*

5.4 DISCUSSION

To our knowledge, this was the first study to report on the development and usability of a mHealth app for MWUs. Five MWUs were recruited and 4 of them completed a 1-week home trial to test the usability of a mobile app designed for measuring and promoting PA in MWUs. After the first lab visit, the technical effectiveness, relative user efficiency, and user satisfaction were determined. All participants were able to complete all assigned tasks which implied that the app pages had a logical flow and were easy to navigate. According to Bevan's article on usability measurement, it was anticipated that it often takes novice users 2 or 3 times longer to complete a task than an expert user [181]. Participants in this study took 1.3 to 2 times longer to complete a task when compared to an expert user, meaning *WheelFit v1.0* was very efficient to use. Overall, participants were satisfied with *WheelFit v1.0* and rated it useful in terms of increasing motivation and knowledge to promote PA in MWUs.

Only MWUs who have experience using a smartphone were recruited as it was anticipated that they would be confident in using a smartphone and that any potential difficulties they encounter would not be due to their naivety of using a smartphone. Even though the app is designed for people who do not engage in regular PA, participants were not excluded based on their current fitness levels or stages of change of PA as we were interested in different aspects of usability. Active MWUs might not perceive *WheelFit v1.0* as useful for themselves, but they could provide comments on other aspects such as the ease of use, design and layout of the app, and relevance of app content to MWUs in general. Overall, participants were satisfied with *WheelFit v1.0* for PA measurement and promotion. All of them rated the app as easy to use, and thought it operated as expected at least 75% of the time. The other 25% of the time was subtracted due to the frequent Bluetooth disconnection between the smartwatch and the phone.

Although participants were generally satisfied with *WheelFit v1.0* as a tool to measure and promote PA, a few weaknesses were identified. Below were suggestions for enhancing the existing app features, and recommendations on additional features for increasing the desirability of the app.

Bluetooth disconnection issue

While no Bluetooth disconnection issue between the wheel sensor and the phone were reported, all participants experienced various degrees of disconnection between the smartwatch and the phone. Two of the participants who used the Huawei Mate 9 Lite phone during the 1-week home trial reported more frequent disconnection (~1 time per 1 to 2 hours) than using the Samsung Galaxy S6 phone (~2 times per day). This suggested that disconnection problem might be due to the phone itself rather than the Bluetooth communication. Regardless of the frequency of disconnection, participants were intolerant of the disconnection and expected the Bluetooth connection between devices to work 100% of the time as it was essential to measure PA.

Comments and suggestions for current app features

Participants were satisfied with the PA information delivered. All participants thought the progress summary graphs were visually appealing and were preferred over the tables. One suggestion was to make the dates shown on the bottom of the graph link to the corresponding date for more details. When being asked their opinions on the hourly breakdown of calories, distance traveled, active time, and push counts within a day, two of the participants said the detailed breakdowns didn't matter because they were only interested in the total distance traveled and total push counts over a day. Furthermore, two participants mentioned that it would be nice to see not just the active time, but also the breakdown of the time spent at sedentary, light, and moderate intensity levels throughout the day. It was expected participants would use fitness tips to learn information about PA and adaptive exercise for MWUs; however, fitness tips were one of the feature perceived as least attractive. This might due to the fact that most of the participants had relatively high exercise self-efficacy and already knew the information. Participants suggested creative ways to deliver this, e.g., through push notifications on the phone or on the watch. Furthermore, reminders were implemented as a simple signal trigger in the current *WheelFit v1.0* to prompt users who already have the ability and motivation to take actions. Other triggers, sparks and facilitators, should also be implemented to support action planning of individuals who lack either the ability or motivation. Users mentioned they would like to create their own workout based on their personal ability and be flexible in their schedule, which makes it easier for people with high motivation but low ability to engage in exercise. Moreover, push notifications of short exercise clips when long bouts of inactivity are detected would be a great spark trigger to those who have the ability to perform desired behavior.

Additional app features and suggestions for future development

In addition to the current app features, participants gave suggestions to enhance its overall functionality. Participant 1 and 3 mentioned it would be nice to have heart rate monitoring (heart rate monitoring was disabled in this study) so that they could keep track of their heart rate during exercises or even throughout the day. Moreover, participant 1 recommended integration of nutrition tracking because caloric intake was as important as calories burnt in maintaining energy balance. He also suggested to have a social network feature where members of the same sport teams could connect, share the PA status with one another, or even compete with each other in terms of who is being the most active in the group. The social network feature would also provide a platform for app users to reach out to each other and form a support network/community. In addition, gamification was brought up by one participant during interviews where they stated that including gaming elements into the app would make the app more fun and entertaining to use. Although the true benefits of gamification for health still needed to be investigated, it has been shown that game elements are correlated to app popularity [186]. Both social network and gamification are features that could potentially improve user engagement and user adherence of the app in the long run. This echoed the focus group results in Chapter 4.

Besides the app features, participants also suggested improvement in the wearable. All participants said they did not have a habit of wearing a watch, and participant 1, 3, and 4 reported discomfort during PA because of the watch. Participant 3 and 4 pointed out that the smartwatch was big and bulky, and that a thinner and smaller watch like Fitbit would be preferred. Furthermore, all participants mentioned that they wished the battery life of the smartwatch could last longer; however, they seemed to be tolerant of the relatively short battery life (7 – 8 hours) because of how quickly the watch could be fully charged (~20 mins from 10% to 100%).

Limitation and future work

One of the limitations of this study was small sample size. Given that most participants already engaged in regular PA and were at stage 5 "Maintenance" or stage 4 "Action" of the stages of change of PA, the results might not be translated to MWUs who lead a less active or sedentary lifestyle. Future study is necessary to test the usability of the app with a larger number of MWUs and in a cohort of MWUs who do not already engage in PA regularly, as we do not know whether the user's level of motivation for lifestyle change affects their perceptions of the app in general.

Since the app was developed for Android phones, a study smartphone was provided to the study participants to ensure access to the app. This created burden to participants as they needed to carry and use an extra phone on a daily basis. Moreover, the iPhone users might not be familiar with the Android phone layouts which might have contributed to longer time taken to complete the assigned tasks and affect the outcome of technical effectiveness. An iOS version of the app should be developed, and both versions of the app should be made available to participants to download on their own mobile devices.

Another limitation was that the user engagement data we collected did not represent the true real-world use of the app since participants were asked to use the sensors and app as much as they could for the study. However, this information is important for future clinical trials on effectiveness as it could help explain why an intervention was effective in increasing PA in MWUs or not. Currently, we were unable to track if users exercised along with the videos when users accessed the workout library; however, future analysis of the movement data from the smartwatch with the matching timestamp of when the exercise video was played should inform us whether users just watched the video or exercised along with it. Moreover, a convenient sample of MWUs were recruited who were already physically active. Therefore, some of the app features might not be as useful or interesting to them which may have caused them to not access pages like fitness tips as they already had the knowledge. Future efforts should be made to recruit MWUs who lead a less active or sedentary lifestyle as they are the target users of *WheelFit.*

5.5 CONCLUSION

Overall, results of this usability study were promising. The *WheelFit* app functioned adequately during the 1-week trial and was well perceived by the intended users. *WheelFit* was effective to use, perceived useful in measuring and promoting PA in MWUs, and MWUs were satisfied with the overall app. The Bluetooth disconnection between the smartphone and the app still need further investigation on its cause and potential solutions. Results of this study provide guidance to the final development cycle of the app in order to meet the needs of the intended user by optimizing the app design and functions before the official app release to the marketplace.

6.0 DISCUSSION AND RECOMMENDATIONS FOR FUTURE WORK

6.1 CONTRIBUTIONS

The purpose of this dissertation is to provide tools that can objectively and accurately measure PA and promote an active, healthy lifestyle in MWUs. The present work started with a systematic review of the available research to determine validity of currently available activity monitors for quantifying PA in MWUs. Three gaps were identified: 1) there were inconsistent results in PA measurement between different survey-based tools; 2) the existing wearable sensors were unable to accurately assess PA in MWUs; 3) there is a lack of tools built to promote PA for MWUs. As a result, a new compendium of PA for MWUs, with various diagnoses, was constructed to supplement the existing compendium based on a wide range of free-living activities. This new compendium can be used for estimating EE as well as for standardizing the assignment of intensities in PA surveys for MWUs. It could also help enhance the comparability of results of surveys and facilitate research describing PA patterns or the dose-response relationships between PA, health, and disease in MWUs.

Based on the results of the systematic review, we determined that the performance of existing activity monitors, used for measuring PA in MWUs, were not on par with those used for tracking PA in ambulatory populations [42]. To address this shortcoming, two sets of two custom algorithms were developed for MWUs based on the commercial monitor, ActiGraph GT3X+, which was worn on the MWUs' wrist and on the upper arm of the dominant side. Prior custom algorithms for estimating EE in MWUs were specific to the commercial monitor used in their development because the algorithms depended on propriety variables as inputs [100]. To ensure our current algorithms have the widest possible application, only the raw acceleration signals from the ActiGraph GT3X+ are used as prediction inputs. If our custom algorithms are going to be applied to other accelerometer-based monitors, it is important to make sure that the x-, y-, and z-axis of both devices match. The first set of algorithms, for the sensors on the wrist and upper arm, were developed to estimate EE in MWUs during different PA; while the second set was developed to classify the intensity of various activities. Results indicate that the accuracy of the EE estimation algorithms we developed are comparable in accuracy to those used in sensors developed for ambulatory populations, with mean relative errors of 10% for both the wrist and the upper arm. The intensity classification algorithms also show promising results with mean errors of less than 10% in distinguishing between sedentary and non-sedentary activities.

To disseminate the custom algorithms outlined in Chapter 3, a smartphone app, *WheelFit v1.0*, was designed as a means to measure and promote PA in MWUs. The app pairs with two commercial wearables (i.e., the smartwatch from Huawei, Inc. and the SensorTag from Texas Instrument, Inc.) via Bluetooth and data from the two sensors is sent to the user's smartphone; which allows the app, which houses the custom algorithms, to track PA as one of the main features. Other app features include goal setting, progress tracking, a workout library, and fitness tips that were developed using the Fogg Behavioral Model. Additionally, multiple focus groups and semi-structured interviews with MWUs and the rehabilitation professionals who worked closely with them helped inform the app's development. When the preliminary usability of *WheelFit v1.0* was examined, the results indicated that MWUs found *WheelFit v1.0* easy to use, effective in measuring and promoting PA; and that they were satisfied with the app enough that they would recommend it to others who might also benefit from it.

6.2 IMPLICATION OF DISSERTATION WORK

The present dissertation studies aim to help MWUs by developing a tool that promotes their participation in PA, and provides a way for them to measure their progress, so that they can develop and maintain a healthy and active lifestyle. This purpose aligns with the goals of the Transformative Exercise Framework which is to: 1) prevent the loss of continuity between rehabilitation and community exercise; 2) improve the quality of services through the customization of exercise programs that target specific health and functional issues; and 3) reduce exercise program/intervention dropout rates by establishing a closer connectivity between physicians, therapists, trainers and participants as well as promoting socially engaging PA through a combination of community-based activities and behavioral strategies to improve motivation [16].

Prevent loss of continuity between rehabilitation and community exercise

The focus of the first two phases, rehabilitation and condition-specific exercise, that are described in the Transformative Exercise Framework is to use PA to restore and improve body functions during the post-rehabilitation period. Trained rehabilitation professionals are heavily involved in the supervision of MWUs during these phases, and are tasked with providing any guidance they might need during the process. Our work aims to provide quantitative tools (i.e., the compendium of PA, the custom algorithm for ActiGraph GT3X+, and *WheelFit v1.0*) to help these trained professionals keep track of the rehabilitation progress of MWUs, identify early onset of physical inactivity, and mitigate the situation before the continuity between rehabilitation and community exercise is completely lost. The focus in the last two phases described in the framework, fitness and lifetime PA participants, is to continue improving body functions while preventing secondary health conditions and chronic diseases by engaging in regular PA. *WheelFit v1.0* is a consumer device MWUs can use to self-monitor their PA and review their progress over time in a manner that keeps them engaged in their PA program.

Improve the quality of services

WheelFit v1.0 was developed as a tool for both PA tracking and promotion. One of the promotional features is the adaptive workout library where a variety of evidence-based home exercises are explained and demonstrated in videos. The exercise videos are categorized into three types: 1) aerobic, 2) shoulder strengthening, and 3) flexibility, and each type is further subdivided into three different difficulty levels (i.e., pain relief, basic, and advanced). MWUs can browse and learn about their exercise options on their own, or they can have trained professionals assign them exercises appropriate to their functional abilities. A custom workout feature will be released in the near future that will allow trained professionals to create a personalized home exercise program, by combining appropriate evidence-based exercises, in order to help MWUs achieve their own personal PA goals. This will be particularly helpful for the second phase, condition-specific exercise, which is described in the framework.

Reduce exercise program/intervention dropout rates

As previously outlined in Chapter 1, MWUs are likely to dropout of their home- and/or community-based exercise programs if their community lacks the necessary support and/or accommodations they need to be successful. *WheelFit* includes features that are designed to address these problems, and were developed using the Fogg Behavioral Model as a guide. The existing features can also be further modified to increase user engagement and adherence. Bond et al. reported that a smartphone display showing real-time feedback significantly increased an end user's motivation to engage in PA [128]. While *WheelFit* already include such a display, incorporating tailored messages, based on a user's performance, to help inform their actions might be another step that would help MWUs reach their PA goals. For example, if a use hasn't made sufficient progress on their daily calorie goal, a message might appear that would prompt the user to take specific actions (e.g., "It's been a while since you last move, do you want to do stretch your limbs a little?"). Smith et al. reported that users particularly enjoyed the push notifications [187], and we can utilize beneficial aspects like this while transforming some of the less attractive functions (i.e., fitness tips) to make them more engaging. For example, instead of providing users with articles full of fitness tips; sending a push notification with a short, fun fact at intervals throughout the day is more likely to increase user engagement. Moreover, the online portal can be utilized as a communication platform and users can sign up to have notifications about local events, or group PA opportunities.

6.3 FUTURE RESEARCH

This present dissertation presents three tools that can be used to measure and promote PA in MWUs: the compendium, the custom wearables' algorithms to track PA in MWUs, and the mHealth application, *WheelFit*. These tools can help quantify and promote PA in MWUs; especially MWUs who have just finished their initial rehabilitation, and are in the process of transitioning from a rehabilitation patient to a lifetime PA participant. While conducting this study, we discovered new avenues of researching PA measurement and promotion in MWUs. This section discusses those newfound opportunities, both from a technical standpoint as well as other possible applications for the developed tools.

6.3.1 Algorithms for quantifying PA in MWUs

One of the limitations of the algorithms we developed for estimating EE and classifying intensity of activities, was that their evaluation of activities involving limb movement that was disproportionate to the physical exertion (e.g., weight lifting or Theraband exercise) was subpar. Future research should explore ways that the algorithms can identify these tasks and better quantify them. One sensor that can potentially be used to quantify PA, and differentiate between the aforementioned tasks, is a surface electromyography (sEMG) sensor, because it objectively measures the electrical signals caused by a muscle contraction. In other studies, sEMG sensor has shown promising results in identifying muscle activity, measuring the amount of muscle activity, and detecting activity onset [188]. Myo (Microsoft, Inc.) is a commercially available gesture control armband that uses sEMG, combined with hand kinematics, to control devices from a distance. The armband detects arm movements, analyzes the electrical activity in the muscles (which are unique to a given hand movement), and then translates that information into a meaningful action for manipulating the devices. Scientists at HERL have studied wheelchair kinematics extensively, from transfers to propulsion techniques. The information from previous research could be combined with new sEMG data to provide better quantitative and qualitative PA measurements for MWUs. The MyoSharp technology stack and development tools could be found at this reference [188]. Even though sEMG sensors could be used to address current shortfalls in quantifying certain types of PA in MWUs, including those activities involving limb movement that was disproportionate to physical exertion, the high complexity of the necessary algorithms may not be practical for implementation as part of a smartphone app. The proper balance of algorithmic performance and the practicality of the implementation will be an important consideration in future work.

Another avenue to explore would be using different machine learning techniques to train algorithms. The present study used the wrapper method; specifically, a forward selection strategy (which selects variables by evaluating possible subsets) was used to select features for training the multivariate linear regression that is used to estimate EE. Then, decision trees were used to classify the intensity of the activities. For feature selection, a forward selection strategy is computationally intensive, and a less computationally intensive method, such as the embedded method (where variable selection was done as part of the learning procedure) could be explored. Linear models were trained for use in this dissertation, because of that any non-linear relationships that exist in data might not be captured. Future research could explore non-linear models, such as support vector machine (SVM), to see if incorporating a non-linear model will improve the current level of prediction performance. Furthermore, ensemble learning methods could also be explored as an alternative method. The two types of ensembles, combining differing base learners and combining same base learners, are robust learning methods because they combine several models to improve machine learning results [189]. For example, when classifying time spent at different intensities, a random forest tree will get better results than a decision tree because it adds an extra layer of randomness by constructing each tree using a different bootstrap sample of the data. This method has been shown to perform better than many single classifiers [189]. While these methods are a promising way to improve algorithm performance, they should only be considered when high performance/accuracy is the goal because they are too complex to get real-time feedback on current mobile platforms.

Another suggestion was to establish a simple way for MWUs to quantify and assess whether or not they engage in enough PA. In the ambulatory population, people can gauge their activity level based on whether or not they have taken 10,000 steps in a given day. Creating a similar metric (e.g., a certain number of propulsion strokes per day) would allow MWUs to easily self-evaluate, which in turn, may encourage them to be more active each day. Future research can address developing this metric, but researchers should work to find a good balance between promoting an active lifestyle and encouraging activities that might lead to an early incidence of repetitive strain injury from joint overuse.

6.3.2 Inclusion of physiological parameters to improve algorithm performance

In addition to looking into other wearables and sensing technology we can also explore variables/signals that can be used to characterize PA. Debates on whether heart rate (or heart rate variability) should, or even can, be used to improve the performance of custom algorithms to predict PA continues. In addition to heart rate (or heart rate variability), PA can also potentially be characterized by the skin galvanic response, a person's body temperature, or a combination of any of the three. While the use of heart rate as an indicator of PA is common in the general population, because a linear relationship between activity intensity and heart rate has been found [190-193], and many studies have shown that heart rate has strong correlation with the intensity of activities; others studies found that it had limited applicability due to diagnoses (e.g., spinal cord injury T4 or above), medication, and emotional stress [54, 194-196]. So, while other physiological parameters (i.e., galvanic skin response and body temperature) were not as popular as heart rate for tracking PA, future studies should endeavor to examine the change of each individual physiological parameters as well as combinations of them in determining the intensity of PA.

6.3.3 Quality of physical activity

Upper extremity injuries are prevalent in MWUs. Studies showed that MWUs have a high risk of developing shoulder pain, carpal tunnel syndrome, and rotator cuff injuries due to either improper techniques or overuse due to repetitive motions [197]. Sensors, such as motion sensing input devices (e.g., Microsoft Kinect, discontinued), and smartwatches can measure the timing, range of motion, and the repetitions of a specific movement [198]. If the users complete the PA in a controlled manner, the smartwatch can be used to track the repetitions and timing of a movement, and the motion sensing devices can provide extra information on the positions of various joints. Future efforts should first explore the feasibility of using a smartwatch to assess the quality of a user's movements. This would then permit applications such as assessing if a user's physical form is correct or not based on range of motion, recording the number of repetitions performed, and the duration of each movement during the exercises. The app could then act as a virtual trainer and provide instant audio-visual feedback that would guide users on how to perform a specific exercise safely and effectively. Furthermore, the ability to detect risky movements in activities of daily living, such as improper hand position during transfer, and how often they are repeated could be an extremely helpful tool to prevent injuries in MWUs.

6.3.4 Improving *WheelFit*

Future research could include interviewing active MWUs, who are already successful reaching the PA guidelines, to try and better understand what it takes for them to be physically active. Their personal strategies could potentially be incorporated into later generations of *WheelFit*. Other future research should investigate how to make the user-app interaction either interesting enough, or entertaining enough, to keep users consistently engaged. Users that are consistently engaged are more likely to adherence to the recommended exercise programs/interventions. Feedback collected from the focus groups, and from the usability study, provided insight into a few ways that we could improve the functionality of *WheelFit*, and make it more desirable to MWUs:

<u>Heart rate monitoring</u>

In addition to tracking heart rate instantaneously, it may be worthwhile to implement a heart rate recording program, which would synchronize with the exercise videos, and inform users whether or not they are achieved the targeted heart rate zone for a specific exercise. This feedback might potentially motivate users to achieve the necessary workout intensity without requiring supervision.

<u>Workout library</u>

The library is currently limited to a few types of exercise videos – aerobics (seated boxing exercises), muscle strengthening, and flexibility exercises. The library is also limited to exercises that are at a basic skill level, and advanced versions of all types of need to be developed. Additionally, for the muscle strengthening videos, the library currently only includes shoulder strengthening exercises, and other muscle groups such as the trunk, arms (biceps/triceps), back, and chest will need to be added.

During the usability testing, we created custom workouts based on our existing videos for the study participants; however, in the future, it would be ideal to have the ability to increase customization for the purpose of action planning. In order to plan a personalized workout, users would need to complete a quick survey. The survey questions would be used to assess the desired types and intensities of exercise, indicate whether the participant experiences any pain (e.g., if they have shoulder pain), pick what gym equipment (none, dumbbells or Theraband) they would prefer to use or have access to, and select how long they would like to work out for. The results would allow users to create workouts based on their physical ability as well as personal interests, and it would also allow rehabilitation professionals to assist in personalizing each exercise program to better meet each patient/client's specific needs.

User engagement

Two functions, social networking and gamification, can be implemented in order to increase end user engagement. For example, features that let users socialize or network with others while providing a "leader board" may increase participation and compliance by encouraging friendly competition. For competitions among friends, setting up small challenges where user is asked to perform certain exercises (e.g., do wheelchair push-up as many as you can) in one minute could make for a quick and fun activity while getting them to participate in PA. Harder, more complicated, challenges could be created especially for MWUs who are on the same sport teams, or across teams using participants in a specific sport. This would allow teammates to compete with each other, outside of regular sport's practice to see who is more active. The results of this challenge would be automatically updated, and participants' ranking will be shown on the "leader board".

Having the ability to share fitness progress on social media platforms, such as Facebook (similar to what commercial fitness trackers do), can facilitate engagement and may help users build their own, personal, social support network. A web forum could be created to provide a channel for people to use to connect with others who live with the same condition (e.g., multiple sclerosis). This way people with similar challenges can share their experiences and tips, such as how to combat fatigue, while allowing others reach out and ask for help if they have questions from people who may have overcome their specific issue.

Right now, a user cannot determine which exercises in the library are appropriate for their functional ability without watching all of the videos to see what each workout involves. This could be solved by adding a filtering system that removes exercises, based on user's injury level/ability, that are unlikely to be appropriate for them. For example, a user with tetraplegia may have limited/impaired triceps' function, so exercises specifically for triceps, or exercises that rely on good triceps function, could be filtered from this particular user's library. The gaming concept of "leveling up" could also be considered as a way of accessing the workout library. Users would start at the lowest difficulty level, and have access to only basic level exercise videos. When a certain number of exercise videos have been explored, or certain amount of time has been spent at this level, the next level will be unlocked and users would find progressively more advanced exercises at each successive level. This type of program structure could be an entertaining way to ensure MWUs build up the necessary skills for the more challenging exercises before they are able to access them in the library. Additionally, a trophy/award system could also be implemented as a way to acknowledge users' efforts and keep them motivated and engaged in the program.

Future effort should also be put into continuing to build the online portal in order to support a MWUs ability to train remotely with a certified trainer or professional. This type of interaction may also help keep user engaged. However, these features are merely suggestions for improving end user engagement and promoting regular PA participation. Future research is needed to examine which features will be most effective at keeping users actively engaged in the program.

6.3.5 Evaluating interventions using *WheelFit*

WheelFit could serve as a support platform for future clinical trials evaluating different strategies that promote health and wellness. For example, self-management is a strategy that showed positive effects in interventions designed to change behaviors. A meta-analysis, conducted by Norris et al., investigated the effect of self-management education on adults with type 2 diabetes; the results showed a decrease in glycated hemoglobin by 0.76% more than the control group at their immediate follow-up, and by 0.26% at their 4 months follow-up [199]. Furthermore, future research could examine the impact of different types of triggers (i.e., sparks, facilitators, and signals) on behavioral changes by comparing the standalone app versus a connected version that would allow social interactions; or it could be used to establish a dose-response relationship between the amount of PA participation and the health benefits/risks in MWUs using *WheelFit*.

6.3.6 Building a physical activity ecosystem

The Human Engineering Research Lab has decades of research experience studying MWUs, from wheelchair kinematics, transfer techniques, wheelchair skills, seating and positioning, manual wheelchair maintenance, and now lifestyle management with *WheelFit*. Future research should explore the possibility of integrating all of these areas of study that are essential to the well-being of MWUs, in order to provide a comprehensive coaching/management system to holistically improve a MWU’s quality of lives.

APPENDIX A – SCI Exercise Self-Efficacy Scale

SCI exercise self-efficacy is defined as one's confidence of individuals with spinal cord injury to plan and carry out physical activities and/or exercise based on their own volition [133].

1. I am confident that I can overcome barriers and challenges with regard to physical activity and exercise if I try hard enough.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

2. I am confident that I can find means and ways to be physically active and exercise.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

3. I am confident that I can accomplish my physical activity and exercise goals that I set.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

4. I am confident that when I am confronted with a barrier to physical activity or exercise I can find several solutions to overcome this barrier.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

5. I am confident that I can be physically active or exercise even when I am tired.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

6. I am confident that I can be physically active or exercise even when I am feeling depressed.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

7. I am confident that I can be physically active or exercise even without the support of my family or friends.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

8. I am confident that I can be physically active or exercise without the help of a therapist or trainer.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

9. I am confident that I can motivate myself to start being physically active or exercising again after I've stopped for a while.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

10. I am confident that I can be physically active or exercise even if I had no access to a gym, exercise, training, or rehabilitation facility.

Not at all true	Rarely true	Moderately true	Always true
1	2	3	4

APPENDIX B – Guidance questions for focus groups with manual wheelchair users

The following are example questions we will be using to guide the discussion in focus groups where manual wheelchair users are involved.

I. Knowledge and previous experience

- Have you ever received information about physical health, fitness, or exercise? When, where, and from whom?
    i. What do you know about the physical activity guidelines, i.e., how much and what kind of exercise you should do to stay healthy?
    ii. How often do you receive this information, and how often would you like to get this information? Is this information readily available? Do you need to actively seek this information?
    iii. What do you do after learning about the health benefits/risks about physical activity or inactivity? Why?
    iv. When do you think is the best time to receive this information?
    v. Do you like the current way you receive physical health and fitness information? If yes, what works for you? If no, what doesn't work for you and how do you like this information to be delivered?
- Do you exercise regularly? If not, why? If yes, how often, in what settings (alone or with friends, at gym class or at home, etc.), and what motivates you?
    i. Do you think you meet the exercise guideline? If not, what stops you from meeting the guideline? And what do you think will help you meet the guideline?
    ii. Have you ever joined any physical activity intervention/program? Do you think it motivates and helps you stay active in the long run? Why or why not?
    iii. How often do you question if you do the exercise the right way or have the right form?
    iv. Why do you only exercise occasionally?
    v. If you exercise occasionally, what do you think is most challenging to form the habit of exercise regularly or have an active lifestyle?
- What do you think about having an app to help you keep track of your physical activity and help you to stay active and healthy?
    i. Have you had experience using a health or fitness app? If no, why not? If yes, what do you like or not like about them?
    ii. What features or functions would you like to have? Why?

iii. What kind of information would you like to receive (e.g., health risk/benefits, exercise guideline, exercise suggestions)? Why?
iv. If you can only choose one feature out of the ones you mentioned, what would that be?
v. How would you use the app? What do you want to accomplish with the app?
vi. How often do you think you will use the app? Why?

II. App content and layout

- Overall
  i. What is your impression of the app as a whole?
  ii. What are features would you like to have, or think is important to have, but is currently not included? Explain.
  iii. Do you think you will be benefit from this app? How?
  iv. Assuming everything is at perfect condition, what will you use this app for? And how often will you use this app?
  v. Will you recommend this to others? Who?
  vi. How much will you pay for this?
- Goal setting page:
  i. Content
    1. Do you think this feature is important if a wheelchair user wants to change from being sedentary to active? Why or why not?
    2. Image you want to be more active and want to set a fitness goal for yourself. What goals do you want to set? How many goals do you have?
    3. What challenges do you have when you try to set goals for yourself?
    4. Can you think of other goals that you want to set but is not included here?
    5. Are there too many goals? Why or why not? If yes, how should we change or improve it?
    6. What goal(s) do you think is the most important to wheelchair users in general? Explain.
    7. How do you know what goals (i.e., values) you should set? Where do you find this information?
    8. Is the information (tips) helpful in terms of setting your first goal?
    9. How often do you think you will change/update your goals?
    10. When do you think is time to change/update your goals?
    11. Any other information you think it will help you set up goals that is not included?
    12. Does goal setting motivate you to be active? How?
    13. What do you like and not like about this page?
  ii. Layout and presentation

1. What do you think about the amount of information displayed? Too much? Too little?
2. What do you think about the order of the goals shown? Do you prefer a specific order?
3. Do the buttons and icons makes sense to you?
4. When a button is pushed, is the information/tips presented in a logical way and as expected? Anything that is confusing, out of place, or difficult to understand?
5. What do you think about the visuals (design or aesthetic) of this page? Color? Font size?
6. How would you make this page more attractive or appealing to users?

- Progress page (include daily and weekly progress):
  i. Content
    1. What do you think about the information on this page? Anything helpful or not helpful?
    2. What kind of information or feedback did you expect to see in here?
    3. Do you think this page motivates you to be more active for the rest of the day? How? If not, what would you change to make it more motivating?
    4. How would you use this information or feedback to help you change your behavior?
    5. How many days/weeks do you think you will look back into? Why?
    6. What do you like and not like about this page?

  ii. Layout and presentation
    1. Is there too much information or feedback? Too little?
    2. Is the information easy to understand?
    3. What do you think about the visual elements?
    4. Do you think the information are in logical order or in an order that help you understand better?
    5. How would you make this page more attractive or better in general?
- Exercise library page:
  i. Content
    1. If you want to exercise at home, what are the concerns or challenges you may have?
    2. Where do you find information on home-based exercise?
    3. Do you think this page is helpful or valuable? Why or why not?
    4. What do you think about the types of exercise included here? Are there other home-based exercises you are interested in but not included here?
    5. How often do you think you would come here to check out the videos?

6. What do you think about the description of the videos? Do the descriptions match the video content?
7. What do you think about the content of the video? Are they appropriate to wheelchair users? Any other information you would want to know in the video?
8. Do you feel safe to exercise along with the video without supervision? If not, what should we do to make you feel safer?
9. How would you exercise along with the video? Will you use phone or tablet or connect to TV?
10. What do you like and not like about the video?

ii. Layout and presentation

1. Are the videos grouped appropriately? If not, how would you group or organize them?
2. What do you think about the format of the video? Is the video too long or short?
3. Does the video have enough visual and audio cues? Does the video structure appropriately?
4. How would you improve the video?

- Reminders page:

i. Content

1. Do you think you need this feature? If yes, how would you use the reminder feature to help you make your exercise plan for the day or week? If no, why not?
2. What do you want to be reminded with? When do you want to be reminded?
3. How would you like us to remind you about being more active regularly?
4. What do you think about having questions to help provide specific exercise suggestions and having an option for you to schedule specific exercises to do in the future, and have the reminders to remind you at the scheduled time?
5. What do you like and not like about this feature?
6. How would you improve this in general?

ii. Layout and presentation

1. Is the information on this page present in a logical way, and easy to understand?
2. What about the visuals? Are they attractive and professional looking?
3. How would you make its appearance better?

- Home page:

i. Content

        1. What information do you expect here? Anything you want to see here that is currently not?
        2. How would you use information on this page to help you stay active? Are the numbers displayed motivating you to achieve the goal? If not, how would you change it to be more motivating?
        3. What do you think about being able to control what variables are displayed here? For example, if I don't care about push counts, that information is hidden. Is that something you want to have?
    ii. Layout and presentation
        1. Too much or little information?
        2. Are the icons intuitive? Anything doesn't make sense or confuse you?
        3. Does the order of the icons matter? If no, how would you change this?
        4. What about the aesthetic?
        5. Can you think of ways to make it more attractive or user-friendly?
- Sensor page:
    i. Content
        1. What information do you expect here?
        2. How would you use the sensors and the app?
        3. What do you think about the options of being connected to only one of the two sensors?
        4. In what circumstance would you want to use only one sensor? Which sensor and why?
        5. What would you change on this page?
    ii. Layout and presentation
        1. What do you think about the design and visuals of the page?
        2. Does the information make sense and easy to understand?
        3. How would you improve the page and make it more attractive?
- Menu page:
    i. Content
        1. What other shortcuts do you think we should add in this menu page?
        2. What do you like and not like about this page?
        3. What else do you think should be included here but is currently not?
        4. What would you change to make it better?
    ii. Layout and presentation
        1. Does the order matter? Is this order okay? If not, how would you re-arrange it?
        2. Do the icons make sense? Anything confusing or not clear here?
        3. How would you improve this page?
- Profile page:
    i. Content

1. What do you think about to this page in general?
2. Anything you think should not be in here? Things that should be here but is not?
3. What do you think we should improve on this page?

ii. Layout and presentation

1. Does everything make sense?
2. What about the design and visuals?
3. Anything you would change?

APPENDIX C – Guidance questions for focus groups with rehabilitation professionals

The following are example questions we will use to guide the discussion in focus groups that involve rehabilitation professionals.

III. Knowledge and previous experience

- Have you ever given information about physical health, fitness, or exercise to your clients? When, where, and to whom (wheelchair users, their family members, care givers, etc.)?
    i. How important do you think this information is to your patients' physical health?
    ii. Do your recommendations follow any physical activity guidelines? The one for general population? The one for special population (e.g., spinal cord injury population)? Or do you give custom recommendations based on your patients' needs?
    iii. How often do you give this information? Do your patients actively ask about this information?
    iv. Do you think your patients follow your advices? Why or why not?
    v. When do you think is the best time to deliver this information?
    vi. How do you deliver the physical health and fitness information to your patient? Do you think it's effective? If yes, what works? If no, what doesn't work and what do you think is a better way?
- Do you prescribe exercises or physical activity interventions/programs? How often? What kind of patients do you prescribe these to?
    i. Do you think your patients stick with your exercise prescriptions? Why or why not?
    ii. Do you think the physical activity intervention motivates and helps your patients stay active in the long run? Why or why not?
    iii. What are the formats of the physical activity interventions? Are there any trainers or exercise experts present to supervise and advise participants the correct forms and safety? What kinds of physical activities are included?
    iv. Do your patients maintain the exercise habit after the interventions? Why or why not?
    v. What do you think is most challenging to motivate your patients to form the habit of exercise regularly or have an active lifestyle?
- What do you think about having an app to help you keep track of your patients' physical activity and help them to stay active and healthy?

i. Have your patients asked about any commercial health or fitness app? Have you checked those out?
ii. What features or functions would you think is good for wheelchair users? Why? What do you think won't work for them?
iii. What kind of information would you like your patients to receive (e.g., health risk/benefits, exercise guideline, exercise suggestions)? Why?
iv. How would you recommend the app to your patients? How would you use the app or advise your patients to use it? What do you and your patients want to accomplish with the app?

IV. App features

- Overall
  i. What is your impression of the app as a whole?
  ii. What are features would you like to have, or think is important to have for changing behavior, but is currently not included? Explain.
  iii. Do you think your patients will be benefit from this app? How?
  iv. Do you think you will benefit from this app? How?
  v. Assuming everything is at perfect condition, what will you use this app for?
  vi. Will you recommend this to your patients or colleagues? Why?
- Goal setting page:
  i. Content
    1. Do you think this feature is important if a wheelchair user wants to change from being sedentary to active? Why or why not?
    2. Image your patient wants to be more active and want to set a fitness goal with you. What goals do you want to set with your patients? How many goals will you advise your patients to have or work with?
    3. What challenges do you have when you try to set goals for your patients?
    4. Can you think of other goals that are beneficial to your patients but is not included here?
    5. Are there too many goals? Why or why not? If yes, how should we change or improve it?
    6. What goal(s) do you think is the most important to wheelchair users in general? Explain.
    7. How often do you think you will change/update your goals?
    8. When do you think is time to change/update your goals?
    9. Any other information you think it will help you or your patients set up goals that is not included?
    10. Do you think goal setting can motivate your patients to be active? How so?
    11. What do you like and not like about this page?

ii. Layout and presentation
    1. What do you think about the amount of information displayed? Too much? Too little?
    2. What do you think about the order of the goals shown? Do you prefer a specific order?
    3. Do the buttons and icons makes sense to you?
    4. When a button is pushed, is the information/tips presented in a logical way and as expected? Anything that is confusing, out of place, or difficult to understand?
    5. What do you think about the visuals (design or aesthetic) of this page? Color? Font size?
    6. How would you make this page more attractive or appealing to users?

- Progress page:
  i. Content
    1. What do you think about the information on this page? Anything helpful or not helpful?
    2. What kind of information or feedback did you expect to see in here?
    3. Do you think this page motivates your patients to be more active for the rest of the day? How? If not, what would you change to make it more motivating?
    4. How would you or your patients use this information or feedback to change their behavior?
    5. How many days/weeks do you think your patients should look back into? Why?
    6. What do you like and not like about this page?

  ii. Layout and presentation
    1. Is there too much information or feedback? Too little?
    2. Do you think the information are in logical order or in an order that help you understand easily?
    3. What do you think about the visual elements?
    4. How would you make this page more attractive or better in general?

- Exercise library page:
  i. Content
    1. If you want to recommend or suggest something for your patients to exercise at home, what are the concerns or challenges you may have?
    2. Where do you find information on home-based exercise for your patients?
    3. Do you think this page is helpful or valuable? Why or why not?

4. What do you think about the types of exercise included here? Are there other home-based exercises you would suggest or prescribe but not included here?
5. How many videos in the library are needed to be considered as good enough? Or how many videos in each category?
6. How often do you think you would come here to check out the videos?
7. What do you think about the description of the videos? Do the descriptions match the video content?
8. What do you think about the content of the video? Are they appropriate to wheelchair users? Any other information you would want to add to the video?
9. Would you let your patients exercise along with the video without supervision? If not, what should we do to make you feel comfortable recommending your patients to follow these videos by themselves?
10. What other problems do you see if your patients exercise along with the videos alone?
11. How would you use the videos in this app to help your patients engage in regular physical activity?
12. What do you like and not like about the video?

ii. Layout and presentation

1. Are the videos grouped appropriately? If not, how would you group or organize them?
2. What do you think about the format of the video? Is the video too long or short?
3. Does the video have enough visual and audio cues? Does the video structure appropriately?
4. How would you improve the video?

- Reminders page:

i. Content

1. Do you think this feature helps your patients to engage in regular physical activities? If yes, how would you or your patients use the reminder feature to create exercise plan for the day or the week? If no, why not?
2. What do you want your patients to be reminded with? When do you is a good time to remind them?
3. How do you think this feature should work?
4. What do you think about having some questions to help provide exercise suggestions and having an option for users to schedule specific exercises to do in the future, and have the reminders to remind users at the scheduled time?

5. What do you like and not like about this feature?
6. How would you improve this in general?

ii. Layout and presentation

1. Is the information on this page present in a logical way, and easy to understand?
2. What about the visuals? Are they attractive and professional looking?
3. How would you make its appearance better?

- Home page:

i. Content

1. What information do you expect here? Anything you want to see here that is currently not?
2. How would you or your patients use information on this page to stay active? Do you think the numbers displayed motivating your patients to achieve the goal? If not, how would you change it to be more motivating?
3. What do you think about being able to control what variables are displayed here? For example, if I don't care about push counts, that information is hidden. Is that something you or your patients would want to have?

ii. Layout and presentation

1. Too much or little information?
2. Are the icons intuitive? Anything doesn't make sense or confuse you?
3. Does the order of the icons matter? If no, how would you change this?
4. What about the aesthetic?
5. Can you think of ways to make it more attractive or user-friendly?

- Sensor page:

i. Content

1. What information do you expect here?
2. How would you or your patients use the sensors and the app?
3. What do you think about the options of being connected to only one of the two sensors?
4. In what circumstance do you see, or recommend, your patients using only one sensor? Which sensor and why?
5. What would you change on this page?

ii. Layout and presentation

1. What do you think about the design and visuals of the page?
2. Does the information make sense and easy to understand?
3. How would you improve the page and make it more attractive?

- Menu page:

i. Content

1. What other shortcuts do you think we should add in this menu page?
2. What do you like and not like about this page?
3. What else do you think should be included here but is currently not?
4. What would you change to make it better?

ii. Layout and presentation

1. Does the order matter? Is this order okay? If not, how would you re-arrange it?
2. Do the icons make sense? Anything confusing or not clear here?
3. How would you improve this page?

- Profile page:

i. Content

1. What do you think about to this page in general?
2. Anything you think should not be in here? Things that should be here but is not?
3. What do you think we should improve on this page?

ii. Layout and presentation

1. Does everything make sense?
2. What about the design and visuals?
3. Anything you would change?

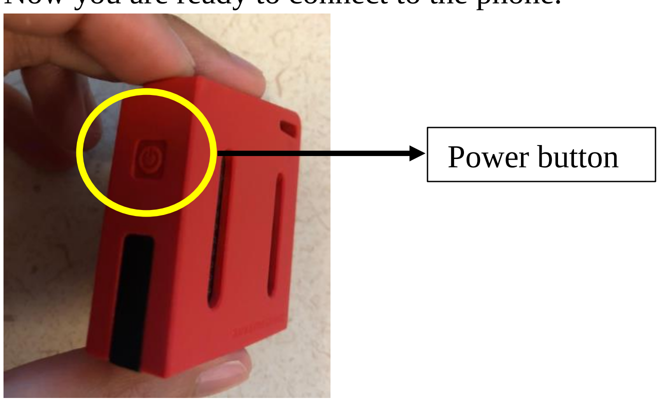
APPENDIX D – Devices initial setup guide for usability study participants

Setting up SensorTag, smart watch, and the WheelFit app:

<u>I. SensorTag</u>

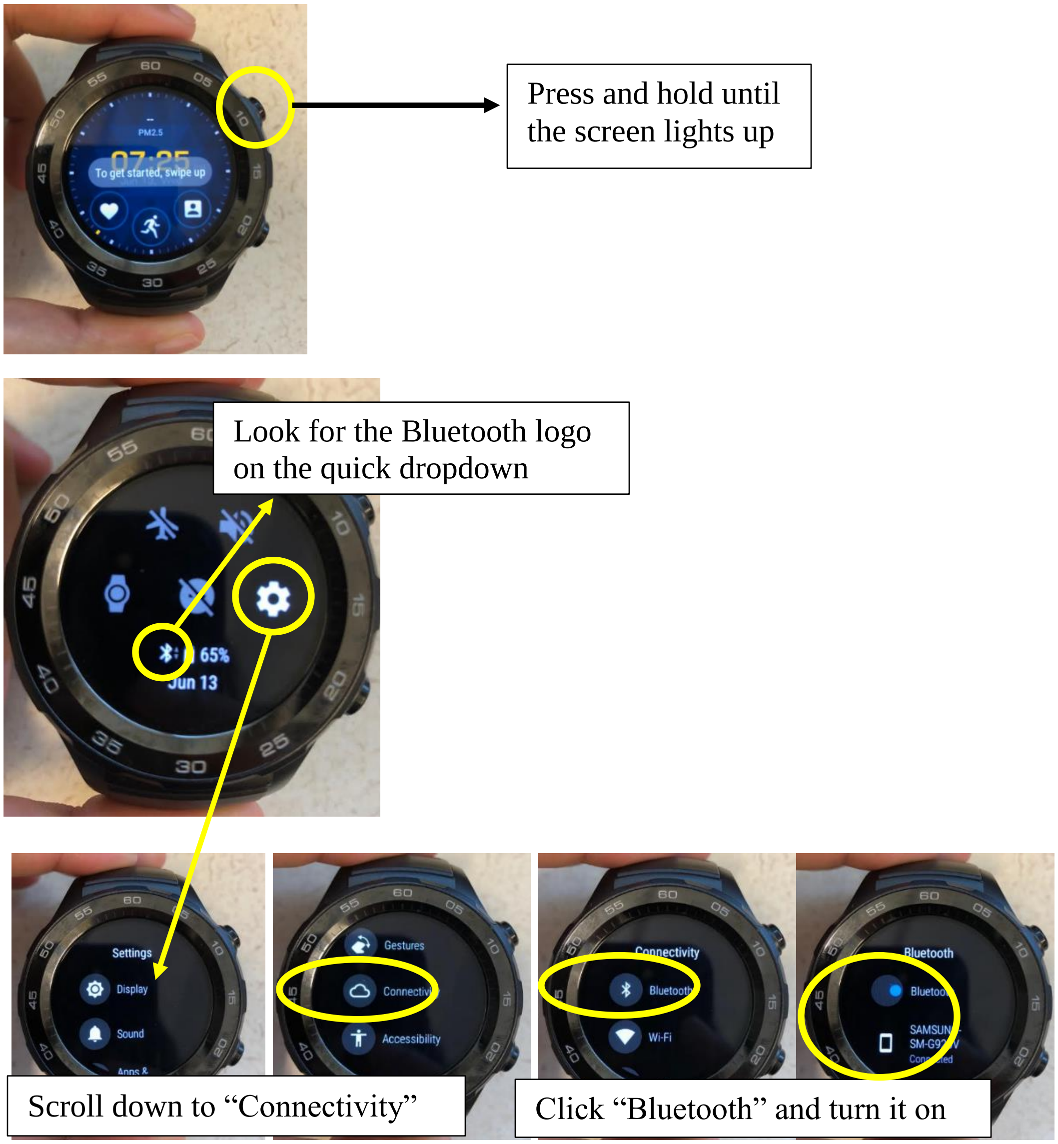
1. The SensorTag should already be turned on. It should be left on at all times. You can tell if the SensorTag is on if there are red and green lights blinking alternatively on the back.


2. If for some reason you need to turn it on yourself, the power button is on the left side of the device with a power logo on it. Press the button until you see red and green blinking lights. Now you are ready to connect to the phone.



<u>II. Smart watch</u>

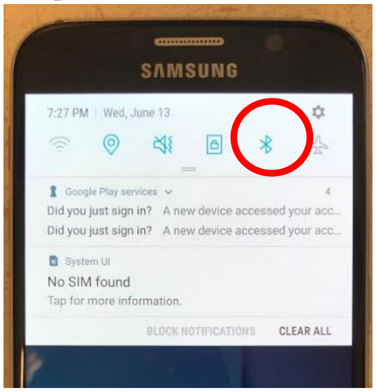
1. Turn on the watch. It should be always on as well; however, it may shut off when it's out of battery. To turn it on, press and hold the top button until the screen lights up.
2. Check if Bluetooth is on. Swipe down on the watch face after the screen lights up, a dropdown menu should show up. The Bluetooth logo should be there if it's on. If the Bluetooth is not on, press the gear logo on the dropdown menu to access "Settings", scroll down and click "Connectivity", then select "Bluetooth" and turn it on.



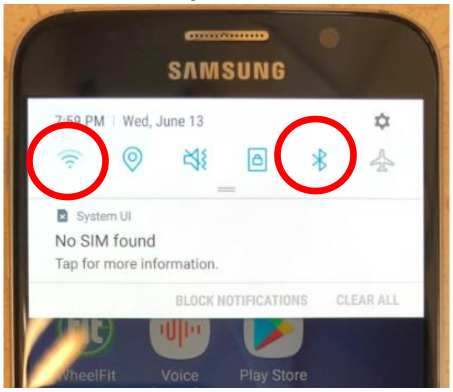
3. Open the “WheelFit” app on the watch. Press the top button, scroll down to “WheelFit” and click on it, the watch face will black out immediately. This means the app is opened.

III. WheelFit app

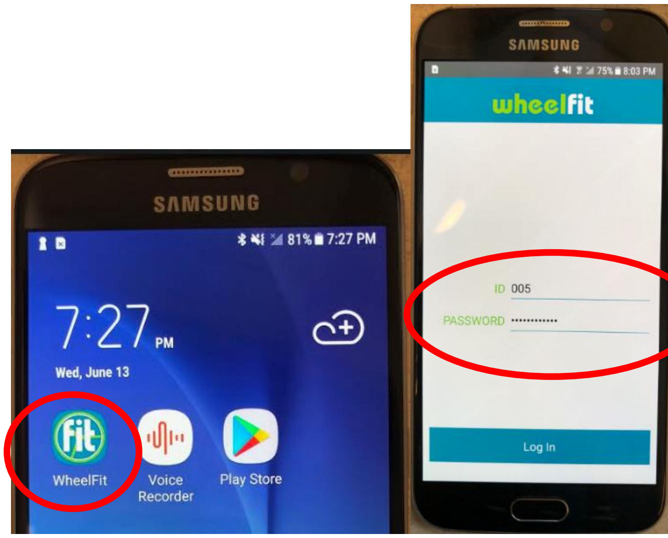
1. Turn on the phone. Press and hold the power button until the phone is turned on.
2. Swipe the screen down to access the dropdown menu. Check if Bluetooth is on.



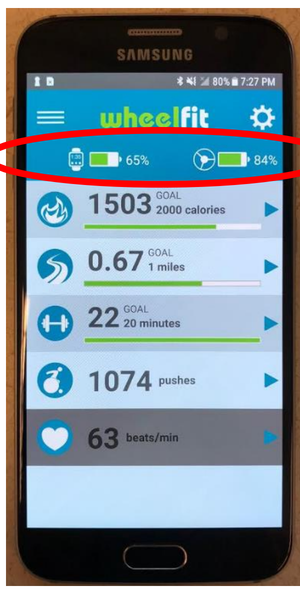
3. Check if Wi-Fi is on. It's recommended that you connect to Wi-Fi when it's available, so you can access the exercise videos and fitness tips in the app at home or at work. To add your home/work Wi-Fi, swipe down on the screen to access the drop-down menu, click on the Wi-Fi icon, select your network and follow the prompt to establish connection.



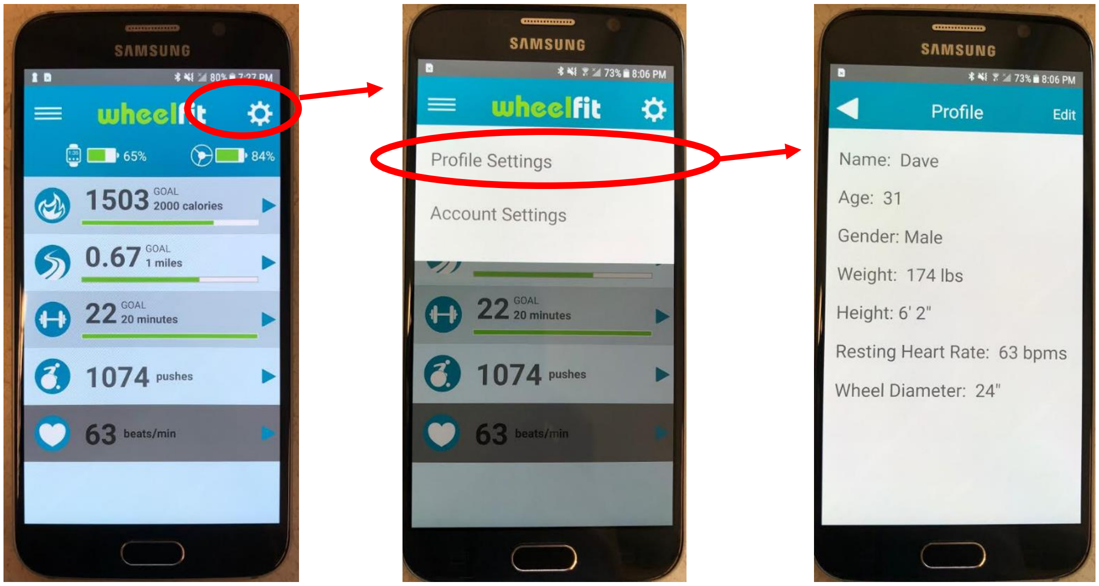
4. Log in to the WheelFit app using the ID and password provided.



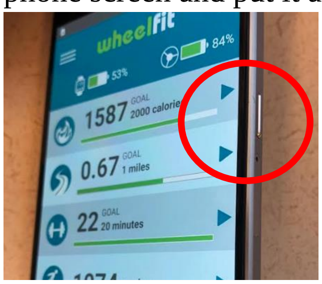
5. Once you're logged in, make sure the SensorTag and smart watch are connected. You should see their battery life after they are successfully connected. It may take a few seconds for the watch to connect. If the watch still shows "disconnected" after a minute. Go to the watch and open the WheelFit app on the watch again (follow the last step in the smart watch section). This will re-establish the connection.



6. Keep your profile updated, especially if your weight changes, age changes, or if you get a new chair with a different wheel diameter, etc.



7. When you are not doing anything with the app, let it run in the background. Simply lock the phone screen and put it away.



APPENDIX E – Troubleshooting guide for usability study participants

WheelFit app

Login ID: ____________________

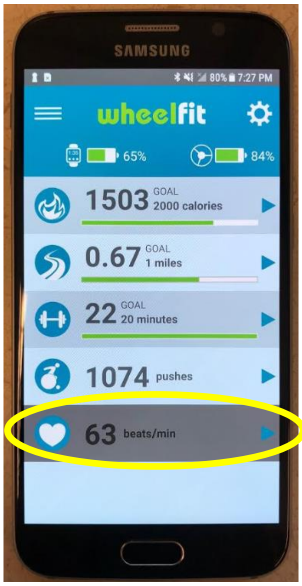
Login Password: ____________________

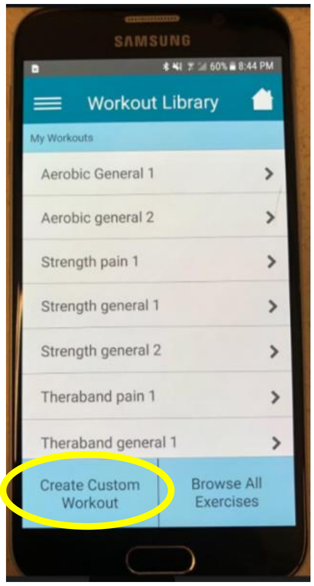
Overall:

1. Need Bluetooth to connect with wearables for activity tracking.
2. Need WiFi to access fitness tips and exercise videos.
3. The phone is provided for research purpose. **DO NOT** use the phone for any personal reasons.

App functions that are currently DISABLED:

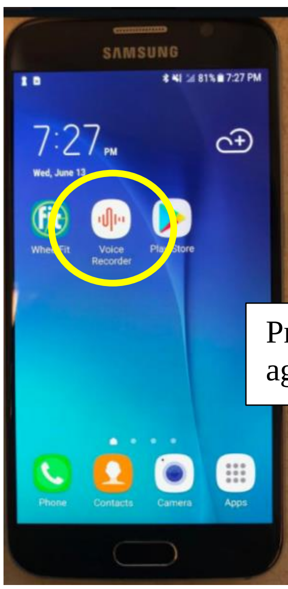
1. Heart rate tracking
2. Create custom workout

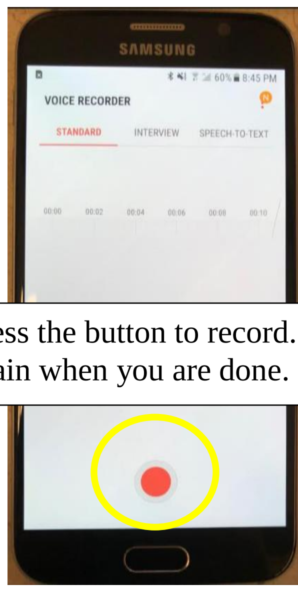




Expectations for using the WheelFit app:

1. Carry the phone with you and have the app run in the background for <u>at least 8 hours a day</u> for activity tracking purposes.
2. Make sure the phone is in range of the wearables. It's recommended that you carry the phone with you wherever you go.
3. Try to meet the goals that you set.
4. <u>Check the app periodically</u> throughout the day to see if the devices are connected to the app. Re-connect if necessary.
5. Use the app functions/features <u>at least 3 times a day</u>, including but not limited to, checking progress, watch exercise videos in the library, workout along with the pre-made workouts, and change goals.
6. Charge the phone <u>every night</u> to ensure it has battery for daily usage.
7. Use the voice recorder to record any app issues you encounter such as app crashes, page freezes, broken links, frequent Bluetooth disconnection…
   Use the following format for recording any instance:
   a. What did you try to do?
   b. What happened?
   c. What did you do to resolve it?
   d. Was the problem resolved at the end?
   e. **Example recording:** I clicked on an exercise video named "Hooks" but it wouldn't play. The app froze, and I couldn't go to other pages. I quit and restarted the app. Everything works fine now.

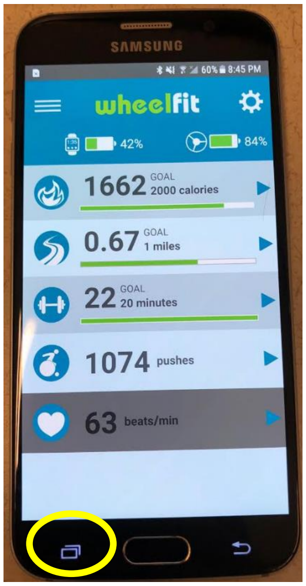


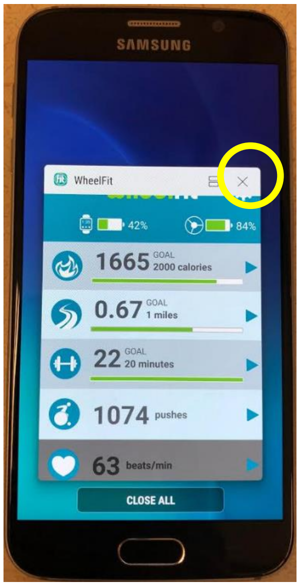


Press the button to record. Press again when you are done.

Troubleshoot for WheelFit app:

1. If the app page freezes, quit the app and restart. To quit, press the bottom left button and click "x" to quit the app.





2. If the app crashes, restart as prompted. Voice record the instance.
3. If the issue persists or if it happens frequently, call Kalai to resolve it as soon as possible.

Smart watch

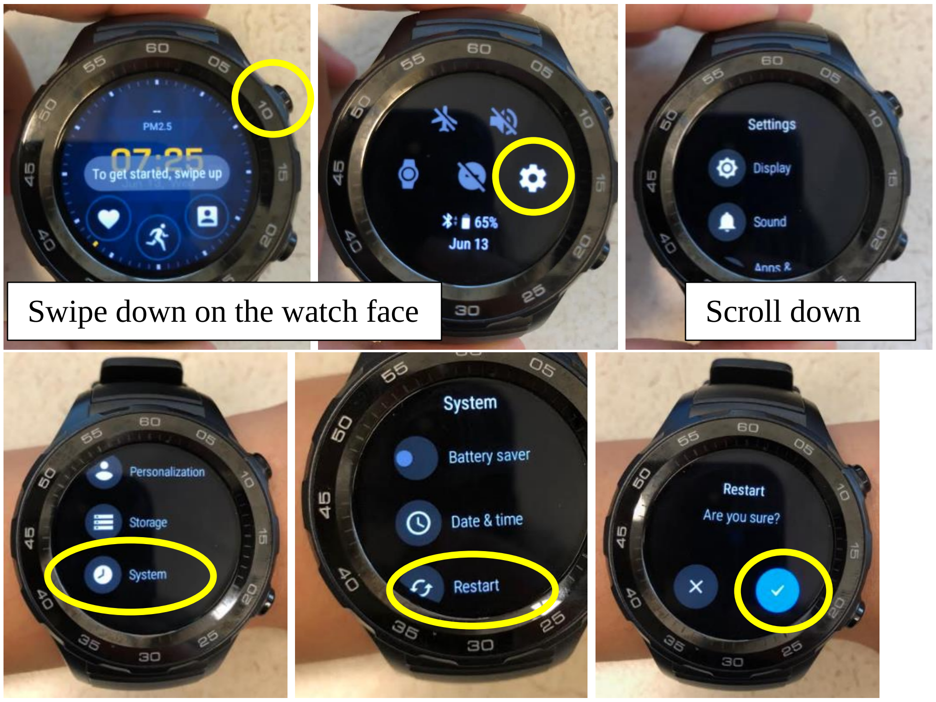
1. Only use the "WheelFit" app on the watch to connect to the phone app.
2. The watch is for research purposes. **DO NOT** use it for any personal reasons.
3. You are allowed to look around in the watch and even use the instant heart rate function, but **DO NOT** change any settings.
4. If you have exercise reminder set up in your phone app, the watch will vibrate when it's time.

Expectations for using Smart watch:

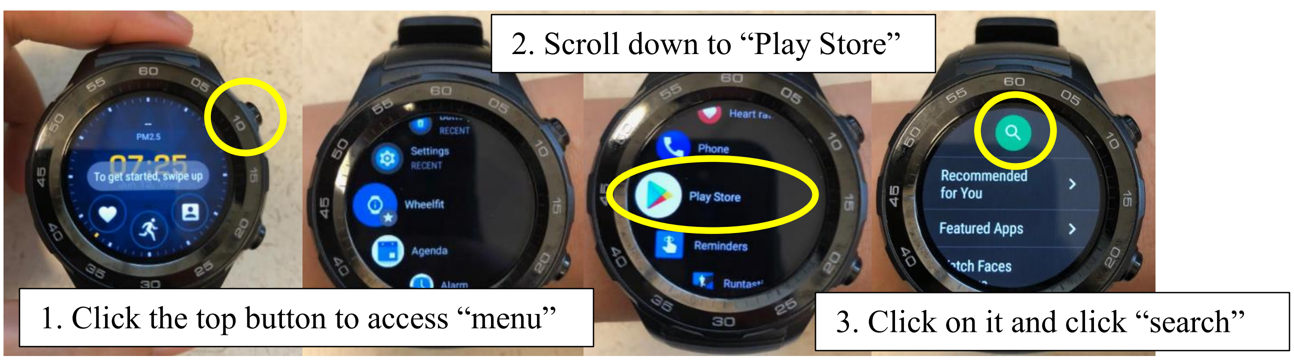
1. Wear the watch for at least 8 hours a day for activity tracking.
2. The watch is water resistant only. **DO NOT** wear it while you shower or swim.
3. Charge the watch every night before bed.
4. If you encounter any issues using the watch, use the phone voice recorder to record the issues using the same format as above.

Troubleshoot for Smart watch:

1. If the watch is unable to stay connected with the phone (connected and then disconnect after a short time), try to restart the watch. To restart the watch, press the top button to light up the watch face, swipe down on the watch face, click "setting", scroll down to "system", click "restart".



2. If restarting the watch doesn't work, try to uninstall the WheelFit app on the watch and re-install it. To uninstall, press on the top button to access the menu, then click "Google Play", click "search" and type in "Wheelfit", uninstall the app. Once it's done uninstalling, install the app again. Once it's done, click on the "WheelFit" app.



<u>SensorTag (wheel sensor)</u>

1. It’s always turned on. **DO NOT** press any buttons or take it off the wheelchair.
2. It’s water resistant but not waterproof. **DO NOT** submerge it under water.
3. You should not need to do anything unless the app shows its battery is less than 10%.
4. It will automatically try to connect to the phone when the phone app is opened. Give it a few seconds to a minute before troubleshooting.

Expectations for using SensorTag:

1. Attach it close to the hub of your rear wheel. **DO NOT** take it off.
2. Try to stay in the wheelchair with the Sensortag attached. If you are switching into a sport wheelchair for workout, e.g., hand cycling for more than an hour, please detach SensorTag from your regular chair and attach it to your sport chair before activity. Make sure you attach it back to your normal chair after the activity.

Troubleshoot for SensorTag

1. If the SensorTag is disconnected from the phone, quit the phone app and reopen it. This will trigger the SensorTag to establish Bluetooth connection with the phone automatically.
2. If the SensorTag is still disconnected after you reopen the app and wait for a minute, check the back of the sensor to see if lights are blinking. If the lights are blinking, restart the phone and open the WheelFit app again to establish a new connection.

**For any persisting problems, contact a study investigator: ____________ at ________________ as soon as possible. You may also text or leave a voice message if no one picks up. You will be contacted as soon as possible to resolve any problems related to using the devices.

APPENDIX F – Pre-home trial survey for usability study participants

1. Do you currently track the distance you travel on a daily basis?

- ◯ Yes, I do (1)
- ◯ No, I do not (2)

2. Are you interested in tracking the propulsion speed on a daily basis?

- ◯ Not Interested (1)
- ◯ Less Interested (2)
- ◯ Neutral (3)
- ◯ Interested (4)
- ◯ Very Interested (5)

3. Are you interested in tracking the propulsion efficiency on a daily basis?

- ◯ Not Interested (1)
- ◯ Less Interested (2)
- ◯ Neutral (3)
- ◯ Interested (4)
- ◯ Very Interested (5)

4. Are you interested in tracking the calories burnt on a daily basis?

- ◯ Not Interested (1)
- ◯ Less Interested (2)
- ◯ Neutral (3)
- ◯ Interested (4)
- ◯ Very Interested (5)

5. Are you interested in tracking the amount of time you spent at sedentary, light, moderate, and vigorous levels on a daily basis?

◯ Not Interested (1)

◯ Less Interested (2)

◯ Neutral (3)

◯ Interested (4)

◯ Very Interested (5)

6. Are you interested in tracking the push counts on a daily basis?

◯ Not Interested (1)

◯ Less Interested (2)

◯ Neutral (3)

◯ Interested (4)

◯ Very Interested (5)

7. Have you ever used any gadgets or tools to track your activity level (i.e., heart rate monitor, GPS locator, tachometer, etc.)?

◯ Yes, I have (1)

◯ No, I have not (2)

Display This Question:
If Have you ever used any gadgets or tools to track your activity level (i.e., heart rate monitor, G... = Yes, I have

8. Please specify which gadgets or tools you have used:

____

Display This Question:
If Have you ever used any gadgets or tools to track your activity level (i.e., heart rate monitor, G... = No, I have not

9. Have you ever attempted to search for and/or use any gadgets or tools?

____

State of Change of Physical Activity

10. I am currently physically active.

○ Yes (1)

○ No (2)

11. I intend to become more physically active in the next six months.

○ Yes (1)

○ No (2)

"For activity to be regular, it must add up to a total of 30 min or more per day and be done at least five days per week. For example, you could perform one 30-min exercise session or perform three 10-min exercise sessions for a total of 30 min."

12. I intend to become more physically active in the next six months.

○ Yes (1)

○ No (2)

13. I have been regularly physically active for the past six months.

○ Yes (1)

○ No (2)

Exercise Self-Efficacy Scale

14. I am confident that I can overcome barriers and challenges with regard to physical activity and exercise if I try hard enough.

- Not at all true (1)
- Rarely True (2)
- Moderately True (3)
- Always True (4)

15. I am confident that I can find means and ways to be physically active and exercise.

- Not at all true (1)
- Rarely True (2)
- Moderately True (3)
- Always True (4)

16. I am confident that I can accomplish my physical activity and exercise goals that I set.

- Not at all true (1)
- Rarely True (2)
- Moderately True (3)
- Always True (4)

17. I am confident that when I am confronted with a barrier to physical activity or exercise I can find several solutions to overcome this barrier.

- ◯ Not at all true (1)
- ◯ Rarely True (2)
- ◯ Moderately True (3)
- ◯ Always True (4)

18. I am confident that I can be physically active or exercise even when I am tired.

- ◯ Not at all true (1)
- ◯ Rarely True (2)
- ◯ Moderately True (3)
- ◯ Always True (4)

19. I am confident that I can be physically active or exercise even when I am feeling depressed.

- ◯ Not at all true (1)
- ◯ Rarely True (2)
- ◯ Moderately True (3)
- ◯ Always True (4)

20. I am confident that I can be physically active or exercise even without the support of my family or friends.

- ◯ Not at all true (1)
- ◯ Rarely True (2)
- ◯ Moderately True (3)
- ◯ Always True (4)

21. I am confident that I can be physically active or exercise without the help of a therapist or trainer.

- ◯ Not at all true (1)
- ◯ Rarely True (2)

◯ Moderately True (3)

◯ Always True (4)

22. I am confident that I can motivate myself to start being physically active or exercising again after I've stopped for a while.

◯ Not at all true (1)

◯ Rarely True (2)

◯ Moderately True (3)

◯ Always True (4)

23. I am confident that I can be physically active or exercise even if I had no access to a gym, exercise, training, or rehabilitation facility.

◯ Not at all true (1)

◯ Rarely True (2)

◯ Moderately True (3)

◯ Always True (4)

24. Do you have a smartphone (i.e., a phone that can access internet)?

◯ Yes (1)

◯ No (2)

Display This Question:

If Do you have a smartphone (i.e., a phone that can access internet)? = Yes

25. Yes (check all that apply):

- ☐ iPhone (1)
- ☐ Blackberry (2)
- ☐ Motorola android (3)
- ☐ HTC android (4)
- ☐ Samsung Galaxy (5)
- ☐ Other (6)

Display This Question:
If Yes(check all that apply): = Other

26. If Other, please specify:

____

Display This Question:
If Do you have a smartphone (i.e., a phone that can access internet)? = No

27. If no, please provide a reason (check all that apply) and skip this section of the questionnaire relating to smartphone usage.

- ☐ Cost (1)
- ☐ I've tried, but I found it difficult to use (2)
- ☐ I do not need other features except calls (3)
- ☐ Other (4)

Display This Question:
If If no, please provide a reason (check all that apply) and skip this section of the questionnaire... = Other

28. If Other, please specify:

____

29. Does your phone have touch screen capability?

- ○ Yes (1)
- ○ No (2)
- ○

Display This Question:
If Does your phone have touch screen capability? = Yes

30. Your phone's touch screen capability is:

- ○ Very easy to use (1)
- ○ Somewhat easy to use (2)
- ○ A little difficult to use (3)
- ○ Difficult to use (4)

---

31. How long have you been using a smartphone?

- ○ Less than a month (1)
- ○ 1-6 month (2)
- ○ 6 month – a year (3)
- ○ 1-2 year (4)
- ○ 2-3 year (5)
- ○ More than 3 years (6)

32. Please state your average hours of smartphone use per day (including phone calls, internet browsing, email, etc.)?

- ◯ Less than 1 hour (1)
- ◯ 1-2 hours (2)
- ◯ 2-4 hours (3)
- ◯ 4-6 hours (4)
- ◯ More than 6 hours (5)

33. How do you carry your mobile phone?

- ◯ In my pocket (1)
- ◯ In my pouch (2)
- ◯ Other (3)

Display This Question:
If How do you carry your mobile phone? = Other

34. If Other, please specify

____

35. When do you not carry your phone?

- ◯ When exercising, or playing sport (1)
- ◯ When at work (2)
- ◯ When at home (3)
- ◯ Other (4)

Display This Question:
If When do you not carry your phone? = Other

36. If Other, please specify:

____

37. How do you typically use your smartphone? (Choose all that apply)

- ☐ Browsing internet (1)
- ☐ Entertaining yourself (listening to music, watching movie, etc.) (2)
- ☐ Accessing social networking site (Facebook, Twitter, etc.) (3)
- ☐ Accessing email (4)
- ☐ Text messaging (5)
- ☐ Other (6)

Display This Question:
If How do you typically use your smartphone? (Choose all that apply) = Other

38. If Other, please specify:

- ○ ____

39. Please rate your fluency in smartphone usage.

- ○ Not Fluent (1)
- ○ Less Fluent (2)
- ○ Competent (3)
- ○ Fluent (4)
- ○ Very Fluent (5)

40. Please rate the importance of smartphone to you.

- ○ Not important (1)
- ○ Less Important (2)
- ○ Neutral (3)
- ○ Important (4)
- ○ Very Important (5)

41. Please rate how satisfied you are with your current smartphone.

- Very Unsatisfied (1)
- Unsatisfied (2)
- Neutral (3)
- Satisfied (4)
- Very Satisfied (5)

42. Please rate your overall impression of WheelFit.

- Not Impressed (1)
- Slightly Impressed (2)
- Somewhat Impressed (3)
- Impressed (4)
- Very Impressed (5)

43. Please rate how desirable WheelFit is as a product for you.

- Not Desirable (1)
- Slightly Desirable (2)
- Somewhat Desirable (3)
- Desirable (4)
- Very Desirable (5)

44. Please rate how useful WheelFit will be for you.

- Not Useful (1)
- Slightly Useful (2)
- Somewhat Useful (3)
- Useful (4)
- Very Useful (5)

45. Rate your degree of confidence by recording a number from 0 to 100 using the scale given below:

	Not Confident	Moderately Confident	Highly Confident
	0 10 20 30	40 50 60	70 80 90 100
I Understand how WheelFit works. (1)			
I can use WheelFit by myself. (2)			

46. Do you think WheelFit will be effective at helping you attain or maintain an active lifestyle? Please elaborate.

____

47. If you are interested in WheelFit, how do you see yourself using it? Please describe what feature(s) you will use and in what circumstances (e.g., I will use it to check my push counts throughout the day and compare it with how much I normally push so that I know if I am stressing my shoulder too much).

____

48. Please rate how easy or difficult the app is to use.

- ○ Very Difficult (1)
- ○ Difficult (2)
- ○ Neutral (3)
- ○ Easy (4)
- ○ Very Easy (5)

49. Please rate the cognitive effort to navigate through the app to get information or change settings.

- Very Difficult (1)
- Difficult (2)
- Neutral (3)
- Easy (4)
- Very Easy (5)

50. Please rate how easy or difficult the content in the app is to understand.

- Very Difficult (1)
- Difficult (2)
- Neutral (3)
- Easy (4)
- Very Easy (5)

51. On first impression, how useful will the personal goal feature be for you?

- Not Useful (1)
- Slightly Useful (2)
- Somewhat Useful (3)
- Useful (4)
- Very Useful (5)

52. On first impression, how useful will the progress feature be for you?

- ◯ Not Useful (1)
- ◯ Slightly Useful (2)
- ◯ Somewhat Useful (3)
- ◯ Useful (4)
- ◯ Very Useful (5)

53. On first impression, how useful will the workout tutorials feature be for you?

- ◯ Not Useful (1)
- ◯ Slightly Useful (2)
- ◯ Somewhat Useful (3)
- ◯ Useful (4)
- ◯ Very Useful (5)

54. On first impression, how useful will the exercise reminder feature be for you?

- ◯ Not Useful (1)
- ◯ Slightly Useful (2)
- ◯ Somewhat Useful (3)
- ◯ Useful (4)
- ◯ Very Useful (5)

55. Rate your degree of confidence for the claims below using the scale given below:

	Not Confident / Moderately Confident / Highly Confident 0 10 20 30 40 50 60 70 80 90 100
I can use the app independently (1)	
I can use the app to its full potential. (2)	

I can use the app on a daily basis. (3)	

56. Describe how you might use the app on a daily basis?

____

57. Are there any parameters or features that interest you the most? Please explain.

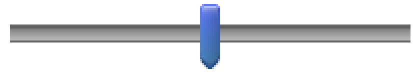
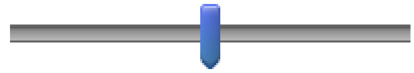
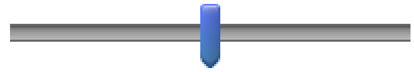
____

58. Do you have any comments or suggestions for the app?

____

59. Please select from 1 to 5 based on how much you agree with the following statements.

	Strongly disagree Strongly agree 1 2 4 5
I think that I would like to use the system frequently. (1)	
I found the system unnecessarily complex. (2)	
I thought the system was easy to use. (3)	
I think that I would need the support of a technical person to be able to use this system. (4)	
I found the various functions in this system were well integrated. (5)	
I thought there was too much inconsistency in this system. (6)	
I would imagine that most people would learn to use this system very quickly. (7)	
I found the system very cumbersome to use. (8)	
I felt very confident using the system. (9)	

I needed to learn a lot of things before I could get going with this system. (10)	
I thought the system might help me become physically more active. (11)	
I thought the system was desirable product for me. (12)	

The End.

APPENDIX G – Post-home trial survey for usability study participants

Part I: Functionality

1. Please rate your overall experience using the app.

- ○ Very Unsatisfied (1)
- ○ Unsatisfied (2)
- ○ Neutral (3)
- ○ Satisfied (4)
- ○ Very Satisfied (5)

2. Please rate how easy/hard it is to use the app on a daily basis.

- ○ Very Difficult (1)
- ○ Difficult (2)
- ○ Neutral (3)
- ○ Easy (4)
- ○ Very Easy (5)

3. Please rate how easy/hard it is to navigate through the app to get information you want or change settings.

- ◯ Very Difficult (1)
- ◯ Difficult (2)
- ◯ Neutral (3)
- ◯ Easy (4)
- ◯ Very Easy (5)

4. Please rate how easy or difficult it is to return back to where you were when you made a mistake.

- ◯ Very Difficult (1)
- ◯ Difficult (2)
- ◯ Neutral (3)
- ◯ Easy (4)
- ◯ Very Easy (5)

5. Please rate how easy or difficult it is to understand the content in the app. This includes wording, graphs, and formatting.

- ◯ Very Difficult (1)
- ◯ Difficult (2)
- ◯ Neutral (3)
- ◯ Easy (4)
- ◯ Very Easy (5)

6. Please rate your satisfaction level with the responsiveness of the app.

- Very Unsatisfied (1)
- Unsatisfied (2)
- Neutral (3)
- Satisfied (4)
- Very Satisfied (5)

7. Please rate how often the app operated as expected on a daily basis.

- Never (1)
- 25% of the time (2)
- 50% of the time (3)
- 75% of the time (4)
- Always (5)

8. Please rate how satisfied you are with the connection speed between the mobile phone and the sensors. This includes when you turn on the app, refresh the connection with the sensors.

- Very Unsatisfied (1)
- Unsatisfied (2)
- Neutral (3)
- Satisfied (4)
- Very Satisfied (5)

9. Please rate how useful the app features in the table were to you.

	Not Useful (1)	Slightly Useful (2)	Somewhat Useful (3)	Useful (4)	Very Useful (5)
Goal Setting (1)	○	○	○	○	○
Suggestions/Tips (2)	○	○	○	○	○
Progress Checking (3)	○	○	○	○	○
Workout Library (4)	○	○	○	○	○
Exercise Reminders (5)	○	○	○	○	○

10. Please rate how useful the parameters in the table were to you.

	Not Useful (1)	Slightly Useful (2)	Somewhat Useful (3)	Useful (4)	Very Useful (5)
Calories Burnt (1)	○	○	○	○	○
Heart Rate (2)	○	○	○	○	○
Distance Traveled (3)	○	○	○	○	○
Active Time (4)	○	○	○	○	○
Push Counts (5)	○	○	○	○	○
Push Efficiency (6)	○	○	○	○	○

11. Please rate how accurate or inaccurate the app was at predicting the parameters: Calories Burnt, Distance Traveled, Active Time, Push Efficiency, and Push Counts in the table.

	Very Inaccurate (1)	Inaccurate (2)	Neutral (3)	Accurate (4)	Very Accurate (5)
Calories Burnt (1)	○	○	○	○	○
Heart Rate (2)	○	○	○	○	○
Distance Traveled (3)	○	○	○	○	○
Active Time (4)	○	○	○	○	○
Push Counts (5)	○	○	○	○	○
Push Efficiency (6)	○	○	○	○	○

12. Please rank the parameters based on its usefulness to you.
1 being the most useful, 2 being the second most useful, and so on.
______ Calories Burnt (1)
______ Heart Rate (2)
______ Distance Traveled (3)
______ Active Time (4)
______ Push Counts (5)
______ Push Efficiency (6)

System Usability Scale

13. I would like to use this system frequently.

- ◯ Strongly Disagree (1)
- ◯ Disagree (2)
- ◯ Neutral (3)
- ◯ Agree (4)
- ◯ Strongly Agree (5)

14. I found the system unnecessarily complex.

- ◯ Strongly Disagree (1)
- ◯ Disagree (2)
- ◯ Neutral (3)
- ◯ Agree (4)
- ◯ Strongly agree (5)

15. I thought the system was easy to use.

- ◯ Strongly Disagree (1)
- ◯ Disagree (2)
- ◯ Neutral (3)
- ◯ Agree (4)
- ◯ Strongly Agree (5)

16. I think that I would need the support of another person to be able to use this system.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

17. I found the various functions in this system were well integrated.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

18. I thought there was too much inconsistency in this system.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

19. I would imagine that most people would learn to use this system very quickly.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

20. I found the system very cumbersome or burdensome to use.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

21. I felt very confident using the system.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

22. I needed to learn a lot of things before I could get going with this system.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

23. I think the system may help me become physically more active.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

24. I think the system is a desirable product for me.

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

<u>Part II: Content & Visualization</u>

The investigator will show the features. We will then ask you to evaluate each feature.

25. Please indicate the usefulness of the feature that show the distribution of your distance traveled.

- ○ Not Useful (1)
- ○ Less Useful (2)
- ○ Somewhat Useful (3)
- ○ Useful (4)
- ○ Very Useful (5)

26. Please indicate the usefulness the feature that shows the distribution of the calories burnt.

- ○ Not Useful (1)
- ○ Less Useful (2)
- ○ Somewhat Useful (3)
- ○ Useful (4)
- ○ Very Useful (5)

27. Please indicate the usefulness the feature that shows the heart rate.

- ○ Not Useful (1)
- ○ Less Useful (2)
- ○ Somewhat Useful (3)
- ○ Useful (4)
- ○ Very Useful (5)

28. Please indicate the usefulness the feature that shows the distribution of the time you spent at sedentary, light, moderate, and vigorous intensity levels.

- ◯ Not Useful (1)
- ◯ Less Useful (2)
- ◯ Somewhat Useful (3)
- ◯ Useful (4)
- ◯ Very Useful (5)

29. Please indicate the usefulness the feature that tells your push efficiency (feet/push).

- ◯ Not Useful (1)
- ◯ Less Useful (2)
- ◯ Somewhat Useful (3)
- ◯ Useful (4)
- ◯ Very Useful (5)

30. Please indicate the usefulness the feature that shows you the push count.

- ◯ Not Useful (1)
- ◯ Less Useful (2)
- ◯ Somewhat Useful (3)
- ◯ Useful (4)
- ◯ Very Useful (5)

31. Please indicate the usefulness of the suggestions/tips for goal setting, or resetting, based on your performance in the past.

- Not Useful (1)
- Less Useful (2)
- Somewhat Useful (3)
- Useful (4)
- Very Useful (5)

32. Please indicate the usefulness of the workout videos in the library for exercise training.

- Not Interested (1)
- Less Interested (2)
- Somewhat Interested (3)
- Interested (4)
- Very Interested (5)

33. Please indicate your interest level in adding a feature that keep track of your weight change.

- Not Useful (1)
- Less Useful (2)
- Somewhat Useful (3)
- Useful (4)
- Very Useful (5)

34. Any other feature(s) you are interested to have but are not mentioned? Please describe.

____

____

Mobile App Rating Scale
App Quality

Section A. Engagement - fun, interesting, customizable, interactive, has prompts (e.g., sends alerts, messages, reminders, feedback, enables sharing)

35. Entertainment: Is the app fun/entertaining to use?

- ○ Dull, not fun or entertaining at all (1)
- ○ Mostly boring (2)
- ○ Ok, fun enough to entertain user for a brief time ((3)
- ○ Moderately fun and entertaining, would entertain user for some time (5-10 mins) (4)
- ○ Highly entertaining and fun, would stimulate repeat use (5)

36. Interest: Is the app interesting to use? Does it present its information in an interesting way?

- ○ Not interesting at all (1)
- ○ Mostly uninteresting (2)
- ○ Ok, neither interesting nor uninteresting; would engage user for brief time ((3)
- ○ Moderately interesting, would engage user for some time (5-10 mins) (4)
- ○ Very interesting, would engage user in repeat use (5)

37. Customization: Does it allow you to customize the settings that you would like to (e.g., personal information, goals, content display, notifications)?

- ◯ Does not allow any customization, or requires setting to be input every time (1)
- ◯ Allows little customization and that limits app's functions (2)
- ◯ Basic customization and that limits app's functions (3)
- ◯ Allows numerous options for customization (4)
- ◯ Allows complete tailoring the user's characteristics/preferences, remembers all settings (5)

38. Interactivity: Does it allow user input, provide feedback, contain prompts (reminders, notifications, etc.)?

- ◯ No interactive features and/or no response to user input (1)
- ◯ Some, but not enough interactive features which limits app's functions (2)
- ◯ Basic interactive features to function adequately (3)
- ◯ Offers a variety of interactive features, feedback, and user input options (4)
- ◯ Very high level of responsiveness through interactive features, feedback and user input options (5)

39. Target group: Is the app content (visuals, language, design) appropriate for manual wheelchair users?

- ◯ Completely inappropriate, unclear, or confusing (1)
- ◯ Mostly inappropriate, unclear, or confusing (2)
- ◯ Acceptable but not specifically designed for manual wheelchair users. May be inappropriate/unclear/confusing at times (3)
- ◯ Designed for manual wheelchair users, with minor issues (4)
- ◯ Designed specifically for manual wheelchair users, no issues found (5)

Section B Functionality: app functioning, easy to learn, navigation, flow logic, and gestural design of app

40. Performance: How accurately/fast do the app features (functions) and components (buttons/menus) work?

- ○ App is broken; no/insufficient/inaccurate response (e.g., crashes/bugs/broken features) (1)
- ○ Some functions work, but lagging or contains major technical problems (2)
- ○ App works overall. Some technical problems need fixing, or is slow at times (3)
- ○ Mostly functional with minor/negligible problems (4)
- ○ Perfect/timely response; no technical bugs found (5)

41. Ease of use: How easy is it to learn how to use the app; how clear are the menu labels, icons and instructions?

- ○ No/limited instructions; menu labels, icons are confusing; complicated (1)
- ○ Takes a lot of time or effort (2)
- ○ Takes some time or effort (3)
- ○ Easy to learn (or has clear instructions) (4)
- ○ Able to use app immediately; intuitive; simple (no instructions needed) (5)

42. Navigation: Does moving between screens make sense; Does app have all necessary links between screens?

- ◯ No logical connection between screens at all/navigation is difficult (1)
- ◯ Understandable after a lot of time/effort (2)
- ◯ Understandable after some time/effort (3)
- ◯ Easy to understand/navigate (4)
- ◯ Perfectly logical easy, clear, and intuitive screen flow throughout, and/or has shortcuts (5)

43. Gestural design: Do taps/swipes/scrolls make sense? Are they consistent across all components/screens?

- ◯ Completely inconsistent/confusing (1)
- ◯ Often inconsistent/confusing (2)
- ◯ Ok with some inconsistencies/confusing elements (3)
- ◯ Mostly consistent/intuitive with negligible problems (4)
- ◯ Perfectly consistent and intuitive (5)

Section C Aesthetics: graphic design, overall visual appeal, color scheme, and stylistic consistency

44. Layout: Is arrangement and size of buttons, icons, menus, and content on the screen appropriate?

○ Very bad design, cluttered, some options impossible to select, locate, see or read (1)

○ Bad design, random, unclear, some options difficult to select/locate/see/read (2)

○ Satisfactory, few problems with selecting/locating/seeing/reading items (3)

○ Mostly clear, able to select/locate/see/read items (4)

○ Professional, simple, clear, orderly, logically organized (5)

45. Graphics: How high is the quality/resolution of graphics used for buttons, icons, menus, and content?

○ Graphics appear amateur, very poor visual design - disproportionate, stylistically inconsistent (1)

○ Low quality/low resolution graphics; low quality visual design - disproportionate (2)

○ Moderate quality graphics and visual design (generally consistent in style) (3)

○ High quality/resolution graphics and visual design - mostly proportionate, consistent in style (4)

○ Very high quality/resolution graphics and visual design - proportionate, consistent in style throughout (5)

46. Visual appeal: How good does the app looks?

○ Ugly, unpleasant to look at, poorly designed, clashing, mismatched colors (1)

○ Bad - poorly designed, bad use of color, visually boring (2)

○ Ok - average, neither pleasant, nor unpleasant (3)

○ Pleasant - seamless graphics - consistent and professionally designed (4)

○ Beautiful - very attractive, memorable, stands out, use of color enhances app (5)

Section D Information: contains high quality information (e.g., text, feedback, measures, references) from credible source

47. Quality of information: Is app content correct, well-written, and relevant to the goal/topic of the app?

○ Irrelevant/inappropriate/incoherent/incorrect (1)

○ Poor. Barely relevant/appropriate/coherent/may be incorrect (2)

○ Moderately relevant/appropriate/coherent/and appears correct (3)

○ Relevant/appropriate/coherent/correct (4)

○ Highly relevant/appropriate/coherent/correct (5)

48. Quantity of information: Is the information within the app comprehensive but concise?

○ Minimal or overwhelming (1)

○ Insufficient or possibly overwhelming (2)

○ Ok but not comprehensive or concise (3)

○ Offers a broad range of information, has some gaps or unnecessary detail; or has no links to more information or resources (4)

○ Comprehensive and concise; contains links to more information and resources (5)

49. Visual information: Is visual explanation of concepts – through charts/graphs/images/videos, etc. – clear, logical, correct?

- Completely unclear/confusing/wrong or necessary but misisng (1)
- Mostly unclear/confusing/wrong (2)
- Ok but often unclear/confusing/wrong (3)
- Mostly clear/logical/correct with negligible issues (4)
- Perfectly clear/logical/correct (5)

50. Credibility of source: Does the information within the app seem to come from a credible source?

- Suspicious source (1)
- Lacks credibility (2)
- Not suspicious but legitimacy of source is unclear (3)
- Possibly comes from a legitimate source (4)
- Definitely comes from a legitimate/specialized source (5)

App Subjective Quality
Section E

51. Would you recommend this app to people who might benefit from it?

- Not at all; I would not recommend this app to anyone (1)
- Not at all; There are very few people I would recommend this app to (2)
- Maybe; There are several people I would recommend this app to (3)
- Maybe; There are many people I would recommend this app to (4)
- Definitely; I would recommend this app to everyone who might benefit from it (5)

52. How often do you think you would use this app in the next 12 months if it's available to you?

- ○ None; I don't think this app is relevant to me (1)
- ○ Once in a few months (2)
- ○ Once in a few weeks (3)
- ○ Once in a few days (4)
- ○ Every day (5)

53. Would you pay for this app?

- ○ No (1)
- ○ Yes, only if it's less than $5 per month (2)
- ○ Yes, only if it's $5 - $10 per month (3)
- ○ Yes, even if it's more than $10 per month (4)

54. What is your overall (star) rating of the app?

- ○ ★ One of the worst apps I've used (1)
- ○ ★★ (2)
- ○ ★★★ Average (3)
- ○ ★★★★ (4)
- ○ ★★★★★ One of the best apps I've used (5)

Perceived Impact
Section F

55. Awareness: This app has increased my awareness of the importance of having an active lifestyle

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly agree (5)

56. Knowledge: This app has increased my knowledge/understanding of how to be physically more active

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

57. Attitudes: The app has changed my attitudes toward more regular physical activity participation

- Strongly Disagree (1)
- Disagree (2)
- Neutral (3)
- Agree (4)
- Strongly Agree (5)

58. Intention to change: The app has increased my intentions/motivation to be physically more active

- ◯ Strongly Disagree (1)
- ◯ Disagree (2)
- ◯ Neutral (3)
- ◯ Agree (4)
- ◯ Strongly Agree (5)

59. Help seeking: This app would encourage me to seek further help when I encounter barriers to physical activity participation

- ◯ Strongly Disagree (1)
- ◯ Disagree (2)
- ◯ Neutral (3)
- ◯ Agree (4)
- ◯ Strongly Agree (5)

60. Behavior change: Use of this app will increase my physical activity levels

- ◯ Strongly Disagree (1)
- ◯ Disagree (2)
- ◯ Neutral (3)
- ◯ Agree (4)
- ◯ Strongly Agree (5)

61. Further comments about the app?

____

Part III: Exercise Self-Efficacy Scale

62. I am confident that I can overcome barriers and challenges with regard to physical activity and exercise if I try hard enough.

- ○ Not at all true (1)
- ○ Rarely true (2)
- ○ Moderately true (3)
- ○ Always true (4)

63. I am confident that I can find means and ways to be physically active and exercise.

- ○ Not at all true (1)
- ○ Rarely true (2)
- ○ Moderately true (3)
- ○ Always true (4)

64. I am confident that I can accomplish my physical activity and exercise goals that I set.

- ○ Not at all true (1)
- ○ Rarely true (2)
- ○ Moderately true (3)
- ○ Always true (4)

65. I am confident that when I am confronted with a barrier to physical activity or exercise I can find several solutions to overcome this barrier.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

66. I am confident that I can be physically active or exercise even when I am tired.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

67. I am confident that I can be physically active or exercise even when I am feeling depressed.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

68. I am confident that I can be physically active or exercise even without the support of my family or friends.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

69. I am confident that I can be physically active or exercise without the help of a therapist or trainer.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

70. I am confident that I can motivate myself to start being physically active or exercising again after I've stopped for a while.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

71. I am confident that I can be physically active or exercise even if I had no access to a gym, exercise, training, or rehabilitation facility.

- Not at all true (1)
- Rarely true (2)
- Moderately true (3)
- Always true (4)

The End

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