Improvement in the Physical and Psychological Well-Being of Persons with Spinal Cord Injuries by Means of Powered Wheelchairs Driven by Dual Power Wheels and Mobile Technologies

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ABSTRACT

This study unites researchers from the fields of psychology, occupational therapy, and engineering to improve the holistic physical and psychological well-being of persons with spinal cord injury (SCI) by using assistive devices (i.e., wheelchairs) and mobile technology (i.e., cell phone and network). These technologies are used to bring persons with SCI through the difficult period of rehabilitation and to return them to their daily life in school or the working environment. First, a SpinoAid Application (APP) is developed to motivate persons with SCI to participate in the community after their injury. Second, we integrate mobile technology with a mobility assistive device to design a smart wheelchair, which is innovated by transforming the pushrim of a manually driven wheelchair into a rim motor. After the rim motor is combined with a battery, a brake, and a controller to become a power wheel, two power wheels are installed on both sides of the wheelchair to become a powered wheelchair. Third, a SmartChair APP is developed with the main functions of reminding persons with SCI to perform exercises, recording the physical condition and the wheelchair using status, and building up a social network for information sharing to increase their exercise habit, prevent cumulative injuries or discomfort of the upper extremities, and enhance their health and quality of life.

Keywords: spinal cord injury, smart wheelchair, mobile technology, holistic health.

1. INTRODUCTION

Traumatic spinal cord injury (SCI) is acute, unexpected, and dramatically alters the course of an individual's life. It causes sudden, often devastating damage to multiple body systems, and greatly affects psychological well-being and social function. Re-integration into society constitutes one of the key goals of rehabilitation for persons with SCI [1-3], as long periods of isolation can be psychologically detrimental to persons with SCI and their families. Reintegration is important particularly for young adults who encounter a sudden traumatic event in life that results in disabilities for the rest of their life. In Taiwan, the mean onset age is 27 years old, and most of the persons of SCI are caused by the injuries in motorcycle or car accidents or in falls. This change in life is difficult to accept for most people, and a great number of people suffering SCI have been isolated. They withdraw from the community and lack the motivation to participate in the society, even though community reintegration has been shown to be related to life satisfaction and quality of life among persons with SCI.

Using a wheelchair helps most persons with SCI to achieve independence in daily function and social participation by compensating for their mobility limitation. However, persons with SCI experience several adverse effects, such as cumulative injury, pain, and discomfort in the upper extremities, low back pain, scoliosis, accidental fall, and injuries. The resultant pain and inconvenience may lead to higher medical expenses, decreased daily functions and social participation, and worsening quality of life [4-6]. This study proposes three assistive devices from the "three M" aspects of reintegration for persons with SCI: (1) a SpinoAid APP that inspires their "motivation" for reintegration, (2) a smart wheelchair for their need for "mobility" for reintegration, and (3) a SmartChair APP that provides them with a healthy and safe "motion" for better quality of life under the guidance of occupational therapists during reintegration.

The SpinoAid and SmartChair APPs apply the intelligence of mobile technology to enhance the quality of life of persons with SCI. These technologies are integrated into an innovative mobility assistive device that becomes a smart wheelchair. The core technology of the proposed wheelchair is innovated by transforming the pushrim of a manually driven wheelchair into a rim motor. Through the large radius of the rim motor, the torque is produced by using a small amount of current. After the rim motor is combined with a battery, a brake, and a controller to become a power wheel, two power wheels are installed on both sides of the wheelchair to become a powered wheelchair. The multifunctional optimisation design of the rim motor and hybrid electromagnetic brake was first introduced in [7]. This novel wheelchair has the following desirable features: manual and electrical operation, foldability, and ability to override obstacles because of its large wheels. Using dual power wheels is crucial for controlling the speed and direction of the powered wheelchair on various road conditions [8, 9].

These devices were developed by experts from psychology, occupational therapy, and engineering to present a human-centered study for improving the holistic health of persons with SCI during their difficult process of reintegration. The rest of this paper is organized as follows: Section 2 describes the SpinoAid APP. Section 3 introduces the innovative smart wheelchair. Section 4 presents the SmartChair APP and its preliminary efficacy in increasing the participation of upper extremities exercises of persons with SCI. Section 5 gives the summary and conclusion.

(a) (b) (c) (d) (e)

Fig. 1. SpinoAid APP: (a) launching page, (b) main page, (c) our stories, (d) independent living, and (e) contact information.

2. SPINOAID APP

Given the widespread use of mobile technology, particularly smart phones, in Taiwan, an APP was developed to motivate persons with SCI and their families to reconnect with the community. The APP called SpinoAid aims to provide valuable information to newly injured or withdrawn SCI persons to motivate them to reintegrate into the society.

The study procedures were approved by the Research Ethical Committee of the National Taiwan University, and informed consent was obtained from each research participant. In-depth interviews were initially conducted with 15 persons suffering SCI (12 males and 3 females) to explore the factors that motivate and encourage persons with SCI to reconnect with the community after the injury, to identify the obstacles that hinder the reintegration of persons with SCI into the society, and to highlight the information that persons with SCI and their families need after the injury. The interviewees had been injured for a wide range of time period, ranging from 6 months to over 30 years, because of various causes, with 53% being injured from road traffic accidents. At the time of interviewing, four interviewers were in paid jobs, one was a university student, and several participated in voluntary work. Interviews were conducted at the university or in suitable places for the interviewees and lasted for about two hours.

The factors encouraging persons with SCI to participate in the community after the injury include (1) support and encouragement from family, (2) concern and care for family members, (3) life stories of persons with SCI, and (4) personality characteristics of persons with SCI. The obstacles hindering the reintegration of persons with SCI into the community are (1) psychological barriers for persons with SCI (e.g., feeling discriminated, concerned about others' reactions, and reluctant to ask for help), (2) insufficient self-care skills to avoid embarrassment from accidental urination or bowel movement and the lack of mobility techniques, (3) overprotection of the family, and (4) barriers in the living environment (e.g., apartments without elevators). The information needed by persons with SCI and their families following the injury consists of the following: (1) definition of SCI, (2) real-life stories of SCI peers, (3) selection of assistive devices, (4) subsidy provided by the government (e.g., subsidy for the purchase of wheelchairs or for the reconstruction of the home environment), (5) tips in dealing with urination, bowel movement, chronic pain, and pressure sores, among others, and (6) others (e.g., employment, schooling, and recreation).

On the basis of the factors identified from the interviews, we developed a prototype of the APP and shot two video clips of the journey that our two interviewees experienced from the initial stage of frustration to the stage of reintegration. Usability testing was then conducted with four of the interviewers and 158 participants with SCI. The APP was modified according to the test results and further tested with four newly injured SCI persons. Figure 1 shows a few selected pages of the final version in traditional Chinese with English translation. The architecture consists of four to six levels. At the top level, the launching page shows the logo of a rising sun symbolizing hope (Fig. 1(a)). The second level shows the three major sections of the APP: *Independent Living*, *Our Stories*, and *Contact Information* (Fig. 1(b)). The spatial layout was designed to highlight that the section of Our Stories was the core of this APP. The third level of this section shows two sub-sections: *The Journey* and *Wonderful Life* (Fig. 1(c)). The Journey includes selected publically available online videos of SCI persons telling their stories of the journey to reintegration and the two clips made for this project. Clicking on the icon of Wonderful Life will take users to three sub-sections on how SCI persons enjoy their life at work or in leisure activities: dreams fulfilling, traveling, and experiencing the limits. For example, clicking on one icon under experiencing the limits will show SCI persons hang gliding and diving, and another will present a slide show of athletic activities we shot in a national sport event for persons with SCI. Fig. 1(d) shows the sub-sections of Independent Living, with each consisting of information for SCI persons to gain skills. Fig. 1(e) shows the sub-sections of Contact Information for connecting with SCI organizations in the local regions of Taiwan and sources where they can obtain help on psychological consultation.

The aim of this APP is to motivate newly injured SCI persons and their families to reintegrate into the community soon after the injury. We hope that the users can gain an insight that they are not alone through the stories shared by their peers who overcome the difficulties. We also hope that the users can obtain valuable information that assists their reintegration into the community. Efforts will be made in the future to promote this

APP among medical professionals, hospital personnel, and district associations of persons with SCI in Taiwan.

3. SMART WHEELCHAIR

Requirements

Most persons with SCI are still young with strong arms. They may not require the traditional powered wheelchair, which is usually heavy, bulky and unfoldable, but they do need a foldable wheelchair that can shift between manual driving mode and power driving mode. A doctor or an occupational therapist can give the wheelchair user a prescription for manual driving duration per day to prevent secondary physical damage.

According to the needs requested by persons with SCI through the interviews, the smart wheelchair was designed with the following features:

1) Shifts between manual and power modes
   The number of pushes by arms or the manual driving distance is recorded. Once it exceeds the doctor's prescription, a warning signal is sent to the user to shift to the power driving mode.
2) Foldable
   Persons with SCI may be able to drive a car to extend their space of activity. A foldable wheelchair can be placed in the trunk and used in the journey.
3) Remotely controllable
   When staying in a hotel room, wheelchair users may want to send the wheelchair away from bed while they are sleeping. A remote control by a smart cell phone can maneuver the wheelchair back and forth in a distance.
4) Safe braking
   The wheelchair must be able to be driven and stopped safely. Both dynamic braking and short circuit braking can be used to decelerate the wheelchair. After the wheelchair comes to a full stop, the power is switched off and the electromagnetic brake is released to lock the wheel mechanically. After the power is switched on at the driving mode, the electromagnetic brake is restored to unlock the wheel.
5) Cross-coupling control of the dual power wheels
   When each of the left and right wheels experiences a road surface of different roughness, the wheelchair deviates from the commanded path. The cross-coupling control strategy is responsible for adjusting the speed ratio of the dual power wheels to maintain a direction of motion that the driver commands under any road circumstance.

Configuration of the Smart Wheelchair

The innovative smart wheelchair is driven by dual power wheels (Fig. 2(a)), each of which is composed of a rim motor (Fig. 2(b)), a motor drive, and a brake unit (Fig.2(c)). The dual power wheels are controlled by an upper control unit with an upper controller and a joystick as the driving interface between the driver and the wheelchair. The rim motor inside the wheel is a novel design that exerts force around the wheel rim, which resembles the force given by the user to generate an enlarged torque on the large rim radius. The motor drive, which is the lower controller or motor control unit (MCU), is responsible for controlling the power wheel according to the command from the upper controller. The MCU is installed beside the brake unit.

The brake unit in Fig. 2(c) consists of an electromagnetic brake and a brake-release mechanism. The electromagnetic brake comprises two solenoid valves, springs, and clutch. When the braking command is given by the upper controller, the dynamic braking and/or short-circuit braking are/is executed, so that a braking force is exerted by the rim motor. After the wheelchair comes to a full stop or the power is switched off, the electromagnetic brake on the brake unit locks the wheelchair mechanically for safety. Once the upper controller gives a driving command, the electromagnetic brake unlocks the wheel to resume driving the wheelchair. The brake-release mechanism is used to unlock the wheel manually when the user wants to shift to the manual driving mode from the power driving mode.

Mobile Technology of the Wheelchair

Mobile technology is used to control the wheelchair remotely through an operation APP on a smart cell phone. The control window is shown in Fig. 2(d). Using his/her cell phone through Bluetooth, the user is able to drive the wheelchair, to send it away, or to call the wheelchair back remotely at any proper time.

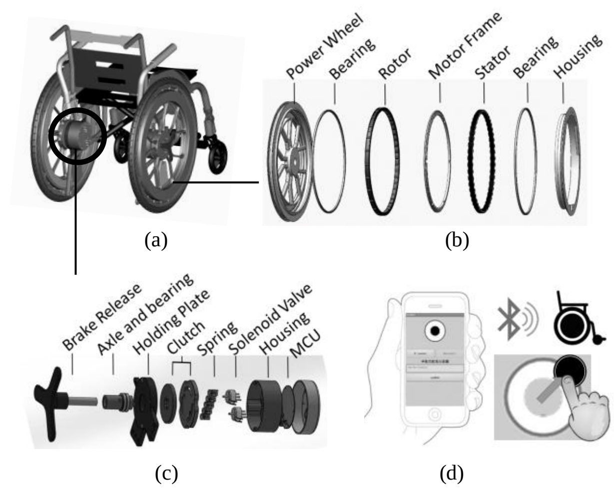

Fig. 2. (a) Configuration of the smart wheelchair driven by dual power wheels, (b) rim motor in the power wheel and its components, (c) brake assembly, and (d) remote control on the smart phone.

In the manual driving mode, the number of pushes by arms is accumulated and recorded by the MCU. Once number exceeds that prescribed by an occupational therapist or a doctor, a warning signal reminds the user to shift from the manual driving mode to the power driving mode to prevent the user's arms from being overused.

Rim Motor Model

The rim motor in each power wheel is a three-phase permanent magnet synchronous motor of sinusoidal back electromotive force (back EMF). The mathematical model of the rim motor is made under the following assumptions:

1) No power loss is considered for the motor and the inverter.
2) The motor operates in the linear range of magnetic materials.
3) The three-phase stator resistances and the self and mutual inductances are equal and constant in the equivalent circuit.

The electrical model of the rim motor is expressed as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}, \tag{1}$$

where i_a, i_b, and i_c are the three-phase currents; e_a, e_b, and e_c are the three-phase back EMFs; R is the phase resistance; L is the self-inductance; and M is the mutual inductance. The mechanical model of the rim motor is expressed as

$$\tau - T_L = J_w \dot{\omega}_m + B_m \omega_m , \tag{2}$$

where T_L is the load torque, J_w is the mass moment of inertia of the rotor, B_m is the damping coefficient, and ω_m is the angular velocity of the motor. Under the assumption of no power loss, the corresponding torque production is approximately expressed as

$$\tau = \frac{p}{2} \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} , \tag{3}$$

where p is the number of poles.

Wheelchair Model

The skeleton of the wheelchair is illustrated in Fig. 3, where ω_L and ω_R are the angular velocities of the left and right wheels, respectively; C is the center of mass of the wheelchair at the center of the two wheels; W is the tread of the wheels; R_w is the wheel radius; and Φ is the attitude angle of the wheelchair. The dynamical model of the wheelchair is built according to the following assumptions:

1) The wheelchair moves on a two-dimensional plane.
2) Tire deformation and dynamics are ignored.
3) Pure rolling without slip occurs between the tire and the ground surface.

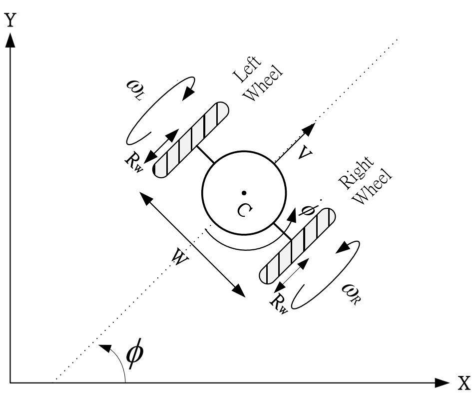

Fig. 3. Skeleton of the wheelchair driven by rim motors.

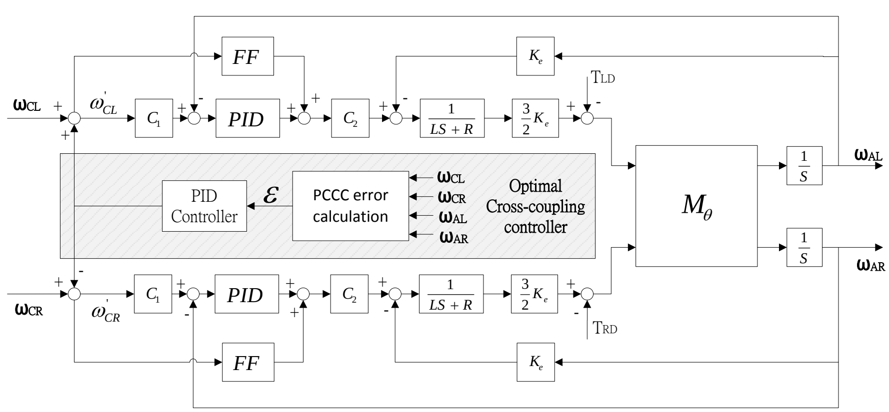

Fig. 4. Optimal cross-coupling control structure.

The dynamical model of the wheelchair is described by

$$\begin{bmatrix} \tau_R \\ \tau_L \end{bmatrix} = M_\theta \begin{bmatrix} \dot{\omega}_R \\ \dot{\omega}_L \end{bmatrix}, \tag{4}$$

and the equivalent inertia matrix is

$$M_\theta = R_w^2 \begin{bmatrix} \frac{M_c}{4} + \frac{J_c}{2} + \frac{J_w}{R_w^2} & \frac{M_c}{4} - \frac{J_c}{W^2} \\ \frac{M_c}{4} - \frac{J_c}{W^2} & \frac{M_c}{4} + \frac{J_c}{2} + \frac{J_w}{R_w^2} \end{bmatrix}, \tag{5}$$

where τ_L and τ_R are the torque production from the left and right power wheels, respectively; M_c is the mass of the wheelchair; and J_w and J_c are the mass moment of inertia of the power wheel and the wheelchair, respectively.

Cross-coupling Control Strategy

The powered wheelchair is operated with two control objectives: the speed of each wheel and the moving direction of the powered wheelchair. Each wheel speed is controlled by a proportional-integral-derivative (PID) feed-forward speed controller, and the wheelchair direction is commanded by the optimal cross-coupling controller that controls the two wheels' speed ratio. Fig. 4 presents the control structure, in which the PID controller is expressed as

$$D(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s \right), \tag{6}$$

where K_p is the proportional gain, T_i is the reset time, and T_d is the differential time.

Fig. 5 explains the concept of the proposed cross-coupling control (PCCC) ordinate axis represents the right wheel's speed ω_R, and the horizontal axis represents the left wheel's speed ω_L. The circle at D is a reference speed point (ω_{DR}, ω_{DL}), and the rectangle at C presents the current speed point (ω_{CR}, ω_{CL}). The dotted line connecting the origin O and the reference speed point D is the desired direction of motion of the wheelchair, and its slope is the reference speed ratio. Infinite curves from the current speed point to the reference speed line are used for setting the wheelchair to the desired direction of motion.

Traditionally, the shortest way is the dashed grey line (CA), which is perpendicular to the line of the reference speed ratio (OD). However, the speed compensation of the right power wheel is different from that of the left power wheel. When one wheel reaches a speed, the other wheel must take a longer time to reach its speed, so that the speed ratio equals the reference speed ratio. The proposed cross-coupling control is responsible for predicting the reference speed and commands each power wheel to the reference ratio within the same time duration. This control is called the time-optimal compensation to make CE equal to EB in Fig. 5. The calculation of the speed ratio error with the minimal time compensation is given by

$$\varepsilon = \frac{\omega_{CR}\omega_{DL} - \omega_{CL}\omega_{DR}}{\cos 45^\circ (\omega_{DR} + \omega_{DL})} . \tag{7}$$

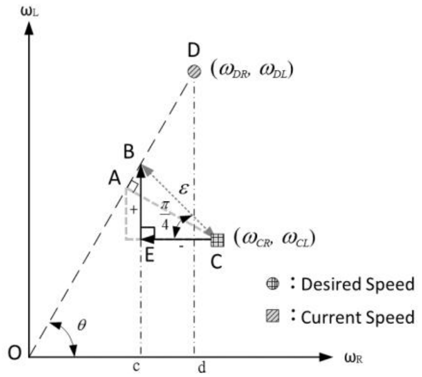

Fig. 5. The traditional and the proposed cross-coupling control methods.

Experiments

The time-optimal cross-coupling control strategy is proved by the following experiment. Two MCUs control the speeds of the left and right power wheels, and the upper controller controls their speed ratio. Fig. 6 illustrates the experimental site of an artificial grass pad that simulates a road disturbance on the floor. A driver weighing 70 kg drove the wheelchair at a speed ratio command of 1.2. During the operation, the left wheel of the powered wheelchair encountered the artificial grass. As shown in Fig. 7, the wheelchair deviated from the reference path without the proposed cross-coupling control, and the speed ratio was well controlled according to the reference when the cross-coupling control was active.

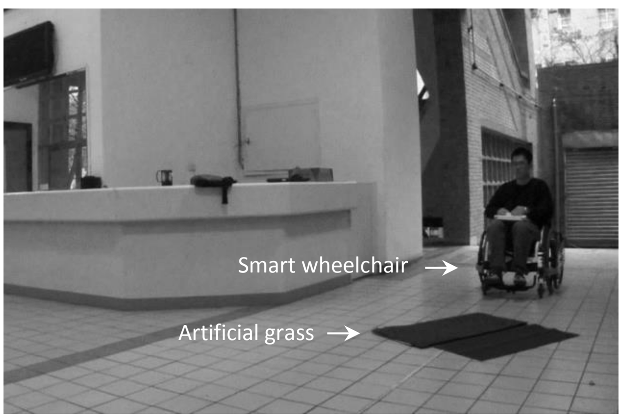

Fig. 6. Experimental site.

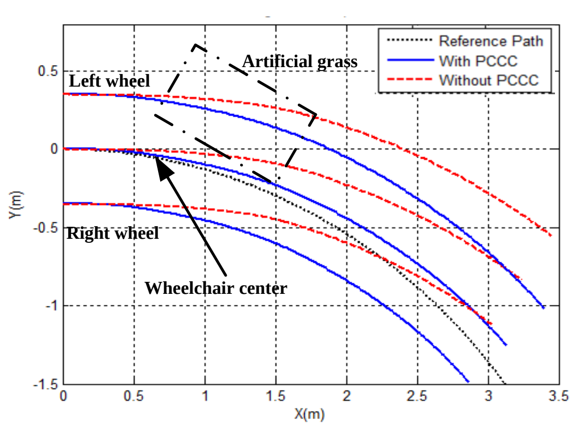

Fig. 7. Trajectories of the left and right wheels before and after the wheelchair drives through the artificial grass with and without the proposed cross-coupling control.

4. SMARTCHAIR APP

Although many APPs for fitness or health promotion of healthy people are available, only a few APPs (most of them provide health information only) have been designed for persons with SCI. We surveyed 121 persons with SCI and found that 74% of the interviewees reported having pain problems in the upper extremities (54.9% in the wrist joints and 55.7% in the shoulder joints). Therefore, we developed the SmartChair APP [10], an intelligent assistance system designed for persons with SCI to prevent the cumulative trauma of upper extremities and to enhance a healthy and safe use of wheelchairs.

To prevent the adverse effects of wheelchair propelling, the following are the strategies proposed in the literature: (1) to decrease excessive or long-distance wheelchair propelling, (2) to perform stretching or strengthening exercises on the upper limbs regularly to decrease the risk of cumulative injuries and relieve discomfort, (3) to increase self-awareness of pain or discomfort, and (4) to check the wheelchair regularly to decrease the risks of incidents (e.g., fall) [4, 11-12]. Moreover, the exercise protocol should be designed for each individual according to his/her physical conditions and reactions to such exercises (i.e. pain or discomfort). Therefore, professionals (occupational or physical therapists) could monitor the related information through the SmartChair APP and then adjust the threshold of the alarm system for over-propelling or modify the exercise protocol for each person as needed.

Initially, we interviewed eight persons with SCI about the need for and opinions on using the APP. The SmartChair APP is proposed to fulfill the following main functions: (1) record the activity level (distance of wheelchair propelling) and energy consumption to warn against excess propelling, (2) record the pain or discomfort of the joints of the upper limbs, (3) give a reminder about the performance of upper limb exercises designed specifically for paraplegia or tetraplegia, (4) build up a social network for information sharing and reinforce a regular exercise habit, and (5) give a reminder about a wheelchair check-up to ensure safety. Fig. 8 shows some screenshots of our SmartChair APP.

Note that for the persons with SCI, using the APP may cause secondary damage of the upper extremity. As individuals have their own unique habits, we tried to provide a customized interface to reduce the number of clicks in using the SmartChair APP. Our system adopted the xAPI [13], which is a standard of the eXperience Application Program Interface, to represent and store the records of users' habits. These records were analyzed to determine the suitable interface layout of our SmartChair APP to provide a good user experience. A simple example is shown in Fig. 9. Users' habits are represented as records in xAPI format, and these records are stored in a database and can be studied through the Web.

Our proposed method is based on intelligence Context Awareness-based Suggestion Engine (iCASE) [14], which considers the user context and the time context. Through the context-awareness of both the mobile device and the wheelchair, information for different situations is collected to provide appropriate services. The next favorite action is recommended on the first page of the APP, thus lightening the user's burden of using the APP. The collected data and analysis can be applied for patients' relatives, medical team, and even medical-related software/hardware developers.

Fig. 8. Screenshots of our SmartChair APP.

Fig. 9. Users' habits are represented as records in xAPI format. These records are stored in the database and can be studied through the Web.

We conducted a preliminary study to evaluate the effect of applying the SmartChair APP on enhancing the participation of upper extremity exercises. The National Taiwan University Hospital's Institutional Review Board approved the study, and a written informed consent was obtained from all participants.

A convenient sample of 23 participants (13 paraplegia and 10 tetraplegia) was recruited, and all the participants attended a two-week mobile application-based intervention. The intervention included the following: (1) A face-to-face educational session, which instructed the participants on how to prevent upper limb injuries and to practice stretching or strengthening exercises through the APP, was conducted. (2) To increase adherence to the exercise program, each participant has to perform the exercise daily and record it on the APP; otherwise, he/she will receive text reminders. The psychological factors were assessed in terms of the Health Action Processes Approach (HAPA). The HAPA is a model that comprises a motivational phase and a volitional phase used to explain health behavior changes. All participants were administered a self-developed questionnaire to identify the phase of behavior change and to measure the motivational and volitional variables, including risk awareness, outcome expectancies, self-efficacy, intention, planning, and action control regarding upper extremity exercise.

Among the 23 participants, 10 were actors (people who already exercise regularly) and 13 were intenders (people who are insufficiently active but intend to exercise). Compared with the actors, the intenders had lower scores in "risk awareness" (p<0.05) and "task self-efficacy" (p<0.05) related to the motivational phase in the pretest. At the end of the intervention, 9 of 13 (69.2%) intenders had become actors of regular upper extremity exercise. In addition, the scores of "risk awareness" (p<0.01) and "action self-efficacy" (p<0.05) improved significantly at the end of the intervention. The two-week SmartChair APP intervention demonstrated a preliminary effect of health behavior change (intenders becoming actors) even if the intervention period was short. Using the SmartChair APP or mobile social network application can be a potential strategy to enhance the motivation and promote the healthy habits (exercises) of wheelchair users with SCI. Future studies should be conducted with a larger sample size and a longer intervention period.

5. CONCLUSIONS

This study introduces three assistive devices from the three M aspects of reintegration for persons with SCI developed by a group of multidisciplinary researchers from the fields of psychology, occupational therapy, and engineering. The SpinoAid APP inspires persons with SCI to be "motivated" for social reintegration. A prototype novel wheelchair driven by dual power wheels provides the "mobility" they need for their reintegration. The SmartChair APP provides them with healthy "motion" and social participation. These assistive devices aim to improve the holistic physical and psychological well-being of persons with SCI, to see them through the difficult period of rehabilitation, and to return them to their daily life and social roles. Preliminary tests on the usability of these devices were conducted on a number of persons with SCI, that is, 15 for the SpinoAid APP and 23 for the SmartChair APP. The novel powered wheelchair driven by dual power wheels is currently in the final process of technology transfer to a local company. Clinical tests will be performed in local hospitals or rehabilitation centers. Further improvement, investigation, and clinical trials are necessary to be performed in the future.

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