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QM-FOrMS: A portable and cost-effective upper extremity rehabilitation system

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ABSTRACT

Long-term rehabilitation opportunities are critical for millions of individuals with chronic upper limb motor deficits striving to improve their motor performance. While formal rehabilitation is well organized in the acute stages of stroke, there is minimal professional support of rehabilitation across the lifespan. In this paper, we introduce an upper extremity rehabilitation system, the Quality of Movement Feedback-Oriented Measurement System (QM-FOrMS), by integrating cost-effective portable sensors and clinically verified motion quality analysis towards individuals with upper limb motor deficits. Specifically, QM-FOrMS is comprised of an eTextile pressure sensitive mat, named Smart Mat, a sensory can, named Smart Can, and a mobile device. A personalizable and adaptive upper limb rehabilitation program is developed, including both unilateral and bilateral functional activities which can be selected from a list or custom designed to further tailor the program to the individual.

1. Introduction

The population in the US is aging, and with increased age there is diminished motor control (Krampe, 2002) in addition to higher risk for neurological insult such as stroke (Santalucia et al., 2015). In 2010, approximately 17 million people had a stroke worldwide adding to the over 33 million survivors of stroke (Javed, 2015). Creating automated systems that measure and give feedback on quality of movement will promote a more proactive approach to maximizing function across the lifespan of individuals with chronic conditions. In rehabilitation centers, QM-FOrMS can expand practice time beyond therapy sessions. Repeated studies demonstrate that patients in inpatient rehabilitation programs are engaged in therapies for a limited amount of their waking hours (Kimberley & Samargia, 2010). With a robust body of research underscoring the importance of practice (Langan, DeLave, Phillips, Pangilinan, & Brown, 2013a, 2013b), providing adequate practice in rehabilitation is central to efficacious interventions (Bell, Wolke, Ortez, Jones, & Kerr, 2015). Encouraging patients to practice activities outside of therapy times has been advocated for in rehabilitation (Connell, McMahon, Harris, Watkins, & Eng, 2014; Oagaz, Sable, Choi, Xu, & Lin, 2018; Vu et al., 2018). Providing a system to track activity and provide feedback

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can promote participation, refine practice and give individuals a better understanding of their abilities to then set goals for themselves (Liu & Chan, 2014).

As demonstrated by previous research, exercise programs that include feedback from a person through a home visit, telephone call or clinic appointment have resulted in better outcomes compared to programs without feedback (Novak, 2011). As it is possible to make motor improvements beyond the acute phase of recovery (Brown, Lewis, McCarthy, Doyle, & Hurvitz, 2010), it is necessary to provide better options for home rehabilitation. Technology-based in-home exercise programs have been shown to be an enjoyable means to have patients partake in rehabilitation activities (Cuthbert et al., 2014). A rehabilitation specific system can first be introduced to individuals in inpatient rehabilitation to offer opportunities for practice. Additionally, it can be sent home with the patient when they are discharged from formal therapies. This approach is a vast improvement compared to the typical written home program issued at discharge. With a static written home exercise program, patients have a limited capacity to evaluate their motor performance and no encouragement to refine their movement.

Our solution is a portable and cost-effective upper extremity rehabilitation system for individuals with chronic upper limb movement deficits. QM-FOrMS innovates and progresses rehabilitation approaches to improve motor function. Specifically, our goal is to develop portable technology that is affordable for home use, flexible for supporting customized exercise programs, and capable of quantifying quality of movement. QM-FOrMS is comprised of an eTextile-based pressure mat, named Smart Mat, a sensory can, named Smart Can, and a mobile device. The Smart Mat provides pressure response and LED light patterns guidance to lead the user's rehabilitation process. Smart Can is embedded with an inertial motion unit (IMU) sensor to capture motion information used in calculating metrics of quality of movement. An android application on the mobile device (e.g. smartphone, tablet) is developed to serve as the rehabilitation graphical user interface (GUI). The GUI is designed with both the clinician and patient in mind. The GUI guides both the creation of customized exercise programs and steps to execute the exercise program. It also allows to configure the system parameters, which are elaborated in subsection 5.3. Performance measures calculated by the system include time to complete, force, accuracy, and normalized jerk score. In this work, we perform a pilot study to validate the functionality and usability across three groups ($n = 15$), including five healthy young adults, six older healthy adult and four individuals with movement impairment. The evaluation results show that patients with upper limb motor deficits have larger jerk scores and require more time to complete a task compared with healthy young and older adults. QM-FOrMS is a promising system solution for independent home-based rehabilitation.

The organization of the remaining paper is as follows. Section 2 introduces the related work on sensor-based rehabilitation systems. Section 3 presents the design consideration. In Section 4, we elaborate the system design including the hardware design and software design. Section 5 presents the rehabilitation exercise design including customized exercise programs and parameters configuration. Section 6 elaborates scoring features. Section 7 presents the evaluation results on time to complete, force, and accuracy. Section 8 discusses the novelty and further development of the system. The paper is concluded in Section 9.

2. Related work on sensors-based rehabilitation systems

Mavroidis et al. (Mavroidis et al., 2005) described how miniature sensor technology can be used to design a new generation of smart rehabilitation devices, including a passive motion elbow device, a knee brace that provides variable resistance by controlling damping via the use of an electro-rheological fluid, and a portable knee device that combines electrical stimulation and biofeedback. Zhou et al. (Zhou, Hu, & Harris, 2005) built a wearable 3-axis inertial sensor-based human arm movement tracking system to aid the rehabilitation of stroke patients. The tracking algorithm is based on a kinematical model that considers the upper and lower forearm. Lee et al. (Lee, Low, & Taher, 2010) developed a wearable wireless sensor network using accelerometers to determine the arm motion in the sagittal plane. Other accelerometer-based wearable watch/bracelet-like systems have also been developed (Ballester, Lathe, Duarte, Duff, & Verschure, 2015; Markopoulos, Timmermans, Beursgens, Van Donselaar, & Seelen, 2011). However, these systems lack adaptivity and cannot be customized for personalized training programs. Giorgino et al. (Giorgino, Tormene, Lorussi, De Rossi, & Quaglini, 2009) used a strain sensing technology, conductive elastomers, for posture recognition in the context of neurological rehabilitation. Tognetti et al. (Tognetti et al., 2005) introduced an unobtrusive garment able to detect the posture and the movement of the upper limb, with particular care to its application in post stroke rehabilitation field by describing the integration of the prototype in a healthcare service. Sung et al. (Sung, Marci, & Pentland, 2005) proposed LiveNet, a flexible wearable platform intended for long-term ambulatory health monitoring with real-time data streaming and context classification. LiveNet incorporates many sensors including a three dimensional (3D) accelerometer, electrocardiogram, electromyography, and galvanic skin conductance. This system is sensor-rich and flexible for users. However, it fails to provide quantitative measurements for the user self-management. Huang et al. (Huang et al., 2012) developed rehabilitation games using a set of stand-alone hardware including a SmartGlove and a Kinect for hand motion and finger angle extraction. However, no motivational feedback is provided. On the other hand, QM-FOrMS is adaptive and programmable for different users. In addition, it can provide both quantitative and motivational visual feedback to motivate users to practice more.

3. Design considerations

Therapists in rehabilitation settings have asked patients playing with the Wii system to concentrate on “function and form” rather than the “high score” (Cuthbert et al., 2014). This indicates that current feedback in commercial video games does not meet the unique needs in rehabilitation. As we aim at developing an effective in-home rehabilitation system across the lifespan, some factors should be taken into account including low cost, functional tasks, in-home usability, unattended program, actionable feedback, personalization, and adaptivity.

Low-cost: The cost of a user-friendly rehabilitation system should be low enough so that patients can afford it. We built QM-FOrMS at an affordable price by using low-cost off-the-shelf commercial products, including 9 degrees of freedom IMU MPU-9250 (InvenSense and Sparkfun imu, 1376) and eTextile (Lin, Wang, Zhuang, Tomita & Xu, 2016a; Xu, Lin, Wang, Hu, Huang & Xu, 2016; Lin, Wang, Cavuoto & Xu, 2017a), and 3D printed products. 3D printing technique offers low-cost customized manufacturing without the expense of creating a new mold for a customized product.

Functional Tasks: For individuals with diminished upper limb function, efficiently manipulating instrumented objects unilaterally or bilaterally is an important aspect of rehabilitation, which provides an experience that readily translates to activities of daily living (ADL) (Chou, Hwang, & Wu, 2012). This is a departure from commercial gaming systems that have been used in it (Wingham, Adie, Turner, Schofield, & Pritchard, 2015), yet are not designed for rehabilitation. For Wii games, the controller is held in one hand and games may be played with a modest amount of wrist motion in a movement pattern that is not directly related to ADLs. The Kinect system (Microsoft and Kinect, 2016) generally is able to monitor the whole body movement, but object manipulation is not addressed. QM-FOrMS provides feedback on the quality of movement rather than an arbitrary game score. While offering innovations in hardware and software, QM-FOrMS allows participants to simulate functional tasks.

In-home Usability: Robotic systems have been created to calculate metrics of quality of movement (Merlo et al., 2013). However, this robotic system is not feasible for home use. The design of QM-FOrMS aims at in-home rehabilitation setting across the lifespan. The activities in our system are functional activities of daily living. Meanwhile, our system can be easily set up on a table or on a kitchen counter for daily use. Thus, practicing these activities can promote independence in daily tasks and be readily carried over in daily life. In addition, Smart Mat in QM-FOrMS is flexible, foldable and rollable, which facilitates the usage and storage in an in-home use environment without occupying too much room space.

Unattended Program: As we targeting QM-FOrMS to be an in-home rehabilitation system, it would be an unattended program. Before starting with the exercise, users can accept configuration from clinicians and select exercise tasks by their own through mobile device GUI App. After exercise, timely feedback can be displayed on the mobile device and saved in a local storage simultaneously, which encourages better self-management of ongoing rehabilitation for users. Moreover, detailed feedback report can also be sent to clinicians through GUI App for remote rehabilitation progress assessment.

Movement Quality Measurement: The normalized jerk score is a measure of smoothness, which provides information on the control of movement, an indication of motor impairment/improvement for stoke patients (Celik et al., 2010). Measurements of movement that include jerk score have been correlated with the status of the disease and reveal significant difference or changes in both individuals and groups of subjects for upper extremity activity levels (Acuna, Amasay, & Karduna, 2010).

Quantitative Feedback: Quantitative measurements and feedback including both quality of movement and time to completion are important in the overall motor performance. Commercial games that represent portable systems used in rehabilitation provide a game score that is difficult to interpret how movement is related to the score. The actionable feedback from QM-FOrMS can motivate patients to practice more and encourage better self-management (Parker, Mawson, Mountain, Nasr, & Zheng, 2014). To be specific, the quantitative feedback allows the participant to track their progress in making smoother movements. This feedback can engage the individual more in their therapy program and promote working on smoother, more efficient movements (Snyder, Colvin, & Gammack, 2011).

Personalization and Adaptivity: A customer centered rehabilitation system should be adaptive to personalize training. The needs of each patient are determined by their unique set of abilities and limitations in movement. QM-FOrMS can customize exercise programs with a mobile App and instrumented objects with 3D printing to meet the needs of the user.

4. QM-FOrMS rehab system design

In this section, we will elaborate the system design of this portable and cost-effective upper extremity rehabilitation system including both hardware and software design.

4.1. System overview

QM-FOrMS is designed to provide the following two functions: first, QM-FOrMS is able to collect sensory information such as pressure and inertial motion information during rehabilitation. Second, the computing engine in QM-FOrMS will analyze the collected motion data and assess the quality of movement. The overall system diagram is shown in Fig. 1, which contains three layers: a clinician layer, a user layer, and a data layer. In the clinician layer, clinicians can create an exercise program by configuring software in the clinician GUI. The software sends commands to the microcontroller connected to the Smart Mat, the LED lights then are configured by the microcontroller to illuminate following specific patterns. The detailed report of quality of movement feedback to the clinician is displayed on the clinician GUI. In the user layer, the patients select and perform exercises from their program. The basic report of quality of movement is displayed on the user GUI for the user. In the data layer, a computing engine manages four functional modules including data collection, feature extraction, post-processing, and performance scoring. The data collection records raw pressure data and IMU data from the hardware. Feature extraction extracts scoring features, which are described in Section 6, from the collected raw data. The post-processing includes data filtering and data fusion. The performance scoring calculates the quality of movement reports for both clinicians and patients.

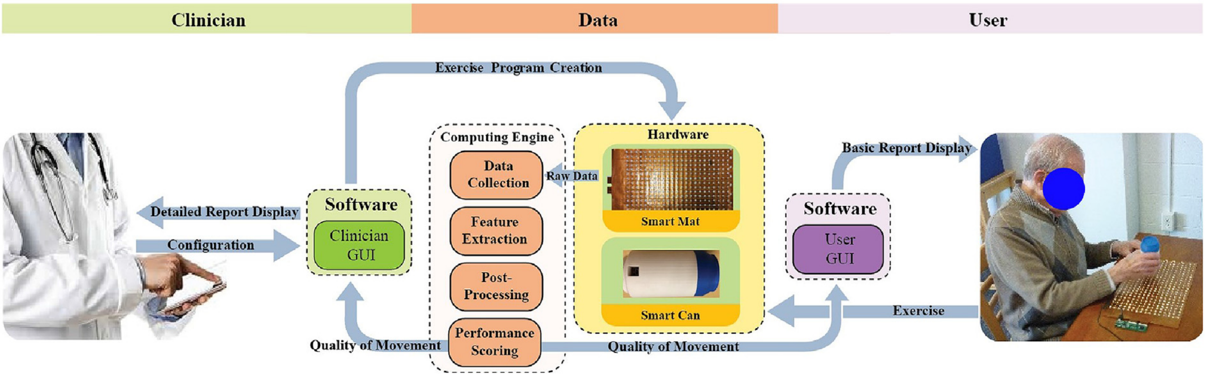


Fig. 1. The overall system diagram including a clinician layer, a user layer, and a data layer. First, a clinician can configure specific rehabilitation task setting to Smart Mat through clinician GUI on a mobile device. Then, a user selects tasks and performs rehabilitation exercises by manipulating Smart Can on Smart Mat. In the mean time, sensory data are collected in mobile device and analyzed by computing engine with specific functional modules of feature extraction, post-processing, and performance scoring. After that, the quality of movement evaluation is sent to the clinician through clinician GUI in the form of a detailed report and to the user through user GUI in the form of a basic report, respectively.

4.2. Hardware design

4.2.1. Smart mat

The Smart Mat is a flexible 40 cm by 24 cm pressure sensor array, based on electronic textile (or eTextile) technology (Xu et al., 2011). There are 384 pressure sensors distributed evenly on the mat with 24 in each row and 16 in each column. Each pressure sensor is calibrated so that the linearity error is less than 3% (Huang, Chen, Xu, & Sarrafzadeh, 2011). The Smart Mat can detect the presence of the pressure caused by the Smart Can or hand on the mat. In QM-FOrMS, we will use the pressure information to determine the completion time, force, and accuracy of the tasks. Each LED light is located at the center of the area surrounded by four pressure sensors. Thus, each of the 96 LED lights is surrounded by four pressure sensors The Smart Mat is connected to a microcontroller, which controls the LED working patterns and collects pressure data from the sensors. Fig. 2 shows the pressure point response on a mobile device when external force is applied on the Smart Mat. Three fingers touched the Smart Mat and three pressure dots appear on the screen of the mobile device at the corresponding location as on the Smart Mat. The Smart Mat is made of a flexible circuit board and eTextile material, as shown in Fig. 2, which makes it flexible, foldable and rollable. The data acquisition device collects pressure information and transfers to the mobile device via a micro-USB cable. The Smart Mat and data acquisition device are also powered by the smartphone via the micro-USB cable. Such novel design provides the portability and facilitates the usage and storage in an in-home use environment.

4.2.2. Smart Can

The shape and 3D model of Smart Can is shown in Fig. 3(a) and (b). It is comprised of a plastic body, a weight adjustment plugin component (the blue component) and a built-in electronic sensing system, which consists of a 9-axis inertial motion sensor, a

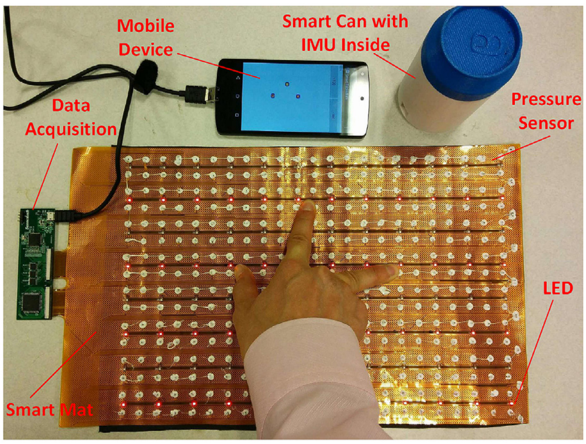


Fig. 2. The pressure point visualization on smartphone (three dots) when external force (pressure from three fingertips) applied on the Smart Mat. Separate components of QM-FOrMS are marked with red including the Smart Can with an embedded IMU sensor, the Smart Mat, a data acquisition device, and a mobile device. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

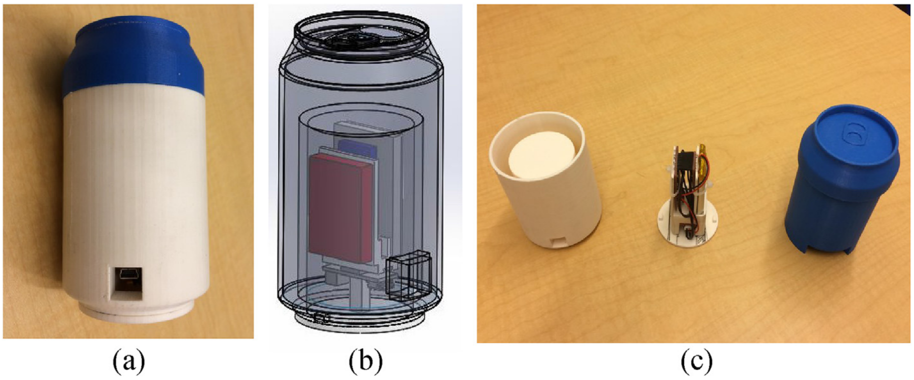


Fig. 3. (a) Outlook of the Smart Can; (b) 3D model design of the Smart Can; (c) Three components of the Smart Can including a can body, a weight adjustment plugin component, and a built-in electronic sensing system.

microcontroller, a Bluetooth module and a rechargeable battery, as shown in Fig. 3(c). The specific IMU sensor we adopted in our Smart Can system is InvenSense MPU-9250, which gives us reliable readings. The calibration on accelerations in X, Y, Z axis is only needed once during the first time setup. After that, calibration is not necessarily needed for all rehab tasks. We have also validated the sensor data with another widely used IMU sensor, Sparkfun 9DOF Razor IMU (Electronics, 2018). The agreement of data from both sensors validated each other. In addition, MPU-9250 contains an onboard digital motion processor (DMP™) capable of processing complex Motion Fusion algorithms, which helps us to obtain an accurate orientation information for the trajectory tracking of the Smart Can. The plastic body and weight adjustment component can be manufactured using advanced 3D printing technique. Therefore, the shape, size, and weight of the can are able to be customized to adapt to the user's specific requirements such as hand size, lifting weight limit, and exercise difficulty. When a user is holding and moving the can, the sensing system can track the acceleration and orientation of the can, and this motion information is wirelessly transmitted to the mobile device. The weight of the Smart Can is easy to adjust, to make it comfortable for different users to use, by replacing plug-in components with different weights.

4.3. *Software design on smartphone*

4.3.1. *User interface design*

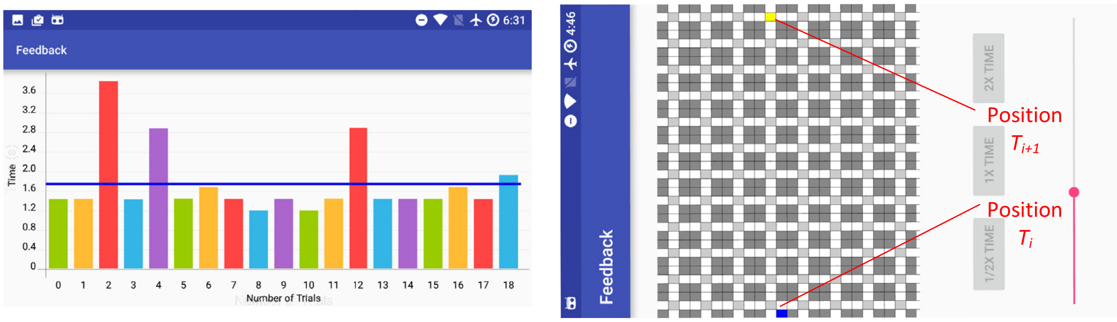
We developed an android-based App on a mobile device which serves as the GUI for the user. Clinicians use the GUI, including *(b) Preset Patterns Selection, (c) Customized Pattern Configuration, (d) Working Mode Selection, (e) LED Clusters Setting, and (f) Area Setting* as shown in Fig. 5, to customize exercise programs, see subsection 5.3 for parameters that may be customized. Patients are guided through exercise programs by the GUI and both groups are given quantitative feedback on performance through the GUI.

In the patient's interface design as shown in Fig. 6, the whole rehabilitation procedure is divided into six steps including selection of exercise to perform, selection of the maximum duration to allow for completion of the exercise, exercise instruction, start button and timer for exercise in progress, performance feedback, and log information. First, the user needs to select the rehabilitation exercises he/she wants to perform, which are described in detail in subsection 5.2. In the next step, there are four options for the maximum duration to complete the activity, which are 1 min, 2 min, 3 min, and 5 min. After that, the exercise instruction will display on the mobile device screen. When the patient understands the activity, they can forward to the next screen and click the start button to begin the activity. Time will be displayed as the patient performs the task. In the middle of exercise, user is free to pause, resume or exit the process. When the whole rehabilitation process is finished, the performance feedback will be displayed on the screen and saved as log information in the database. To be specific, two buttons, 'Show Basic Report' and 'Show Detailed Report' will pop up to enable the user selection on which report to see. The basic report is designed mainly for patients which shows the improvement percentage comparing with the average of the previous rehabilitation results. The detailed report is designed for the clinician, it contains all the raw scoring feature values described in Section 6. These will help the clinician to assess the rehabilitation results comprehensively.

4.3.2. *Visual performance feedback*

Performance feedback is critical in rehabilitation as it informs the patient of their progress to more specifically direct their rehabilitation efforts, motivate them to continue, and encourage better self-management of the rehabilitation program. Therefore, how to improve the user adherence of the rehabilitation system is another primary design consideration. Effective visual performance feedback plays an important role in rehabilitation that it makes the rehabilitation procedure less tedious and more attractive to patients (Walker, Brouwer, & Culham, 2000), which motivates patients practice more frequently so that the exercise task can be readily carried over in daily life. Our GUI App design has considered the visual performance feedback after rehabilitation. Here we take one old adult performing *Task 1* **Transport Can**, described in Section 7, as an example to show visual feedback results.

Statistic Feedback: Statistic feedback is one representation of quantitative feedback. The time to complete and their average value across all trials are shown in Fig. 4(a). We observed that 3 bars representing the second, fourth, and twelfth trial are above average. Participant spent more time on these three trials is because he/she did not trigger the pressure point to turn the LED light off at the first



(a) Statistic feedback. (b) Replay feedback.

Fig. 4. Visual performance feedback on smartphone.

contact on the Smart Mat. Thus, extra time was needed to turn the LED light off.

Replay Feedback: We found users observing how a series of activities being performed during rehabilitation exercise usually make them interested in doing it again and sticking to the rehabilitation. Fig. 4(b) is a screen shot of a video of replaying the performed rehabilitation activities. The replay speed can be chosen as normal speed, half normal speed, and double speed by clicking buttons at the bottom part of the screen. The display on the screen emulates the structure of the Smart Mat with four dark gray cells together depicting a pressure sensor and one light gray cell in each intersection depicting the LED light. In real experiment, the pressure only appears for around 240 ms. Also, when the moment pressure is applied, the LED switches, meaning the pressure will always look off. For better visualization, we tweaked the way the data is read, which shows pressure longer and keeps the LED light lit during pressure being applied. The blue and yellow cells represent two actual contact points on each side of the Smart Mat from *Task 1* triggered by the Smart Can.

5. QM-FOrMS rehab exercise design

5.1. Task-specific therapeutic approach

Currently there is no one therapeutic approach that serves as the "gold standard" for stroke rehabilitation. A task-specific therapeutic approach has been encouraged by some (National Stroke Foundatio, 2007). The current design of our system uses a familiar shape, the Smart Can, to perform repetitive practice of functional tasks that may have meaning to the patient. Choosing a task that can be progressively adapted to appropriately challenge and engage the patient is important (Richards, Malouin, & Nadeau, 2015). The choice of a unilateral task to focus on movement of the impaired arm/hand or a bilateral task to work on coordination between hands can be used to tailor the program. The majority of functional upper-limb tasks incorporate some combination of four movement components: reaching, grasping, manipulating (includes moving the object), and releasing an object (Guccione, Avers, & Wong, 2011). Our system addresses all four of these movement components. The exercise programs may be customized to fit the needs of the patient as reaching versus reaching and grasping can change the challenge of the task.

5.2. Customized exercise programs

A plethora of functional activities can be devised by using the Smart Mat with the Smart Can.

5.2.1. Smart mat exercise

The force sensors imbedded in the Smart Mat can be used to focus attention on timing and grading of force with arm and hand movements. The multiple LED lights and multiple color of LED lights can be used to direct specific types of movements. A wide array of exercises may be derived from these basic components. For example, depending on the location of the LED target, the movement elicited could involve movement at the elbow or at the shoulder. Use of more than one color of LED could depict unilateral or bilateral movement. This allows clinicians to customize activities to address movement deficits unique to a patient. Clinicians can enter in directions for customized activities. In addition, QM-FOrMS is pre-programed with descriptions of exercises commonly used in rehabilitation. Here are examples of some pre-programmed Smart Mat exercises.

Palm up and palm down: (pronation/supination) Start with your palm down on the LED light. When the next target appears, touch it with your palm facing upward. Continue to alternate between palm down and up as you touch the targets.

Elbow flexion/extension: Place hand on the illuminated LED (LED will be illuminated in the front row). Extend your arm to reach the next target (illuminated LED in the back row). Keep your trunk still as you are moving your arm. Continue to bend and extend your elbow to hit the targets.

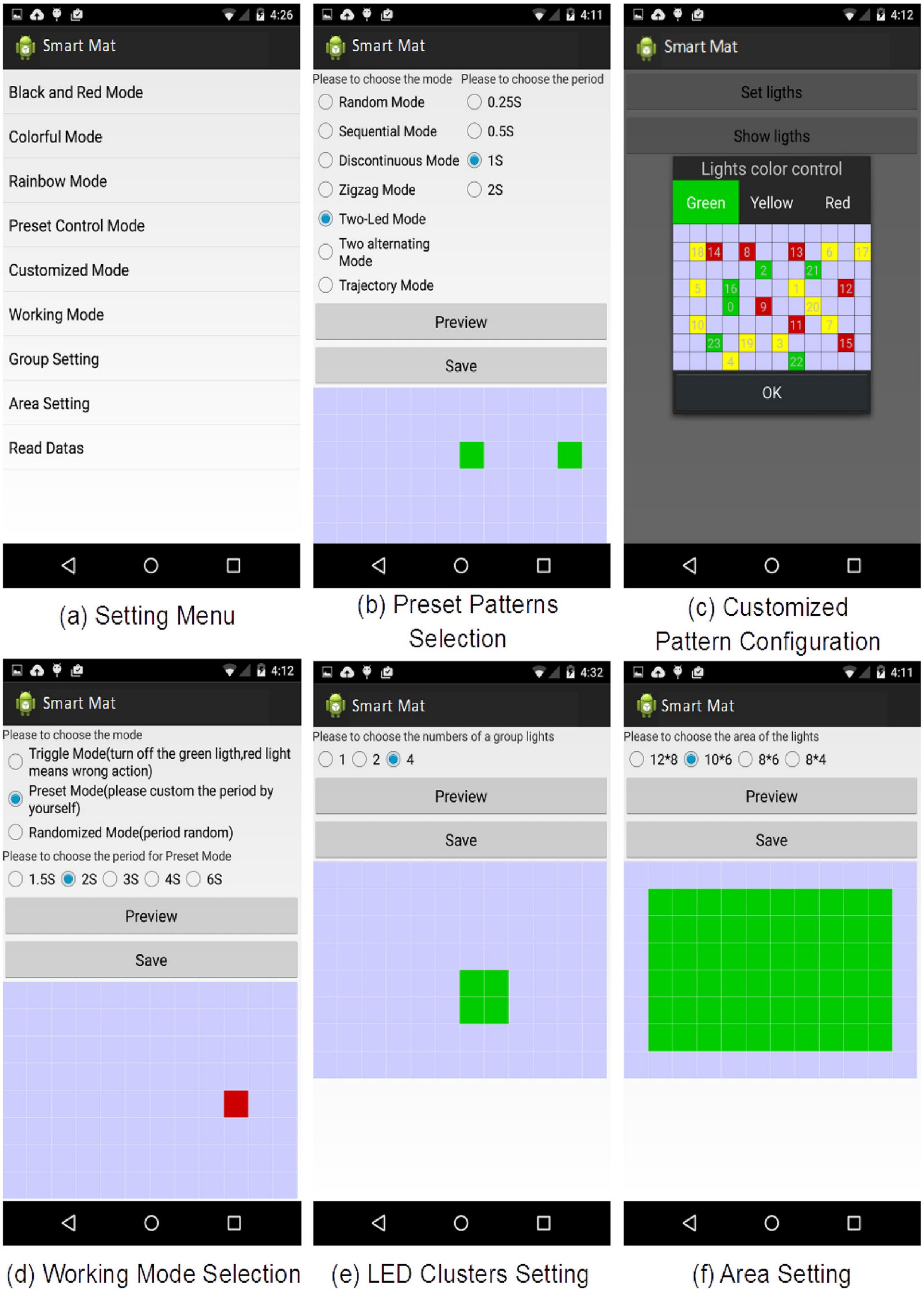


Fig. 5. The clinician-end interface design of mobile App. A clinician can configure the exercise tasks through the following settings: (a) Setting Menu; (b) Preset Patterns Selection; (c) Customized Pattern Configuration; (d) Working Mode Selection; (e) LED Clusters Setting; (f) Area Setting.

5.2.2. Smart mat and Smart Can exercise

The appropriate level of difficulty can be adjusted by selecting either unilateral or bilateral activities and by adjusting the size of targets. Clinicians can create exercises or choose from pre-programmed exercises that include, but are not limited to the following:

Lift: Lifting the Smart Can from Smart Mat into the air and put it back onto the Smart Mat. Repeat the procedure.

Transport can: Lift the can and move it to the illuminated target. Set the can down on the target. Continue to move the can to the

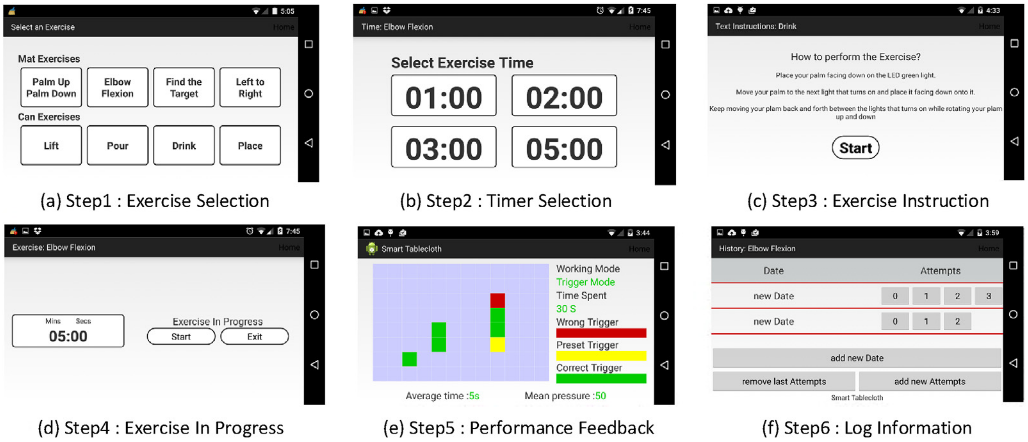


Fig. 6. The patient-end interface design of mobile App. Patients selection: (a) Step 1: Exercise Selection; (b) Step 2: Timer Selection. Then, the task is guided by displays on the screen including (c) Step 3: Exercise Instruction; (d) Step 4: Exercise In Progress. After rehabilitation, the patient can view the statistic results in (e) Step 5: Performance Feedback; (f) Log Information.

illuminated target when it appears.

Pour: Grasp the can, lift and position the can as if to pour the contents out of the can. Place the can back on the Smart Mat. Repeat the procedure.

Drink: Grasp, and lift the Smart Can close to the mouth (within 1–2 inches) and pretend to take a drink from the can. Place the can back on the start position on the Smart Mat. Repeat the procedure.

5.3. Parameters configuration for target selection

The use of LEDs for programmable targets adds to the flexibility and usability of the system. This, system parameter can be configured to select location of the LED being illuminated for the target, the number of LEDs being illuminated to adjust the target size, the pattern of LEDs sequentially or simultaneously being illuminated and the color of the LED target. The sequencing and color of targets can be used to elicit a series of unilateral or bilateral movements. For example, with two colors (red and green) LED setting, we can demand the user to turn off the red LED using left hand and turn off the green LED using right hand. In this way, the user can work on sequencing bilateral movements. All of these parameters can be customized to tailor the program to the patient, as shown in Fig. 5. Also, we have included some preset patterns for sequence of LED target illumination.

Preset patterns selection: We predefine several LED target working patterns including "random", "sequential", "discontinuous", "zigzag", "two-LED", "two alternating", and "trajectory". The options of time interval configuration between one LED light turns on and another LED light turns off are 0.25 s, 0.5 s, 1 s, 2 s, and random period. Among these patterns, "sequential", "discontinuous", "two-LED", "trajectory" are unilateral tasks, while "random", "zigzag", "two alternating" are bilateral tasks.

Customized pattern configuration: In this setting, the clinician can configure the LED lights on/off sequence and color, depending on the specific rehabilitation need for the patient. The customized pattern configuration can be saved as a profile file. When a patient wants to complete this activity, he/she only has to load the saved profile file.

Working mode selection: Two modes are defined here including "trigger" and "preset". In "trigger" mode, a patient touches an illuminated LED turning it off and "triggering" another LED light to turn on. In "preset" mode, the frequency of LED lights turning on/off is based on the time interval configuration in the preset patterns selection setting.

LED clusters setting: This setting configures several adjacent LED lights into one group, which turn on/off as a whole at the same time when at least one of pressure sensors in the cluster is triggered. The options of number of LED lights in one group are 1, 2, and 4.

Area setting: This setting confines the area that LED lights are working. It is represented by number of LED lights in a row multiply number of LED lights in a column. The options are 128, 106, 86, and 84.

6. Scoring features

During the exercise program data from the Smart Can and Smart Mat are recorded by the mobile App. The features for scoring, categorized in Table 1, can be extracted from these data.

The normalized jerk score was selected out of several possible movement quality metrics. This metric has been demonstrated to change with movement-based interventions in individuals' post-stroke (Langan et al., 2013a, 2013b). This score is defined as the time derivative of acceleration, used to quantify smoothness and coordination in sensory-motor performance studies. The main appeal of a jerk-based measure is that the motion profile simply needs to be a fifth-order polynomial function relating displacement in each degree of freedom to time. We use the dimensionless squared smoothness measure, normalized jerk score (NJS), below as it is independent of the length of duration of movement. Using the acceleration and position readings, the NJS can be computed as:

$$NJS = \sqrt{\frac{1}{2}\int_{t_1}^{t_2}\left(\left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2 + \left(\frac{d^3x}{dt^3}\right)^2\right)dt\,\frac{(\Delta t)^5}{A^2}}, \tag{1}$$

where x, y, z are the displacement in three directions, and $\frac{d^3}{dt^3}$ is obtained directly from the stabilized readings of the accelerometer in x, y, z axis, respectively, Δt is $t_2 - t_1$ or the duration of the movement, and A is the amplitude of displacement (also known as extent).

"Time to complete" measures the amount of time to complete the task. The timer starts when the Smart Can (or hand) is lifted and ends when the can (or hand) lands on the final target on the Smart Mat. Force is measured by the instantaneous pressure value when the patient places the Smart Can on the Smart Mat. Accuracy depends on proximity to the correct target. Applying pressure a longer distance away from the target results in lower accuracy. We are able to expand the scoring metrics displayed in the detailed report to include metrics such as trajectory and orientation of the object and coordination in timing between hands.

7. Evaluation

7.1. Protocol of experiment

7.1.1. Subjects and instructions

The data collection is conducted in the Department of Rehabilitation Science in the University at Buffalo. We have collected data from *three* groups including 1) healthy young adults, 2) healthy older adults and 3) individuals with movement impairment. These three different groups demonstrate the range of human performance. Efficient movement is most readily demonstrated by young adults. As we age, efficiency in movement frequently diminishes. Following neurological insult such as stroke, greater movement impairments are noted. We recruited five healthy young adults with their ages in the range of $21-27$, six healthy older adults with their ages in the range of $63-90$, and four individuals with movement impairment with their ages in the range of $53-61$ participated in our experiment. The detailed information is shown in Table 2. Our team holds an active IRB protocol in the University at Buffalo (#:645489), which allows for recording motion information through sensors while performing upper extremity rehabilitation exercises. All participants consented to participate in the study. During the data collection, the smart mat is placed on the same desk for each subject. Before the data collection, each participant is required to sit on a chair in front of the desk. The height of the chair is adjustable, so that the participant could adjust the chair height and the distance to the desk to make himself/herself comfortable enough for the rehab data collection.

7.1.2. Rehabilitation tasks

QM-FOrMS allows flexibility so the movement patterns and level of difficulty can be adjusted for each patient. We designated three tasks for the purpose of justifying the validity and novelty of QM-FOrMS, as shown in Fig. 7. ***Task 1***, **Transport Can (Left to Right and Back)**, specifically lifting a can and placing it on a target on the right. Fig. 1 shows an older adult performs such task on a table. This task encourages shoulder external rotation when the participant uses their right hand and maintains a vertical trunk. ***Task 2*** is the motion of pouring: **Pour**. This task emulates pouring water from a can to a glass in daily life. The manipulation of the Smart Can in this task is more challenging than in *Task 1* with the addition of pronation and supination of the forearm to perform the pouring motion. ***Task 3***, **Transport Can (Forward and Backward)**, is a modification of *Task 1* and demonstrates by changing the target on the mat, the patient will alter upper limb movement. In *Task 3* the Smart Can will be moved from the front to the back of the mat. This task encourages elbow extension.

Each task was designed to repeat 10 times for each participant. All three tasks adopt one LED/cluster and the whole working area on Smart Mat setting. Data collected from the Smart Can and Smart Mat will be stored in a smartphone then uploaded to a cloud platform for further analysis.

7.2. Evaluation performance

We evaluate the participant's rehabilitation with the classical metrics (see Table 1): (a) time to complete, (b) positioning accuracy and (c) positioning force. Specifically, we illustrate results of time to complete, positioning accuracy, and positioning force in Fig. 8,

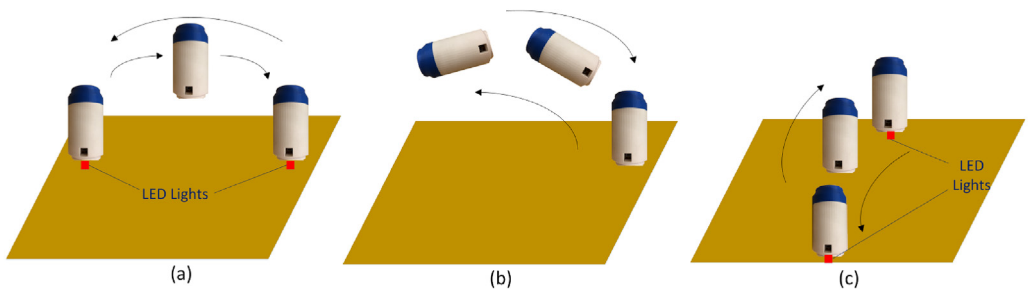


Fig. 7. Tasks designed (a) Task 1: Transport Can (Left to Right and Back); (b) Task 2: Pour; (c) Task 3: Transport Can (Forward and Backward).

Table 1
The categorization of features for scoring. (* represents features not evaluated in this study).

Index	Category	Features
1	Efficiency	Jerk score
2		Trajectory*
3		Time to complete
4	Control	Positioning Force
5		Positioning Accuracy
6		Orientation*
7	Coordination	Timing between hands (Bilateral)*

Table 2
The gender, age, and height information of all participants.

Group	Young Adult					Older Adult						Patient			
Participant	1	2	3	4	5	1	2	3	4	5	6	1	2	3	4
Gender	M	M	M	F	F	M	F	F	M	F	F	F	F	M	F
Age	22	21	23	21	27	84	64	86	90	63	65	59	58	61	53
Height	5′7	5′8	5′9	5′3	5′4	5′11	5′8	5′2	5′3	5′4	5′6	5′4	5′3	5′9	5′7

where the height of the colorful bar represents the average value of a group of participants with certain age range and half height of the black vertical line on each bar indicates the standard deviation.

7.2.1. Time to complete

Time to complete a task is a metric commonly used in rehabilitation as many assessments use stopwatches. As illustrated in Fig. 8(a), young adults demonstrate the least amount of time and little variability in their response, which is similar to what is recorded in the literature (American Physical Therapy, 2013). The time to complete is represented in the form of "mean $\pm$ standard deviation (sd)" as 1.36$\pm$0.04, 1.41$\pm$0.05, and 1.34$\pm$0.13 for *Task 1, Task 2, and Task 3,* respectively. We observed that though older adults require more time than young adults, they still can finish tasks without apparent pause. The time to complete is 1.61$\pm$0.09, 1.59$\pm$ 0.07, and 1.60$\pm$ 0.10 for each task. Comparatively, individuals with movement impairment require even more time and demonstrate increased variability. The time to complete is 2.25$\pm$0.51, 2.25$\pm$0.72, and 2.07$\pm$0.50 for each task. The reason of this is because individuals with movement impairment experienced a variety degrees of pause and deviation from normal track during the rehabilitation process. To differentiate healthy and impaired groups, time to complete is a good metric since both mean and standard deviation of impaired group are much higher than the ones in healthy groups, and the maximum value in healthy groups is still lower than the minimum value in impaired group. Beyond, time to completion QM-FOrMS offers further metrics that better informs the users of the motor performance.

7.2.2. Positioning accuracy

Smart Mat can sense the pressure on each pressure sensor when external force is applied by the Smart Can. If the pressure point generated by the Smart Can falls in the area comprised of four pressure sensors that is around the alight LED light, we consider this case as the 100% positioning accuracy. If the pressure point deviates from the area of sensors, the positioning accuracy is lowered. Fig. 8(b) shows that young adults achieved 100% accuracy in placing the Smart Can on the target, older adults are a little worse, while individuals with movement impairment were apt to place the can farther from the target with lower average accuracy and large standard deviation as 92.5$\pm$7.2, 95.4$\pm$5.8, and 92.8$\pm$6.7 for each task. Based on the positioning accuracy measurement that the results from individuals with movement impairment are lower than healthy groups, we can also differentiate healthy/impaired groups. However, we observed that the performance difference in position accuracy is not as prominent as time to complete. This is due to our definition of positioning accuracy which is based on the displacement distance. In order to make positioning accuracy a robust classification metric, we can increase the sensitivity of distance in the definition of positioning accuracy.

7.2.3. Positioning force

We have also included the positioning force metric, which is the amount of force applied with setting the can on the mat, as the ability to control force production can be challenging following stroke (Kang & Cauraugh, 2015). Fig. 8(c) demonstrates individuals with movement impairment use more force to put the Smart Can on the Smart Mat, which is 837$\pm$19, 816$\pm$17, and 838$\pm$ 44 for each task. Examination of velocity related data indicates they were unable to smoothly decelerate the Smart Can. We also noticed older adults have the largest standard deviation across three tasks. This is due to the large age range in older adults group which is from 63 to 90, and each individual in this group has disparate motion control abilities.

Overall, Fig. 8(a) and (b) show consistence in performance that young adults performed best, older adults worse, and individuals with movement impairment even worse, while result in Fig. 8(c) is inconsistent across three tasks. We conclude that time to complete is the best feature to differentiate three different groups, but positioning force may not be feasible for this purpose.

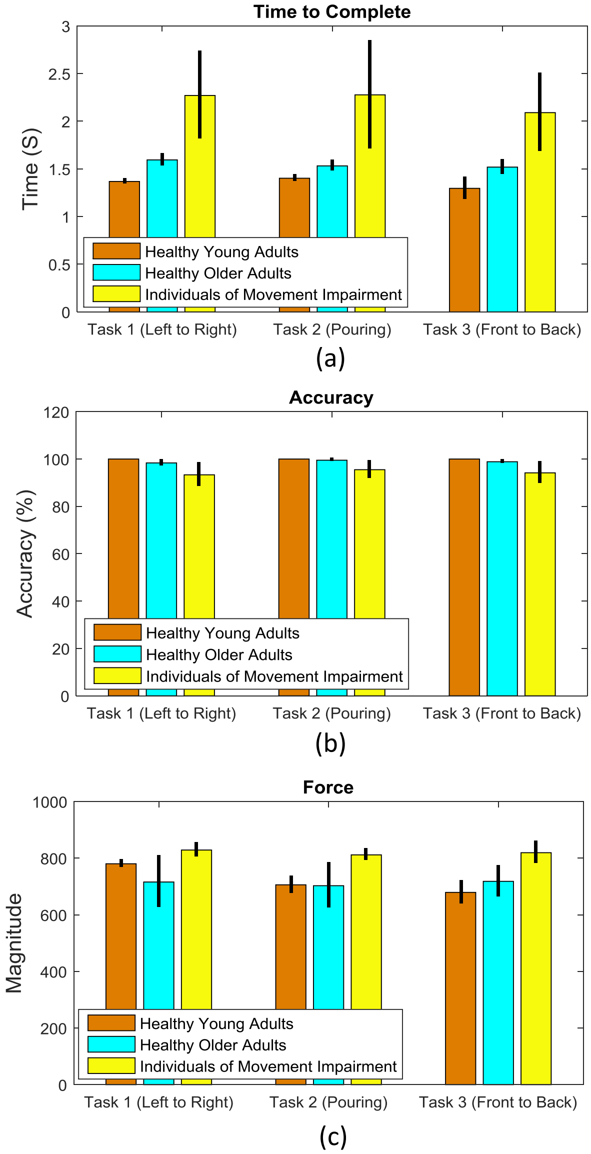


Fig. 8. Comparison among three groups for all three tasks. (a) Time to complete; (b) Positioning accuracy; (c) Positioning force.

7.3. Jerk score study

Box Plot: We also study the normalized jerk score (NJS) of rehabilitation tasks among three groups. The box plot comparison of jerk score among three groups is illustrated in Fig. 9. The box plot includes a rich set of normalized jerk score statistics, including the maximum (i.e., the ceiling value), the minimum (i.e., the floor value), the average (i.e., the inside dot), the median (i.e., the middle line) and the standard deviation (i.e., half height of the bar). The average value can above or below median, and the closeness of two values indicates samples are evenly distributed. We can see that results from three groups are consistent across three tasks. Specifically, young adults have the lowest jerk score whereas individuals with movement impairment have the greatest jerk score. Moreover, young adults have the lowest standard deviation of NJS, i.e., the performance variation, among three groups in all tasks. Especially, NJS from young adults are lower than most older adults and all individuals with movement impairment.

Group Classification: The exact jerk scores are shown in Table 3. Thus, it is possible to differentiate young adults from other two groups by looking at NJS across all three tasks. On the other hand, older adults have the highest standard deviation of NJS. This is because the age range of older adults is large, ranging from 63 to 90, that each individual has disparate motion control abilities. In other words, the performance of older adults approaching 63-year old is close to the performance of young adults, while the performance of ones approaching 90-year old is close to individuals with movement impairment. Therefore, the variation in older adults is larger than other two groups.

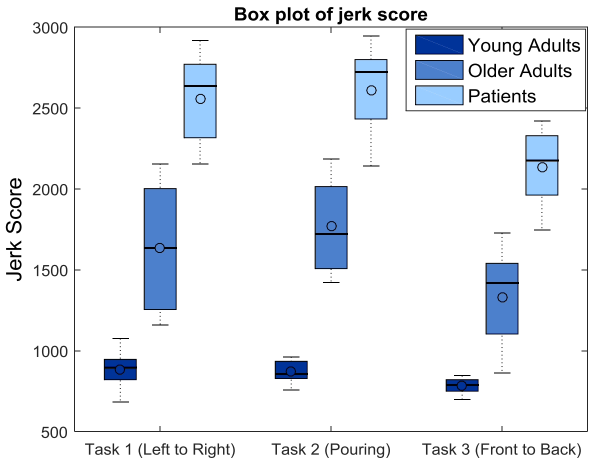


Fig. 9. Box plot comparison of jerk score among three groups.

Table 3
Normalized Jerk scores from all groups across three tasks.

NJS (mean ± sd)	Young adults	Older adults	Patients
Task 1	884±125	1637±422	2555±301
Task 2	872±75	1768±321	2611±295
Task 3	782±52	1329±329	2132±254

By taking a closer look at these results, we find that the performance in *Task 1* and *Task* 3 has the most distinguishable result to classify three groups. More specifically, there is no overlap of NJS values among three groups in both *Task 1* and *Task 3*, while there is a noticeable overlap in *Task 2* between older adults and stroke patients. This is because that the pouring task requires a higher coordination on both physical (pronation and supination of the forearm) and cognitive capabilities. The increasing difficulty level in tasks leads to the close performance between these two groups. Also, it is not surprising that the performance in young adults is far away from other two groups. Therefore, the challenging task is more suitable to recognize healthy young groups, while not accurate enough to classify vulnerable groups such as older adults and patients. We also noticed that the average values are smaller than median values for patients across three tasks, which shows there are one or multiple participants have terribly worse performance than others, hence the average value is dragged down below median value. The mean and median are close in young and older adults. Especially for young adults, these two values are overlapped which indicates samples from young adults are distributed more evenly.

In summary, the combined data from QM-FOrMS clearly depict not only does it take longer to complete a task after movement impairment, but also the quality of movement diminishes. In rehabilitation, it is important to consider how well a movement is made in addition to how fast.

7.4. Impact of repetitions

The number of repetitions is an important parameter, the appropriate choice of which has a large impact on the effectiveness and usability of the rehabilitation. Large number of repetitions may cause fatigue of participants' hands, especially for stroke patients using dysfunctional hands. Thus, the jerk score will be increased in such case.

7.4.1. Analysis

We investigated the impact of repetitions by varying the number of repetitions from 6 to 20 in the rehabilitation process in a separated experiment, as depicted using error bar in Fig. 10. Jerk scores are analyzed using all three tasks for different groups of participants. The average jerk scores are represented by green triangles, red circles, and blue stars for young adults, older adults, and individuals with movement impairment, respectively. The half height of each error bar represents the standard deviation. We notice that repetitions almost have no impact on young adults since the average value of jerk score is stable with small standard deviation. This result confirms our hypothesis that young adults are capable of bearing tens of repetitive exercises while maintaining a smooth motion trajectory. For older adults and stroke patients, their jerk scores increase gradually as the number of repetitions increases. This is because participants from vulnerable groups are readily to feel tried with intensive exercise, and the repetitive transition and lifting exercises consume their energy in arms and hands. Thus, the precise control ability is compromised, which leads to more shake during exercises. The increasing trend for older adults is similar to a linear increasing, while jerk scores in individuals with movement impairment increase even faster because patients consumed more energy for focusing than normal people and are more likely to lose control. On the other hand, it is irrational to just select small number of repetitions because insufficient exercises may not be able to sufficiently quantify

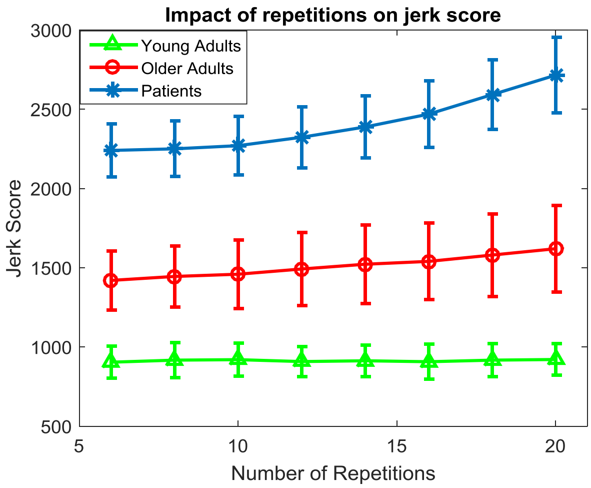


Fig. 10. Impact of repetitions on jerk score among three groups.

the task performance, hence do harm to the effectiveness of the rehabilitation system.

7.4.2. Optimal number of repetitions

To determine the optimal choice of the number of repetitions, we should consider both the effectiveness of the rehabilitation system and the impact of fatigue for users, especially individuals with movement impairment. We noticed that when the number of repetition is below 10 the increasing rate of average jerk score is tiny, which suggests all participants are comfortable with the number of repetition of 10 for exercises. And data collected from 10 repetitions are sufficient to obtain some statistical results. Therefore, 10 is optimal choice of the number of repetitions in our experiment and was adopted in our experimental setting.

8. Discussion

System Usability: The development of QM-FOrMS for use in a life-span approach to rehabilitation is novel in its instrumentation of objects, portability, low cost and comprehensive assessment of motor performance. The system allows individuals to manipulate an object in a manner consistent with ADLs, including moving a can mimics clearing a space on your counter or putting groceries away, simulating pouring mirrors serving a refreshment, practicing these tasks can improve functional mobility (Chou et al., 2012). The system test has shown that the well-rounded information QM-FOrMS can provide to users will motivate increased practice.

Rehabilitation Metrics: The results in the pilot study have indicated that kinematic-based metrics (Kim et al., 2013; Li et al., 2018) such as jerk score can distinguish between groups well. These results are promising as the efficient and consistent performance demonstrated by the young adults in terms of jerk score across tasks lends itself well to using this group as a "gold standard" for performance. This can lead to innovative new assessments measuring change in performance. At a time when demonstrating improvement in motor performance is paramount in clinical practice, improving assessments is very important.

Further Enhancement: The pilot study supports further development of this system. In the future, the system will be further enhanced and fully assessed in the following aspects. First, more rehab activities will be explored, such as drinking, lifting, and sequentially moving. Furthermore, activity recognition algorithms (Lin et al., 2016b, 2017b) can be integrated into the system to automatically recognize the rehab exercise and provide the corresponding feedback. Second, we plan to include a larger cohort for all three groups for a large population test. To further improve the satisfaction of the users, we have established clinician and patient focus groups. To date, we have conducted focused interviews with these groups. As we progress the system we will interview all participants using standardized assessments such as the System Usability Scale (SUS) (U.S. Department, 2014) and additional questionnaires to gain user insight on the system and progress the usability of the system with the purpose of enriching rehabilitation efforts.

9. Conclusion

In this paper, we designed a portable and cost-effective upper extremity rehabilitation system, named QM-FOrMS, for individuals with upper limb movement deficits. It comprises a Smart Mat, a Smart Can, and a mobile device. QM-FOrMS is suitable for home use, flexible to support customized setting, and capable of providing quality of movement measurement. The evaluation results from the three different groups and the three designated tasks showed that patients with upper limb motor deficits have larger jerk scores and require more time to complete a task compared with healthy young and older adults. In addition, we analyzed which metric is more suitable for classifying different groups. We found time to complete the task and jerk score are distinguishable features. We also discussed the impact of repetitions and stated 10 repetition is the optimal choice. In future work, we plan to apply QM-FOrMS with a large cohort of in-home upper extremity rehabilitation.

Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smhl.2019.100080.

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