A Portable and Cost-Effective Upper Extremity Rehabilitation System for Individuals with Upper Limb Motor Deficits

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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 through self-managed rehabilitation programs. However, 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. Quantitative evaluation of the motor performance from the QM-FOrMS is derived from fine-grained kinematic measurements. We ran a pilot study with three groups, including five baseline subjects (i.e., healthy young adults), six older adults and four individuals with movement impairment. The experimental results show that QM-FOrMS can provide the detailed feature during the unattended rehabilitation exercise, and proposed metrics can distinguish the evaluation results across group.**

I. Introduction

The population in the US is aging [1], and with increased age there is diminished motor control [2, 3] in addition to higher risk for neurological insult such as stroke [4]. In 2010, approximately 17 million people had a stroke worldwide adding to the over 33 million survivors of stroke [5]. 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. Repeated studies demonstrate that patients in inpatient rehabilitation programs are engaged in therapies for a limited amount of their waking hours [6, 7]. With a robust body of research underscoring the importance of practice [8, 9], providing adequate practice in rehabilitation is central to efficacious interventions [8, 10]. Encouraging patients to practice activities outside of therapy times has been advocated for in rehabilitation [11, 12]. Providing a system to track activity and provide feedback can promote participation, refine practice and give individuals a better understanding of their abilities to then set goals for themselves [13-15].

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 [13, 15]. Technology-based in-home exercise programs have been shown to be an enjoyable means to have patients partake in activity [16, 17]. A rehabilitation specific system can first be introduced to individuals in inpatient rehabilitation to offer greater 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. As it is possible to make motor improvements beyond the acute phase of recovery [18, 19], it is necessary to provide better options for home rehabilitation.

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 guidance to execute the exercise program. It also allows configuration of system parameters, which are elaborated in Section III-C. 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

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978-1-5090-3090-3/16/$31.00 ©2016 IEEE

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.

II. Background and Related work

Our design concept is innovative in both hardware and software. Instrumenting objects for patients to manipulate provides an experience that readily translates to activities of daily living (ADL). This is a departure from commercial gaming systems such as the Wii that have been used in rehabilitation [20-22], yet are not designed for rehabilitation. The controller is held in one hand and games may be played with a modest amount of wrist motion in a movement pattern that isn't directly related to ADLs. If the Kinect system is used in rehabilitation, generally body movement is monitored, but object manipulation is not addressed. Our software also departs from commercial gaming systems; it 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.

A. Pitfalls in Developing an In-home Rehabilitation Device

1) Specification

For individuals with diminished upper limb function, efficiently manipulating objects unilaterally or bilaterally is an important aspect of rehabilitation and frequently involves working at a table. Again commercial units do not fully accommodate these goals. Wii games with the use of only one controller do not provide an opportunity to refine coordination of bilateral movements. The Kinect system uses an infrared sensor allowing movement controlled play, yet this motion based system has limitation recognizing users in seated position behind a table.

2) Detailed Features

In rehabilitation, both motor control 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.

3) Cost and Portability

Our system is designed to be portable and affordable for home use, mainly made of eTextile pressure sensors and IMU sensors imbedded into plastic molds of objects with functional relevance such as the shape of a can. Robotic systems have been created to calculate metrics of quality of movement such as the jerk score [23]. However, this robotic system is not feasible for home use. Other systems that authors report are portable and measure kinematics are custom designed for research and do not emphasize usability by clinicians or patients [24].

4) Personalization and Adaptivity

A customer centered rehabilitation system should be adaptive in order to personalize training. The needs of each patient are determined by their unique set of abilities and limitations in movement. Exercise programs need to be customized to meet the needs of the user.

B. Related Work

1) Justification of Motion Feedback Information

The normalized jerk score provides information on the control of movement, an indication of impairment, which is used in research. Calculations of a normalized jerk score have been used to assess impairment in functional activities in individuals with neurological deficits such as tardive dyskinesia [25] and Friedreich's Ataxia [26]. Measurements of movement that include jerk score have been correlated with the status of the disease [27] and reveal significant difference or changes in both individuals and groups of subjects for upper extremity activity levels [27].

2) Existing Sensors-based Rehabilitation Systems

Giorgino *et al.* [28] used a strain sensing technology, conductive elastomers, for posture recognition in the context of neurological rehabilitation. Mavroidis *et al.* [29] describe 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. Jovanov *et al.* [30] introduced a multi-tier telemedicine system and described how to optimize the prototype wireless body area network (WBAN) implementation for computer-assisted physical rehabilitation applications and ambulatory monitoring. Tognetti *et al.* [31] 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.

III. Design Consideration

A. Customized Exercise Programs

The design of the portable rehabilitation system focuses on upper-extremity exercises that can be carried out on a table. The exercise programs may be customized to fit the needs of the patient. This can include less complex movements such as unilateral hand or arm movements or more complex movements such as bilateral manipulation of instrumented objects. To measure the performance of manipulation of instrumented objects, we introduce Smart Mat and Smart Can, the detailed design is elaborated in Section IV-B. A plethora of functional activities can be devised by using the Smart Mat with the Smart Can.

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

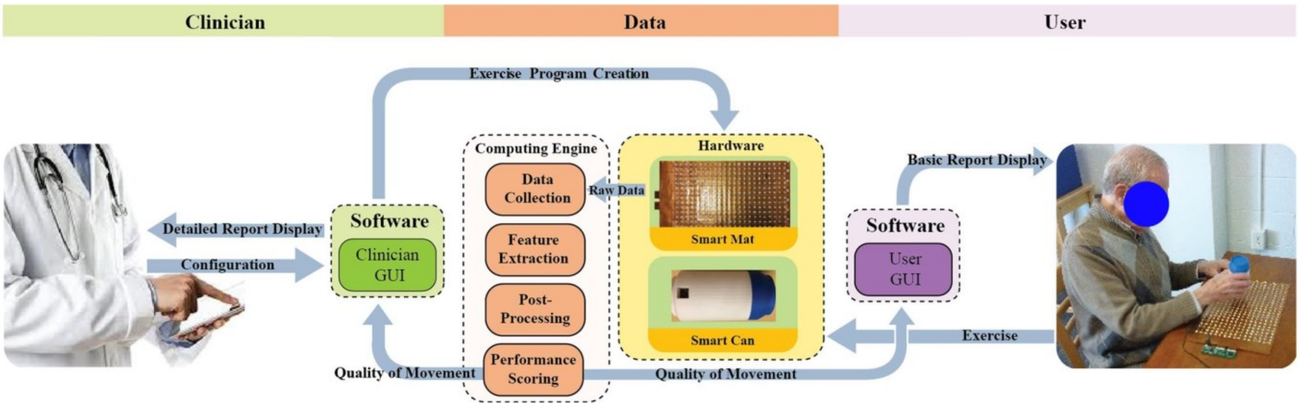

Figure 1. The overall system diagram including clinician, patients, and rehabilitation system.

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 palm 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.

2) Smart Mat and Smart Can Exercise

The appropriate level of difficulty with activities 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 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.

B. Parameters Configuration for Target Selection for Exercises

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. All of these parameters can be customized to tailor the program to the patient. 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. 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 12×8, 10×6, 8×6, and 8×4.

IV. 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.

A. 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 via a micro-USB cable to the microcontroller connected to the Smart Mat, the LED lights then are configured by the microcontroller to illuminate following specific patterns. The configuration of the LED lights working patterns can be set in the mobile App under system parameters. 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 subsection IV-C2, 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.

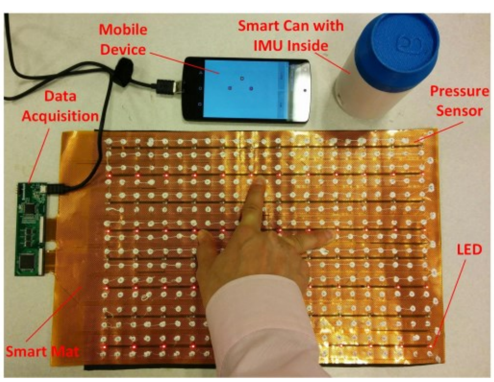

Figure 2. The pressure point visualization on smartphone when external force applied on the smart mat. Each component of QM-FOrMS is marked with red.

B. Hardware Design

1) Smart Mat

The Smart Mat is a flexible 40 cm by 24 cm pressure sensor array, based on electronic textile (or eTextile) technology [32]. 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% [33]. 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 times 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 smartphone when external force is applied on the Smart Mat. Three fingers touched the Smart Mat and three pressure points appear on the smartphone 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. Such novel design provides the portability and facilitates the storage in an in-home use environment.

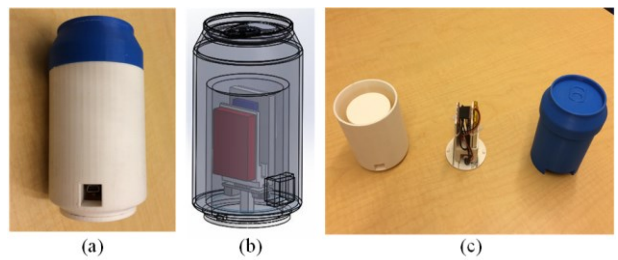

Figure 3. (a) Outlook of Smart Can; (b) 3D model of Smart Can; (c) Each components of Smart Can including white body, blue weight adjustment plugin component, and a built-in electronic sensing system.

2) Smart Can

The shape and 3D model of Smart Can is shown in Fig. 3 (a) and Fig. 3 (b). It is comprised of a plastic body, a weight adjustment plugin component and a built-in electronic sensing system, which consists of a 9-axis motion sensor, a microcontroller, a Bluetooth module and a rechargeable battery, as shown in Fig. 3 (c). 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 plugin components with different weights.

C. Software Design

1) Mobile App Design

We developed an android-based App on a mobile device which serves as the GUI for the user. Clinicians use the GUI to customize exercise programs (Fig. 4), see subsection III-C for parameters than may be customized. Patients are guided through exercise programs by the GUI (Fig. 5) and both groups are given quantitative feedback on motor performance through the GUI.

In the patient's interface design, 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

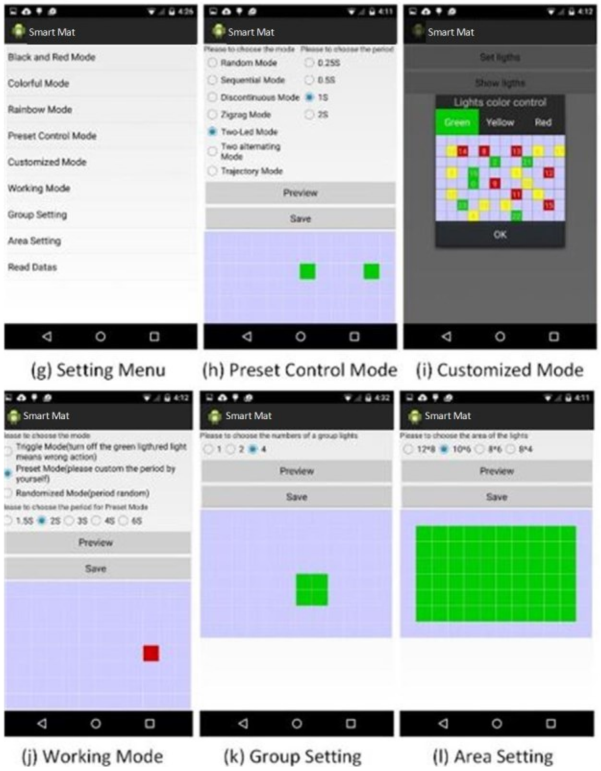

Figure 4. The clinician-end interface design of mobile App.

feedback, and log information. First, the user needs to select the rehabilitation exercises he/she wants to perform, which are described in detail in Section III-B. In the next step, there are four options for the maximum duration to complete the activity, which are 1 minute, 2 minutes, 3 minutes, and 5 minutes. 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 IV-C2. These will help the clinician to assess the rehabilitation results comprehensively.

2) *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 I, can be extracted from these data.

Metrics, such as jerk score, have not commonly been used in rehabilitation and provide a novel way to assess changes in motor performance and promote improvements in quality of movement. This score is defined as the time derivative of acceleration, used to quantify smoothness and coordination in sensory-motor performance studies. A 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:

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

where $\frac{d3}{dt3}$ is obtained directly from the stabilized readings of the accelerometer, Δt is t2 – t1 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 is lifted and ends when the can 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.

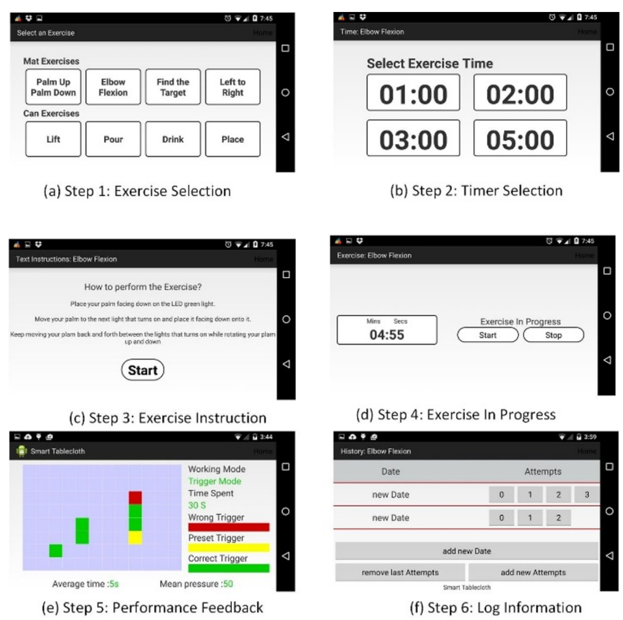

Figure 5. The patient-end interface design of mobile App.

V. EVALUATION

In this section, we will evaluate the functionality of QM-FOrMS that is effective in collecting user data and providing task performance evaluation.

A. *Experimental Setup*

We have collected data from three groups including healthy young adults, healthy older adults, and individuals with movement impairment. The 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. Our team holds an active IRB protocol in the State University of New York at Buffalo (#:645489), which allows for recording motion information through sensors while performing upper extremity rehabilitation exercises. All participants consented to participating in the study.

TABLE I. THE CATEGORIZATION OF FEATURES FOR SCORING[1].

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

We designated three tasks for the purpose of justifying the validity and novelty of QM-FOrMS, as shown in Fig. 6. *Task 1*, ***Transport Can (Left to Right and Back)***, specifically lifting a can and placing it on a target on the right (Fig 7). 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***. 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. QM-FOrMS allows flexibility so the movement patterns and level of difficulty can be adjusted for each patient.

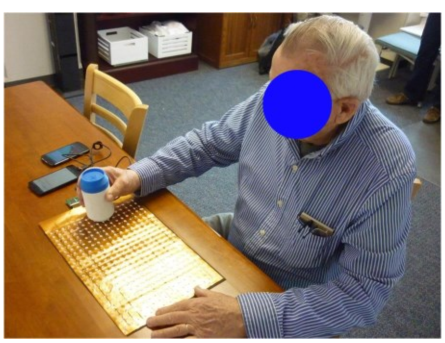

Figure 7. An older adult performs Task 1 by transporting Smart Can from left to right.

B. Experimental results

The following scoring features are measured in the pilot study: time to complete, force, accuracy and jerk score. Time

[1] The features marked with '*' are not in the current system, and will be included in the future design.

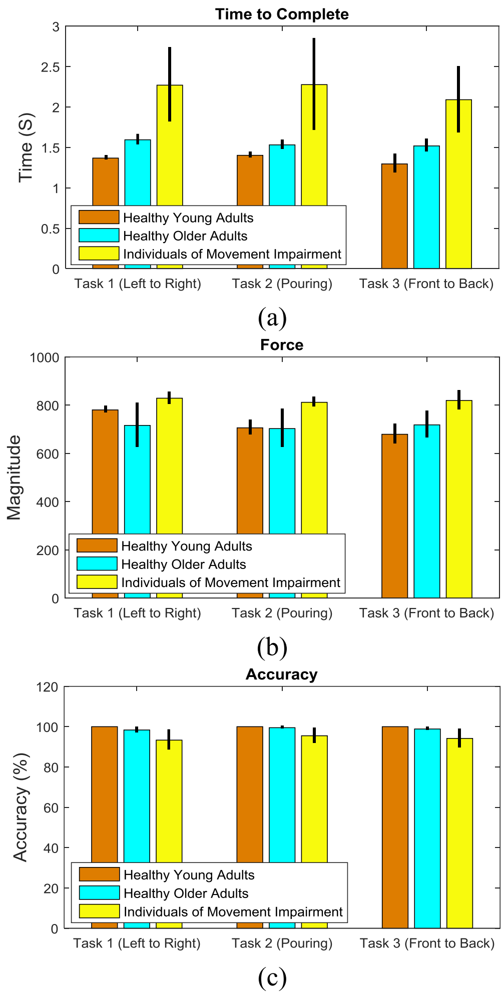

Figure 8. Comparison among three groups for all three tasks. (a) Time to complete; (b) Force; (c) Accuracy.

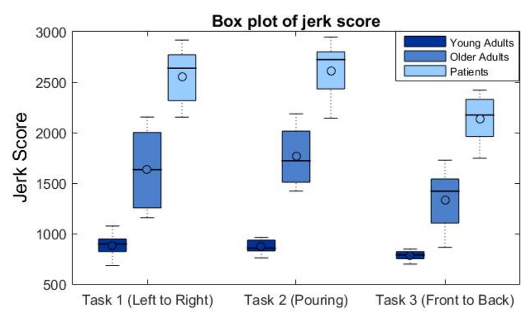

Figure 9. Error bar comparison of Jerk score among three groups.

to complete a task (Fig. 8 a) is a metric commonly used in rehabilitation as many assessments use stopwatches. Similar to what is recorded in the literature, young adults demonstrate the least amount of time and little variability in their response [34]. Comparatively, older adults require more time and individuals with movement impairment require even more time and demonstrate increased variability. Beyond, time to completion QM-FOrMS offers further metrics that better informs the users of the motor performance. Fig. 8 (b) shows individuals with movement impairment use more force to put the Smart Can on the Smart Mat. Examination of velocity related data indicates they were unable to smoothly decelerate the Smart Can. Fig. 8 (c) shows that young adults achieved 100% accuracy in placing the Smart Can on the target, while individuals with movement impairment were apt to place the can farther from the target. The metric that most clearly illustrated difference in motor performance between the three groups was the normalized jerk score (Fig. 9). Young adults have the lowest jerk score whereas the individuals with movement impairment have the greatest jerk score. The combined data from QM-FOrMS clearly depicts 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. QM-FOrMS can track and encourage improvements through collecting data and providing feedback.

VI. 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 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 future work, we plan to apply QM-FOrMS with a large cohort of in-home upper extremity rehabilitation.

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