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# Development of an EMG-ACC-Based Upper Limb Rehabilitation Training System

Ling Liu, Xiang Chen*, Zhiyuan Lu, Shuai Cao, De Wu, Xu Zhang

***Abstract*— This paper focuses on the development of an upper limb rehabilitation training system designed for use by children with cerebral palsy (CP). It attempts to meet the requirements of in-home training by taking advantage of the combination of portable accelerometers (ACC) and surface electromyography (SEMG) sensors worn on the upper limb to capture functional movements. In the proposed system, the EMG-ACC acquisition device works essentially as wireless game controller, and three rehabilitation games were designed for improving upper limb motor function under a clinician's guidance. The games were developed on the Android platform based on a physical engine called Box2D. The results of a system performance test demonstrated that the developed games can respond to the upper limb actions within 210ms. Positive questionnaire feedbacks from twenty CP subjects who participated in the game test verified both the feasibility and usability of the system. Results of a long-term game training conducted with three CP subjects demonstrated that CP patients could improve in their game performance through repetitive training, and persistent training was needed to improve and enhance the rehabilitation effect. According to our experimental results, the novel multi-feedback SEMG-ACC-based user interface improved the users' initiative and performance in rehabilitation training.**

***Index Terms*— Cerebral Palsy, rehabilitation, accelerometer, electromyography, Android**

## I. Introduction

Cerebral palsy (CP) is a non-progressive disorder of movement or posture due to an anomaly of the developing brain [1]. Motor dysfunctions, such as dysbasia or a limited range of motion, are the most frequently occurring symptoms in children with CP. These motor dysfunctions are usually of special concern to most clinicians and families. Rehabilitation training for children with CP, especially upper limb motor rehabilitation, has attracted more and more researchers' interests because of its importance in improving the quality of life and independence of the patients. Other common symptoms affecting the arm and hand in CP patients include dystonia, spasticity and sensory impairment [2]. These motor and sensory impairments result in difficulties in reaching, grasping and rotating. Therefore hand movement and joint motion rehabilitation training are important for upper limb motor recovery. Patients additionally require a long rehabilitation process even after their initial clinical treatments. Most clinical rehabilitation methods for upper limb dyskinesia, such as occupational therapy (OT), need the presence of at least one therapist during the rehabilitation session to assist the patient. However, with the increase in the CP patient population size, a shortage of therapists has become a severe challenge. In addition, long rehabilitation training cycles with high hospitalization costs are beyond the economic capabilities of most families.

Recently, home rehabilitation [3]-[5] has increased in popularity because of the familiarity of the home environment as well as the ease of potential long-term rehabilitation training. Besides the advantage of reducing financial burden, the home environment also has the benefit of training time flexibility. Based on the needs of home rehabilitation, the design and development of a rehabilitation prototype has become a research focus in many institutions. For instance, Daniel Cioi et al. [6] provided patients with a mechanically assisted device to train ankle strength, and rehabilitation robotics were used for passive training in severe patients. Meghan Huber et al. [7] piloted their remotely monitored in-home gaming technology for improving hand function using an ultra-sensing glove. Different game principles are also being applied to help motivate CP patients to complete these in-home rehabilitation trainings. C. Bryanton et al. [8] demonstrated that game-based exercise may improve exercise compliance and enhance exercise effectiveness. Mason E. Nixon et al. [9] also utilized game design principles to develop a therapy game for upper extremity rehabilitation. Additionally, with the advent of various commercial game development platforms such as the Wii, Xbox, and PlayStation, researchers have combined these technologies with virtual rehabilitation and showed that good performance can be obtained in Virtual Reality (VR) based rehabilitation games [10]-[12].

Most of these training systems consist of two parts: motion data acquisition modules and corresponding rehabilitation training software. Home rehabilitation training systems face a lot of problems, especially in motion data acquisition. Accurate motion capture data is very important for a robust motor rehabilitation prototype. Cameras, inertial sensors, or data

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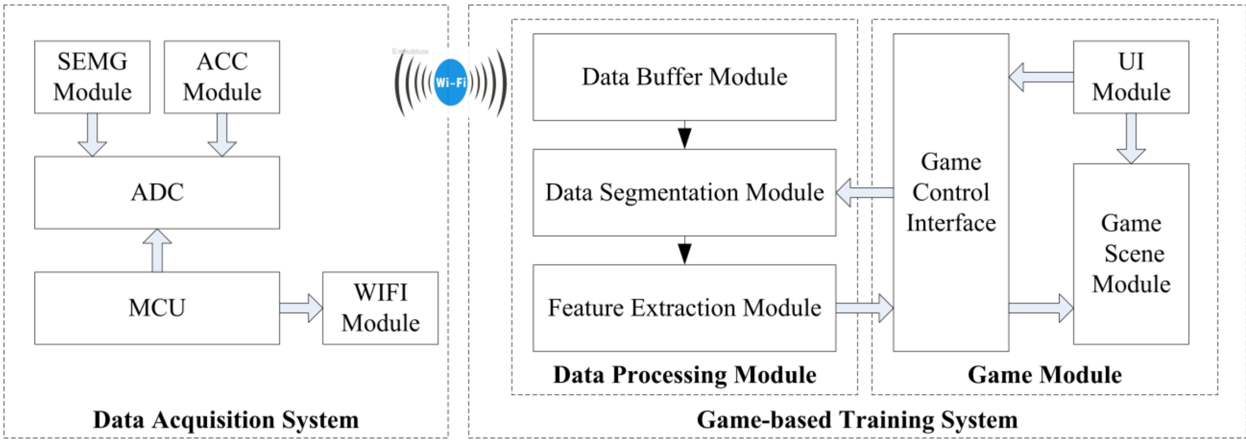


Fig. 1. Structure of the EMG-ACC-Based Upper Limb Rehabilitation Training System, SEMG represents surface electromyography, ACC represents accelerometer, ADC is Analog to Digital Converter, MCU is Micro Controller Unit, and UI means User Interface.

gloves are some of the most commonly used motion capturing techniques. However, most rehabilitation training prototypes based on these techniques are unsuitable for home use or are hard to implement for children with CP. For instance, a data glove can detect fine hand motions such as finger flexion or extension, but it must be personally customized to fit different users. Conversely, universal systems such as the Wii or PlayStation require players to hold a game controller, which may be difficult for patients with CP. Microsoft Kinect can provide a better game experience with no need to hold a game controller but it is still a challenge to detect fine motions such as wrist rotations.

SEMG sensors and accelerometers are also widely used to capture motion, and are both suitable for wearable applications. Not only useful in measuring control and biofeedback information [13]-[18], EMG can also provide significant motion-related information for rehabilitation assessments [19]-[20]. Accelerometers are also an important sensor for motion data capture, and have been integrated into most new smartphones. Accelerometers have already been widely integrated into wearable health-monitoring devices for gait detection and fall detection [21]-[23]. In addition, accelerometers have been used in rehabilitation games to provide feedback information [24].

Our pilot studies demonstrated that combining SEMG and ACC in training applications could produce better results [25]-[27]. Qian Wang et al. [26] presented a framework of gait analysis for children with cerebral palsy using SEMG and ACC signals. Zhiyuan Lu et al. [25] proposed a gesture based interactive system based on SEMG and ACC. Based on our previous research findings, this paper aims to provide an EMG-ACC game-based upper limb rehabilitation system prototype for home use, which includes a wearable game controller and several games on Android designed for specific functional training.The rest of the paper is organized as follows: In part II, a system overview is presented including the system framework and the developed rehabilitation games; Part III introduces the experimental setup and results; Part IV includes discussion and future work; Part V gives a conclusion.

## II. System Overview And Game Design

### A. *The Rehabilitation Training System Overview*

The developed rehabilitation training system consists of two parts: the data acquisition system and the game-based training system (Fig. 1). The data acquisition system was designed to capture the joint motion signals (ACC) and muscle activity signals (SEMG). The game-based training system was developed on the Lenovo Pad Idea Tab S6000-F (1.2GHz ARM CPU, 1G RAM, WIFI support, running Android 4.2 OS). As a wireless system, the communication mechanism between them was designed by using the Client/Server mode, in which the data acquisition system works as the server, while the training system is designed as the client. TCP/IP based socket was adopted to send/receive signals between the server and client.

### B. *Training Objectives and Tasks*

To meet the requirements of upper limb motor rehabilitation and guarantee the effectiveness of the designed games, we consulted a clinician and therapist about what kind of rehabilitation training tasks would usually be prescribed to improve specific motor dysfunctions. Several common symptoms of upper limb dysfunction were given according to the local clinician's descriptions and observations:

- Limited extension of elbow and fingers
- Limited supination or pronation of the forearm
- Low finger force

Others (e.g. Thumb abduction)Considering both the needs of these symptoms and the capabilities of our motion detection technology, three specific training tasks were designed and mapped into three task-oriented games in our system. The games focused on improving the flexibility of wrist joints, elbow joints, and the ability of finger force control. These three tasks were:

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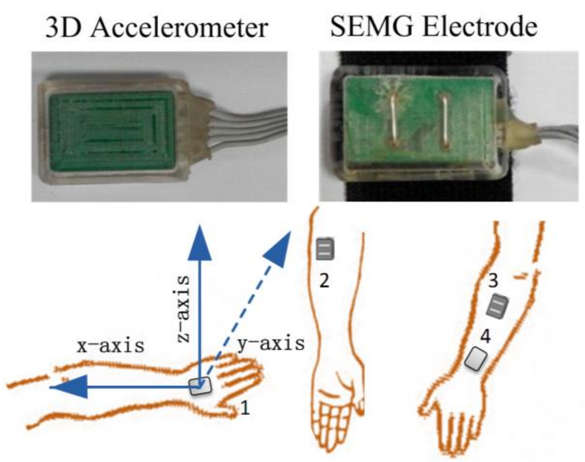



Fig. 2. The sensor setup of the 3D accelerometers and SEMG electrodes. The 3D accelerometers should be placed at the targeted positions 1 and 4 with x-axis along with forearm. The SEMG sensors should be placed on the targeted muscles with the two electrode bars perpendicular to the muscle fiber direction. Position 2 represents the flexor carpi radialis and position 3 represents the extensor digitorum.

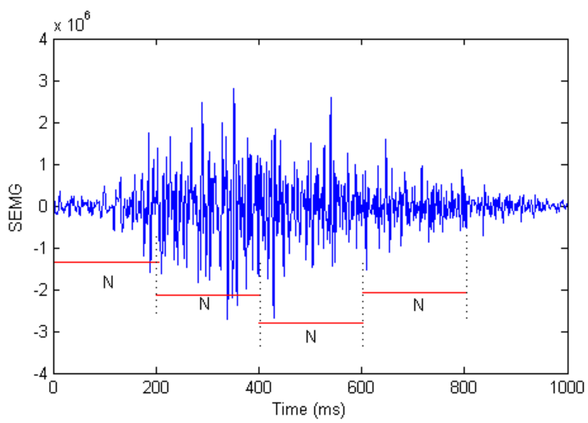
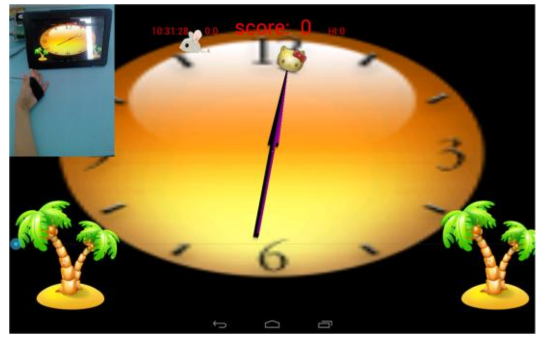



Fig.3. The non-overlapped windowing method applied to the baseline eliminated SEMG. The vertical axis displays the amplified SEMG. N is the length of window.

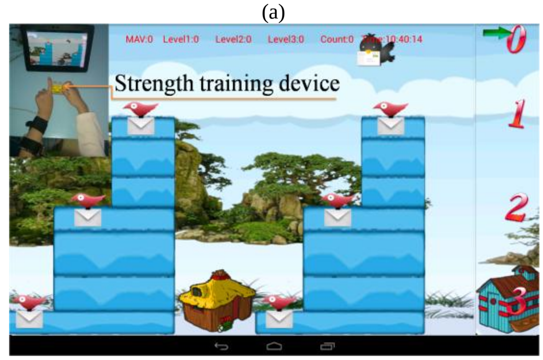
- Rotate the affected forearm or wrist with the arm on a table (supination or pronation).
- Press the strength training accessories using different levels of finger force.
- Flex/extend the affected elbow joint or lift the affected arm vertically.

## C. Data Acquisition System

According to the training objectives and tasks, four sites on the forearm were chosen for the sensors (Fig. 2). The data acquisition system was designed to be a customized multi-channel SEMG-ACC signal capture device which consists of five main modules as shown in Fig1. The SEMG and ACC Modules were connected to the ADC (Analog to Digital Converter), which collects the motion data. The microcontroller reads the data from the ADC and then sends it out using the WIFI Module. The SEMG Module contains two bipolar Ag-AgCl surface electrodes, and both filter and amplifier circuits. A 35mm×25mm×8mm electrode was adopted to record the raw SEMG signals from the skin. The surface SEMG recordings were first filtered by a band-pass




(a)

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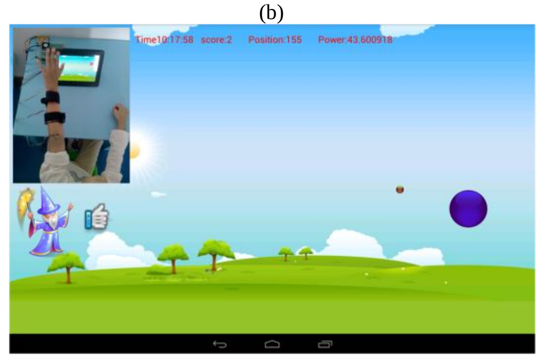

(c)

Fig. 4. Screenshots of the three games: (a)-Catch the Mouse, (b)-The Post Bird, (c)-Shoot the Ball.

filter with cut-off frequencies of 20 Hz and 500 Hz, and then amplified by 1200 times. The ACC Module includes one tri-axis accelerometer (Freescale Semiconductor, MMA7361L) and related decoupling and filtering circuits. The sampling rate was 1 kHz for the SEMG signals and 100 Hz for the ACC signals.

## D. Data Processing Module

The Data Buffer Module (Fig. 1) was designed to receive and parse the raw data format and then store the multi-channel signals into a data buffer. During the data parsing, the raw SEMG signals are preprocessed by removing the mean value of baseline noise and the tri-axis values of ACC are calibrated using the rotation method [28] to get the calibration coefficient; In the Data Segmentation Module, the preprocessed SEMG stream is divided into frames with a length of N=200ms utilizing the non-overlapped windowing method depicted in Fig 3. Feature extraction for SEMG is implemented on every frame. The Feature Extraction Module is designed to extract the corresponding motion features including angle and muscle activity information. Here, angle information is obtained by

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utilizing the calibrated tri-axis values. The angle $\varphi$ is calculated by the formula as bellow:

$$\varphi = \arccos\left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right) \quad y \le 0 \tag{1}$$

$$\varphi = 2\pi - \arccos\left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right) \quad y > 0 \tag{2}$$

In equation (1) (2), $x, y, z$ are the calibrated tri-axis values. During the y-z plane rotating around the x-axis as shown in Fig 2, $\varphi$ directly represents the orientation of z-axis in 3-D space, and the range of $\varphi$ are $0\text{-}\pi$ in equation (1), $\pi\text{-}2\pi$ in equation (2), so the total range is $0\text{-}2\pi$ .

For quantifying muscle activity, the MAV (Mean Absolute Value), RMS (Root Mean Square), MDF (Medium Frequency) were extracted as the main features:

$$MAV_t = \frac{1}{N}\sum_{i=1}^{N} | SEMG_{t-i} | \tag{3}$$

$$RMS_t = \sqrt{\frac{1}{N}\sum_{i=1}^{N} | SEMG_{t-i} |^2} \tag{4}$$

$$\int_{0}^{MDF} P(f)df = \int_{MDF}^{\infty} P(f)df \tag{5}$$

In equation (3), $MAV_t$ is the mean absolute value of SEMG during the time segment from t-N to t, $N$ is the length of window. In equation (5), $P(f)$ is the frequency spectrum of SEMG from t-*N* to t.

### *E. Rehabilitation Training Game Design*

The key factors for the game design include adapting the training games to the patients' motor dysfunction, by providing effective feedback and adapting to different patients' motor ability. Based on the previously mentioned tasks, three task-oriented movement exercise games were designed for the finger, wrist, and shoulder joints (or elbow joint) of CP patients. A physical engine, Box2D, was adopted to enable combining a motion control game with visual, audio, and perceptual feedback information, aiding the CP children in accomplishing the game tasks. As shown in Fig. 1, there are three parts in the Game Module. The UI Module is the direct configuration interface for the end-user, and the Game Control Interface is invoked by the UI module to get the motion feature to control the corresponding game in the Game Scene Module. In the following, three games are introduced in detail.

*ACC-based Game: Catch the Mouse*

The game called Catch the Mouse shown in Fig. 4(a) was designed to prompt the patient to try their best to rotate their arm or wrist to control the cat's rotation on the clock. In this game, the ACC is placed on the back of the hand with the x-axis along the user's forearm as shown in Fig. 2 (Position 1). The orientation of the z-axis (quantified by an angle $\varphi$ ) directly represents the palm's position in space. Based on this knowledge, $\varphi$ is mapped into the cat's position on the clock. When the palm is down ( $\varphi$=180$^o$ ), the arrow with the cat points to six; while when the palm is up ( $\varphi$=0$^o$ or 360$^o$ ), the arrow points to twelve. If palm faces left ( $\varphi$=270$^o$ ), the arrow points to nine, conversely if to the right, it points to the three ( $\varphi$=90$^o$ ).

The task for the player in this game is to help the cat catch the mouse. Each successful encounter is rewarded with one point accumulated as the score. Meanwhile, once the mouse is caught, the mouse will squeak and blink, then it will run away to a random "safe place" (far away from the cat). The progress bar in the bottom of the screen is designed to adjust the mouse's position if the player can't catch the mouse. During the training process, the score, trained time and the position of the cat are shown on the top of the screen. In this game, the player needs to rotate his wrist back and forth to accumulate higher scores. Flexibility of the wrist movement is intended to be improved by repetitive joint rotation in the game task.

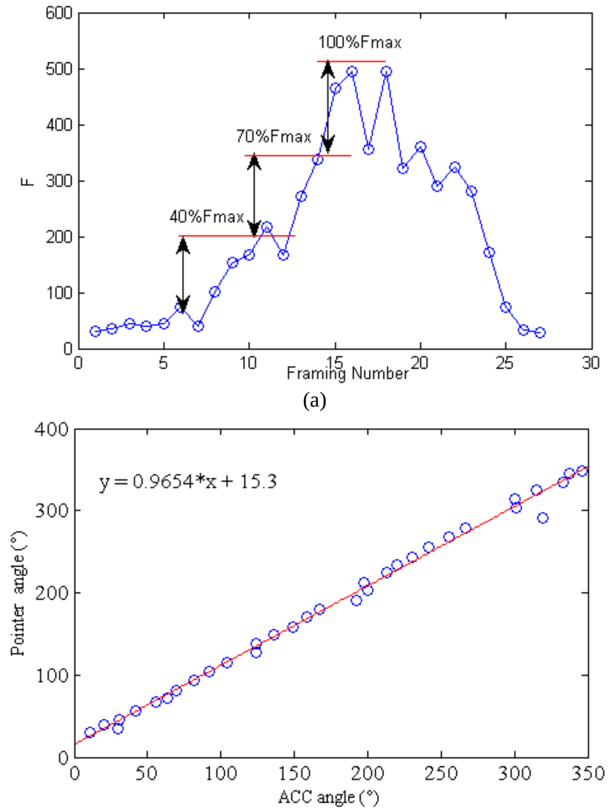
*EMG-based Game: The Post Bird*

The EMG-based game shown in Fig. 4(b) is designed to guide the CP patient to extend or flex fingers voluntarily to control the up-down movement of the flying bird. A SEMG electrode should be placed on the flexor carpi radialis as shown in Fig. 2 (Position 2). In this game, the bird flies in the sky with velocity $V$ in the horizontal direction. The player needs to pull it down by flexing or pressing his finger(s) so that the bird can deliver letters to the destination houses. The downward traction F applied to the flying bird is controlled by the MAV of the SEMG signals as:

$$F = A * MAV_t \qquad MAV_t > Th \tag{6}$$

In equation (6), $A$ is a constant coefficient which can be set in the user configuration interface. The threshold value $Th$ is defined to determine when the player's finger force would make the bird fly down; $Th$ can be explained as a difficulty coefficient which is set before playing the game. Furthermore, the vertical force F was quantized into three levels according to its proportion to the force $F_{max}$ during maximal voluntary contraction (MVC): If F is smaller than 40% $F_{max}$, the bird can only reach to the height of the top step; if F is above 70%$F_{max}$, the bird can reach to the bottom step; otherwise, it flies at the height of the middle step. The three steps are marked blue in Fig. 4(b).

A letter is delivered only when the bird reaches the house following the 3 steps, which requires the player to achieve and maintain specific force levels. During the training process, the current MAV and the number of successfully finished tasks are shown on the top of the screen. The green arrow and red numbers on the left of the screen were designed to indicate the real-time finger strength level. This game is intended to enhance the CP sufferer's hand-eye coordination, finger




(a)

(b)

Fig. 5. (a): The profile of the vertical force $F = A * MAV_t$ for 5 seconds with the window length N=200ms, A=1000. $F_{max}$ depends on personal maximal voluntary contraction ability and can be set in UI. (b): The linear regression result for accelerometer angle and pointer angle in the game of Catch the Mouse.

flexibility, and strength control ability through repetitive finger extension and flexion tasks.

*ACC-EMG-based Game: Shoot the Ball*

This game shown in Fig. 4(c) is developed to motivate CP patients 1) to flex/extend their elbow joint or lift their arms vertically in order to control the height of the magician and 2) to extend their fingers (shooting gesture) in order to shoot magic balls to hit the targets. The Magician was controlled by an ACC on the back of the forearm (Position 4 in Fig. 2) and a SEMG electrode on the extensor digitorum muscle (Position 3 in Fig. 2). Only the calibrated z-axis value is mapped into the height of the magician using formula (8) where B is a constant. A magic ball is shot if $MAV_t > Th$ and the speed of the ball is directly controlled by $V$ defined in equation (9) where C and D are constants. The threshold $Th$ can be adjusted to adapt for different player's level using the scrollbar in the game scene.

$$Pos = B * z \quad (8)$$

$$V = C * MAV_t + D \qquad MAV_t > Th \quad (9)$$

After it is shot, the ball moves horizontally to the right. If it hits the target, the player gets one point. Subsequently, a new target will appear on a random position on the right side of the screen to indicate the start of another trial. Also, the position, score, and the present MAV are shown on the top of the screen. During the training process, the player is required to reach the corresponding height of the ball by adjusting the position of his/her arm. Shoulder or elbow joint movement, as well as finger extension are intended to be trained by playing the game.

## III. System Tests and Results

### A. System Performance Test

To examine the performance of the designed rehabilitation games, we tested the total time delay and the accuracy of the game control strategy. These two aspects are the basic factors in ensuring a positive experience. In an interactive application, the system delay must be acceptable. The total time delay was calculated from the moment when the data acquisition system began to capture the motion data to the moment when the Game Scene Module got the game control signal. This was adopted to depict the delay performance of our proposed system. From the structure of the system, the total delay primarily consists of the network (WIFI) delay and the application response time. The application response time includes data processing time and the response time of the game control interface. For each game's application response time, we tested ten times and got the average delay to represent the system delay. For Catch the Mouse, the average delay was about 84ms. For The Post Bird and Shoot the Ball, the average delays were about 208ms and 95ms respectively.

For the game called Catch the Mouse, we also tested the accuracy of the angle mapping strategy. We made the y-z plane rotate around around the x-axis, computed the ACC angle ($\varphi$) in space and mapped it to the pointer's angle in the game scene at the same time. By calculating the linear correlation coefficient $R$ between them, this mapping strategy was proven to be feasible with an $R = 0.9654$ as shown in Fig. 5(b).

### B. Game Training Test

In order to evaluate the feasibility, usability, acceptability of the developed system and the effectiveness of the game-based rehabilitation training, a series of experiments were conducted in the First Affiliated Hospital of Anhui Medical University, with the approval by the institution's Ethics Review Committee.

*Game Experience Test*

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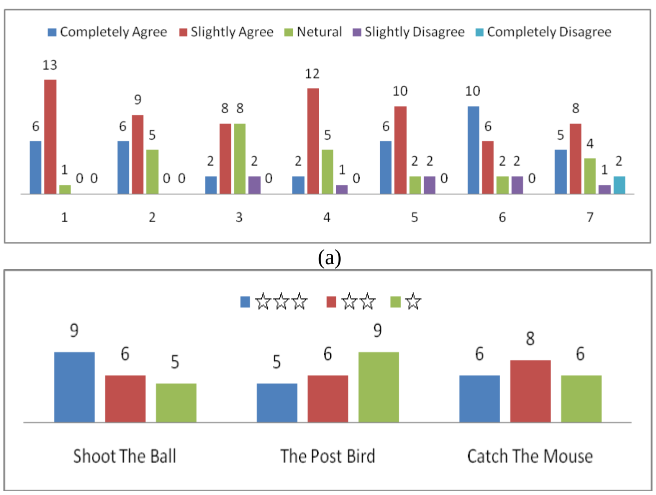
TABLE I
QUESTIONNAIRE

| Questions | Score | STD |
|---|---|---|
| 1. It is comfortable to wear the game controller, 1= uncomfortable / cried while wearing, 3=tolerable uncomfortable, 5=comfortable. (comfort) | 4.25 | 0.55 |
| 2. The given information and guide in the games are easy to understand, 1=didn't understand / moved randomly even with additional explanation, 3=didn't understand until additional explanation was given, 5=understood within several trials. (understandability) | 4.05 | 0.76 |
| 3. The games are easy, fast to feel sense of accomplishment, 1=couldn't play at all, 3=terminated halfway because of frustration, 5=accomplished with joy. (easiness) | 3.50 | 0.83 |
| 4. The feedback information of score, sound and graphic help me to finish the games better, 1=hated it / don't want to play, 5=tried to get higher score / turned happy because of the sound or animation effects. (efficacy of feedback) | 3.75 | 0.72 |
| 5. The games are interesting, motivating for me, 1=refused to start, 5=tried to get higher scores / tried different ways to see what would happen. ( interestingness) | 4.20 | 0.92 |
| 6. I can focus during the game-based training, 1=was always looking around, 5=was always concentrated and was willing to play longer. (attention) | 4.20 | 1.01 |
| 7. I can feel the fatigue during the game training, 1=too tired so that terminated halfway, 3=was tired, 5=wasn't tired. (fatigue) | 3.65 | 1.23 |




(a)

(b)

Fig. 6. The questionnaire results of game experience test. The numbers on the column chart (a) represent the quantity of the participants who showed the corresponding attitude. The numbers on the column chart (b) represent the quantity of the participants who showed preference for the corresponding game. ☆☆☆means like very much. ☆☆means not bad, ☆means do not like.

To examine the user experiences of the system, twenty CP subjects (CP1-CP20, 8 males, 12 females, 8.7 ± 2.8 year old) from the Affiliated Hospital of Anhui University were recruited to participate in the game experience test. Inclusion criteria for CP children were: a) be diagnosed with cerebral palsy; b) have no history of other diseases that also lead to motor deficits; c) able to move voluntarily; d) have normal cognitive capacity; e) have not taken similar game-based rehabilitation training before. All the subjects were recruited with their guardians' written consent. During the test, the subject (player) sat comfortably on a chair wearing the game controller (ACC and/or SEMG sensors) as shown in Fig. 2, and were asked to play these three games using the hand to be trained (usually the right hand). The three games were introduced to the subject one by one in a random order. The subject had enough time to learn how to play, and kept playing one game until he/she wanted to switch to the next. The training time of each game was recorded by the system. After playing the three games, they were asked to fulfill a questionnaire and give a rank to these three games with their Guardians. Guardians needed to communicate with the subjects about their feelings in order to help fulfill the questionnaire. The questions listed in Table I contain seven aspects: comfort, understandability, ease, efficacy of feedback, interestingness, attention, and fatigue. A five-point scale from 1 (completely disagree) to 5 (completely agree) was used to assess the seven aspects. Scoring instructions (Table I) were presented on the questionnaire in order to make scoring as objective as possible and to ensure consistency in case subjects were unable to express the feelings directly.

TABLE II
THE SELF-SELECTED TRAINING TIME FOR THE THREE GAMES OF TWENTY CP PARTICIPANTS

| Subjects (G,A,H,T) | Train Time (minutes) | | | |
|---|---|---|---|---|
| | Game I | Game II | Game III | Total |
| CP1 (M,8,L, athetoid) | 5 | 6 | 9 | 20 |
| CP2 (M,10,L, atonia) | 8 | 8 | 18 | 34 |
| CP3 (F,12,L, athetoid) | 7 | 8 | 11 | 26 |
| CP4 (F,10,R, spastic) | 6 | 5 | 6 | 17 |
| CP5 (F,9,R, atonia) | 8 | 6 | 13 | 27 |
| CP6 (M,13,L, spastic) | 8 | 13 | 16 | 37 |
| CP7 (M,9,R, spastic) | 5 | 7 | 10 | 22 |
| CP8 (F,6,R, atonia) | 0 | 0 | 0 | 0 |
| CP9 (F,3,R,mixed) | 5 | 6 | 5 | 16 |
| CP10 (M,3,R,mixed) | 6 | 3 | 5 | 14 |
| CP11 (F,12,R, atonia) | 8 | 12 | 6 | 26 |
| CP12 (F,11,R, spastic) | 5 | 9 | 4 | 18 |
| CP13 (F,8,R, athetoid) | 7 | 7 | 4 | 18 |
| CP14 (M,9,L, spastic) | 2 | 9 | 6 | 17 |
| CP15 (F,8,L, spastic) | 5 | 8 | 8 | 21 |
| CP16 (M,8,R, spastic) | 0 | 7 | 4 | 11 |
| CP17 (F,8,R,athetoid) | 11 | 6 | 6 | 23 |
| CP18 (M,13,L, spastic) | 7 | 11 | 10 | 28 |
| CP19 (M,6,R, spastic) | 6 | 9 | 8 | 23 |
| CP20 (M,8,R,athetoid) | 5 | 3 | 3 | 11 |
| Average | 5.7±2.7 | 7.2±3.1 | 7.6±4.4 | 20.5±8.4 |

Abbreviation: G-Gender, A-Age (years), H-Side of the Tested Hand, T-Type of the CP sufferer; F-Female, M-Male, L-Left, R-Right; Game I represents Shoot The Ball, Game II represents The Post Bird, Game III represents Catch The Mouse

The right part of Table I gives the average score and standard deviation (STD) for each question. Positive feedback (score>4.0) was achieved on comfort, understandability, interestingness, and attention. Fig. 6(a) shows the distribution of the scores for the seven questions. Only one subject preserved a neutral attitude on question 1 who disliked the indentation on her skin caused by the SEMG electrodes. 5 participants needed additional explanations before playing the game (relevant to the question 2 of the questionnaire). 70% of the participants said they benefited from the game elements such as sound and graphics, while some subjects felt the game task was a little difficult. Most participants had the feeling of fatigue (according to question 7) and were motivated by and attracted to the games (according to question 5).

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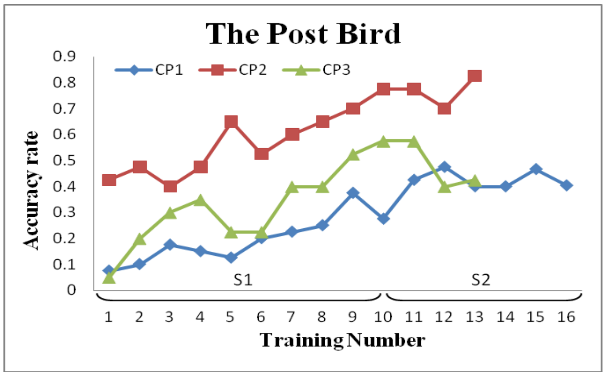
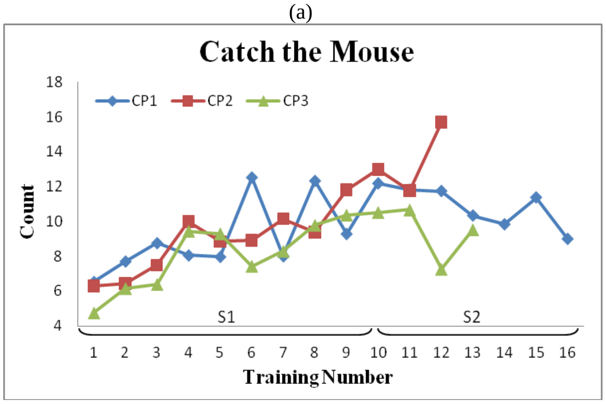
TABLE III
THE DETAILED INFORMATION FOR THREE SUBJECTS

| Subject | Gender | Age | Type | FMA(66) | ADL(156) |
|---|---|---|---|---|---|
| CP1 | M | 8 | Athetoid | 44 | 108 |
| CP2 | M | 10 | Atonia | 56 | 135 |
| CP3 | F | 12 | Athetoid | 57 | 141 |




(a)

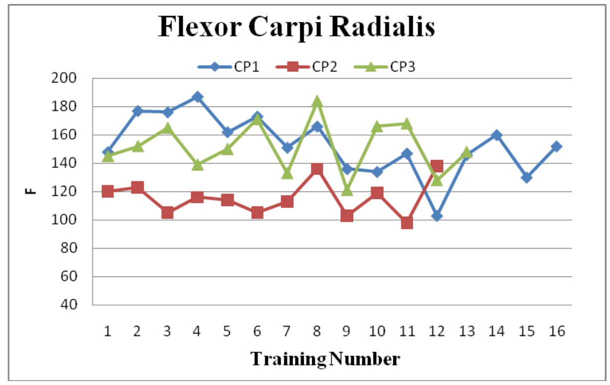



(b)

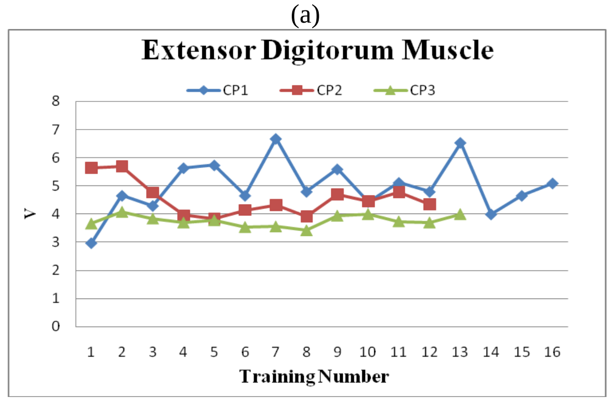
Fig. 7. The training effect test results of The Post Bird (a) and Catch the Mouse (b). Accuracy rate represents the proportion of the correctly finished tasks in The Post Bird. Count was defined as the average points earned per minute in Catch the Mouse.

TABLE IV
THE MEAN VALUE AND STANDARD DEVIATION OF SEMG RELATED DATA DURING THE TRAINING

| AVE/ STD | CP1 | CP2 | CP3 |
|---|---|---|---|
| F | 153 / 22.64 | 115 / 12.45 | 152 / 18.57 |
| V | 4.98 / 0.99 | 4.54 / 0.61 | 3.78 / 0.20 |




(a)




(b)

Fig. 8. The SEMG-related data F (a) and V (b) during the whole training circle. F represents the mean force applied to the bird when the bird arrives at the house. V represents the average velocity of the bullet V in Shoot the Ball.

Personal preferences for the three games were shown in Fig. 6(b). Generally, both Shoot the Ball and Catch the Mouse were more popular than The Post Bird. Furthermore, we observed that among the nine subjects with spasticity (CP4, CP6-CP7, CP12, CP14-CP16, and CP18-CP19), only CP4 marked “Catch the Mouse” as his favorite game. Among the five athetoid CP patients (CP1, CP3, CP13, CP17, CP20), no one marked “The Post Bird” as their favorite game. Two (CP5, CP8) of the four subjects with atonia (CP2, CP5, CP8, CP11) showed little interest in “Shoot the Ball”. In addition, some of the children gave their reasons why they liked these games including: 1) the mouse’s squeak was interesting and changing color attracted their attention, so that they were interested in catching the cunning mouse; 2) they were glad to see the magician controlled by their hands. They liked shooting the target because they were able to control the speed of the ball.

Subjects could focus on the three games for a total of 20.5 ± 8.4 minutes on average as shown in Table II. It can also be found that the older subjects (10 subjects, 9-13 years old, 25.2 minutes averagely) could focus significant longer ($p=0.013<0.05$, $U=16.5$, Mann-Whitney U Test) than the younger subjects (10 subjects, 3-8 years old, 15.7 minutes mean time) if grouping subjects by age. 2 subjects in the younger group even failed to focus on more than one of the games. According to the subjects’ guardians, most of our subjects seemed to be able to focus longer on our game-based training than traditional therapies.

*Training Effect Test*

To examine the training effect of using the designed system, three subjects (CP1-CP3) were selected from the previous 20 to participate in long-term game intervention training. The upper-extremity subsection of the Fugl-Meyer Assessment (FMA, 0 = lowest score, 66 = highest score) scale [10] was used for a measurement of impairment. A local ADL scale (ADL, 0 = lowest score, 156 = highest score) for upper-extremity was used to evaluate the subjects’ ability to eat, drink, wear clothes etc. Detailed clinical information of these three subjects is given in Table III. These three subjects were chosen because they showed great interest in participating in this test. They were also able to 1) make the cat and the mouse meet at least forty times in Catch the Mouse, 2) help the flying bird to arrive at forty destination houses in The Post Bird, and 3) shoot at least sixty targets in the game of Shoot the Ball in one visit.

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This long-term training consisted of two stages. In the first stage (S1), all the subjects received about 30mins/visit of game intervention training in one month (2-3 visits per week). The second stage (S2) was conducted once a week (about 30mins/visit) for one and a half months following the S1 stage. CP2 and CP3 had shorter training times in S2 to accommodate their school work. During the training period, the subjects' performances in each game were recorded (Fig. 7 and Fig. 8). The horizontal axis of each figure indicates the training number and the vertical axis shows the game-related data including accuracy rate, count (the average points earned per minute in Catch the Mouse), the average velocity of the bullet V in Shoot the Ball and the average force F when the bird arrives at the house in The Post Bird.

## IV. Discussion and Future Work

### *A. System Design*

The EMG-ACC game-based training system was specially developed to facilitate upper limb motor recovery in CP children. Fast-response times and accurate game control in the system guaranteed a positive interactive experience. All these three games could respond within 300ms, which is considered a requirement for a real-time EMG-controlled system [29], [30]. The game experience questionnaire also demonstrates this usability. The results of the long-term training additionally reflect on the CP patients' ability to improve their game performance through repetitive game training.

Although all of our experiments required separate visits to the hospital, we believe that the training system could easily be setup at home. The application program (with built-in games) can be installed on an Android device such as a mobile phone, and our acquisition system can work well if Wi-Fi is available. At most two sensors are required in one game, and our sensors are not sensitive to the exact position of placement. As long as the accelerometers are placed horizontally when the hand is in a horizontal position, and the SEMG sensors are placed around the positions marked in Fig. 2, our system should be able to adapt to the differences in session to session placement. We believe it should be simple for the guardian to find the right positions.

The proposed training system was developed for Android because it is a popular operating system and available on most mobile/tablet devices, making it quite applicable for home use. In fact, in recent years, there have been several attempts to develop rehabilitation applications on the Android platform for CP or stroke patients. For instance, Shuo Qiao et al. [31] proposed an inertial sensor-based system and developed a gesture-learning game on Android for wrist rehabilitation. Dario Deponti et al. [32] also provided an Android-based application for wrist rehabilitation using the internal accelerometer and camera of the phone itself. Younggeun Choi et al. [33] presented a home-made data glove and implemented a "Pick & Move" rehabilitation exercise in their augmented reality (AR) game on Android. Each presented the system architecture and provided a training game. Comparatively speaking, our system contains more training games while also combining SEMG sensors and accelerometers for upper limb motor recovery.

The wearable EMG-ACC based game controllers also provide intuitive and interesting interactions with the system. More and more commercial gaming platforms have been employed in CP rehabilitation and have shown great applicable value [34]. In traditional game systems, CP patients usually must hold a game controller in order to use these platforms for upper limb training (e.g. Sony PlayStation Move and Wii). However, this is not an easy task for most CP patients. Microsoft Kinect is easy to use, but is unable to detect either force levels or fine motions such as axial arm rotation [35]. Using our proposed system, CP patients can move their upper limb freely while a wearable EMG-ACC capture device records their hand and arm motions. This kind of input device was attractive to our CP subjects without causing sensible discomfort according to the questionnaire.

Lastly, multiform feedbacks were provided in the proposed training games which improved subject interest and involvement. Feedback is often advocated for proper game-based rehabilitation training systems. The most frequently-used method is to build a direct mapping strategy between the real motion and the virtual movement. For instance, a patient wearing a data glove can control a virtual hand that moves exactly the same as the patient's hand to finish some daily activities in a simulated world (the game sense). CP children are hardly interested in such kinds of feedback, but they were attracted by the graphic and audio feedbacks in our games according to the questionnaire. By means of mapping the features into the real game scene, players could directly feel how their movement controlled the game sprites. Meanwhile, SEMG can also provide force-related feedback. However, the score as a textual feedback did not motivate everyone because some patients had no sense of numerical information. Although there were no "game over" or "time up" messages in our games, scores and times could be hidden in case they stress the subjects (none of our subjects was stressed by the score or time during our experiments).

### *B. Training Performance*

As shown in Fig. 7 (a) and (b), all the subjects yielded improved their game performance during the long-term training. The improvement of accuracy in The Post Bird indicated that the subjects became more skilled in controlling their finger strength. Meanwhile, the rising count indicated that they could rotate their wrist more accurately and rapidly after the task-oriented training. In other words, the uptrend in both accuracy and count reflected their improvement in motor control. This is presumed to have been obtained through the repeated actions during the long-term game intervention training. From Fig. 7, we can also observe that, when the training interval was extended during S2 stage, the accuracy rate did not show significant increase nor any decline. Count also decreased sometimes for CP1 and CP3. These results indicate that keeping continuous and moderate-intensity rehabilitation training is the basic criterion needed for improving motor function. The different game performances also can be seen from Fig.7 (a). CP2 maintained a better game performance (higher accuracy rate than CP1 and CP3) in every trial to play "The Post Bird". CP2 also showed great promise in achieving a higher level from the increasing accuracy and count. CP3 also made greater progress than CP1 during the first stage (accuracy rate in S1, CP3-5% to 57.5%, CP1-7.5% to 27.5%).

As CP2's flexor muscle and CP3's extensor muscle revealed weakness in physical examination, we investigated the training effect on flexor carpi radialis and extensor digitorum according to the SEMG-related parameters: F and V. As shown in Fig. 8, there was no significant improvement in F for CP2 during the long term training. As for CP3, V stayed nearly unchanged during the whole training. However, we cannot conclude that this training had no effect on improving their muscle weakness. More training is likely needed to show improvements in muscle strength. Additionally, the CP children varied greatly in impairment level and motor dysfunction. The main problem for CP2 was hypotonia, while for CP1 and CP3, muscle over activity or involuntary muscle activity affected their motor function. The mean value (AVE) and standard deviations (STD) of F and V for the three subjects were calculated and recorded in Table IV. Based on the diagram and statistical results, we compared the differences in the same type CP patients (athetoid type, CP1 and CP3), and the differences between the two types of CP patients. Here, wide fluctuation range in F and V can be seen for CP1. However, there is little fluctuation in V for CP3 (V, AVE=3.78, STD=0.20). As compared to CP1 and CP3, F and V remains relatively stable for CP2.

Although our preliminary game-based rehabilitation scheme obtained good performance in attracting and motivating CP patients in training, the rehabilitation training effect was found to be related to the severity and the type of motor dysfunctions. CP1 and CP3 are both athetoid patients, so their poor performances are directly related to their motor deficits. We found that CP3 made greater progress than CP1 during the first training stage (Fig. 7 (a)). In fact, during the training, there were more involuntary tremor movements occurring in CP1's finger motions, including bend and stretch. Here, the FMA score (FMA, CP3>CP1, Table III) and fluctuation in SEMG-related data F (STD, CP3>CP1; AVE, CP1≈CP3, Table IV) may be related to different levels of abnormal muscle contraction as muscle tone fluctuates with voluntary movement for patients with athetosis. Even though the FMA score showed no big difference for CP2 and CP3 (FMA, CP2≈CP3, Table III), CP2 completed the training task better during the whole training (Fig. 7 (a)). Important to note is that CP2 and CP3 also have different types of motor dysfunctions. As CP2 has atonia, his main problem was muscle weakness. It was difficult for him to use a high force level to control the bird to get to the bottom step. CP3's main impairment was high muscle tone occurring suddenly or involuntary movements when maintaining a certain posture or movement. It was difficult for the patient to sustain the proper force level (F in three levels) to make the bird stay at the corresponding step. Meanwhile, CP patients' preferences for the three games are also related to their motor dysfunction. Bad performance resulted from motor deficit may decrease their motivation in game training, and low motivation may subsequently affect their game performance. So in rehabilitation game design, the severity and the type of motor dysfunctions as well as other factors that would distract or frustrate the patients should be considered.

### *C. Limitations and Future Work*

The accelerometer is sensitive to both gravity and its own acceleration. Therefore, it cannot measure the subject's rotation angle accurately if the hand trembles seriously. As a result, several subjects experienced imprecise control in the game of Catch the Mouse. Additionally, both 2D and 3D technologies have been used in rehabilitation systems in order to maximize cognitive curiosity and intrinsic interest in the instructional design. This work was based on 2D technologies so it had some limitations such as oversimplified game scenarios, lack of flow experience and diversity. The system is expected to be improved by upgrading to an immersive 3D video game platform, which can use VR or AR techniques to give participants real world experience in a simulated virtual environment.

Because the motor dysfunction of CP is very complicated, game-based rehabilitation method still require further in-depth study. This system provides only three games designed for a few hand functions, while there are still many other kinds of hand functions to be improved for CP patients. In future work, we will integrate more sensors, such as a gyroscope, or pressure and image sensor, to get more motion related information in order to design more immersive game applications to meet the needs of CP rehabilitation. We will recruit more subjects in the future, and have their clinical assessments before and after the training in order to quantify the improvement.

## V. Conclusion

This paper described the development of a real-time, interactive, EMG-ACC game-based training system and presented the results of system performance, game experience and the training effect. The real-time games designed based on a clinician's suggestion gave most of the CP patients a novel training experience. Our rehabilitation training system can provide visual and audio feedback to improve the subjects' interests in active training and was proven to be a feasible and usable tool for CP patients. The advantages and contributions of the proposed system mainly include the following four parts:

1) SEMG sensor and accelerometer are integrated together in a wireless and wearable game controller, which can overcome the difficulty of holding a game controller for interactive game training.

2) Three interactive rehabilitation training games for upper limb function recovery were developed. To guarantee the effectiveness of these training games for CP rehabilitation, the training tasks were designed under a clinician's guidance.

3) The real-time rehabilitation training system was developed on the Android platform which makes it easily accessible, and a potential fit for home rehabilitation.

4) Multiform feedback, which can greatly improve the users' initiative in rehabilitation training, was integrated into the

designed training games based on a Box 2D physical engine.

CP children with differing severity of motor dysfunction achieved improved game performance after a long-term intervention training using this system. We discussed how motor dysfunction influences a CP patients' game performance and gave some suggestions on the design of future rehabilitation games. We believe this prototype expanded the possibilities for home rehabilitation.

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