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A HOME-BASED NEUROREHABILITATION SYSTEM FOR CHILDREN WITH UPPER EXTREMITY IMPAIRMENTS

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Abstract: The objective of this paper is to introduce a novel low-cost human-computer interface (HCI) system for home-based massed practice for children with upper limb impairment due to brain injury. The proposed system targets motions around the wrist. Successful massed practice, a type of neurorehabilitation, may be of value for children with brain injury because it facilitates impaired limb use. Use of automated, home-based systems could provide a practical means for massed practice. However, the optimal strategy to deliver and monitor home-based massed practice is still unclear. We integrated a motion sensor, video games, and HCI software technologies to create a useful home-based massed practice at targeted joints. The system records joint angle and number of movements using a low-cost custom hand-held sensor. The sensor acts as an input device to play video games. We demonstrated the system's functionality and provided preliminary observations on usage by children with brain injury and typically developing children, including joint motions and muscle activation.

Keywords: massed practice, brain injury, home-based video game system.

Introduction

Patients with motor dysfunction due to musculoskeletal or nervous system injuries need structured repetitive motion practice to gain or regain muscle power or fine or gross motor control (Saposnik & Levin, 2011). Motivation and safe practice at home are key factors for increasing practice of prescribed motions (Wu, Wilcox, Donoghue, Crisco, & Kerman, 2012). Thus, what is needed are a system and a method to safely and reliably deliver massed practice at the home-setting which tailor the needs/capabilities of each individual to achieve the therapeutic benefits and record and track the performance changes.

Cerebral palsy (CP) is the most common pediatric developmental disability (Arneson et al., 2009) corresponding to a high estimated lifetime cost of $921,000 per case ("Economic costs associated with mental retardation, cerebral palsy, hearing loss, and vision impairment--United States, 2003," 2004). Hand function deficits seen in the children with hemiplegic cerebral palsy prevent children from achieving their full potential for healthy and productive lives and independence. Improved hand function can dramatically broaden lifelong opportunities necessary for normal social and motor skill development as well as employment.

Results from studies of constraint-induced movement therapy and robotic therapy demonstrate that massed practice (intensive training within a set period of time) can improve arm function (Charles, Wolf, Schneider, & Gordon, 2006; Lo et al., 2009). However these approaches are expensive and require intensive supervision. As a result these forms of increasing therapy cannot be made available to every child. Home-based therapy coupled with recent advances in electronic technologies could provide children with a low-cost way to carry out massed practice. Current forms of home-based therapy, such as conducting therapist-prescribed range-of-motion exercises and potentially playing video games with commercial controllers (Andrysek et al., 2012; Deutsch, Borbely, Filler, Huhn, & Guarrera-Bowlby, 2008; Hurkmans, van den Berg-Emons, & Stam, 2010; Lange, Flynn, Proffitt, Chang, & Rizzo, 2010) are used to extend therapy into the home setting. However, self-conducted exercise, such as range of motion exercise, has the disadvantage of compromised compliance due to a lack of motivation in patients (Jurkiewicz, Marzolini, & Oh, 2011). Moreover self-conducted exercise and current forms of video game-play for selective motor control neither take undesirable motions into consideration nor do they tightly constrain training movements. Hence current home-based therapies fail to meet the objective of highly-structured practice (repetitive training of specific joints along with real-time feedback) that is preferred for promoting recovery (Kerr, Cheng, & Jones, 2011; Levin, Kleim, & Wolf, 2009; Taub, Uswatte, & Pidikiti, 1999). However, a number of studies have demonstrated the efficacy of video game-based rehabilitation for a broad range of conditions, mostly for adult clients. For example, video game-based systems have been developed to provide motor rehabilitation to adults who have suffered strokes(Cameirao, Bermudez, Duarte Oller, & Verschure, 2009). Golomb et al used gloves equipped with angle detecting sensors to rehabilitate hand functions of three adolescents with hemiplegic cerebral palsy. They found improvements after 3 months of training (Golomb et al., 2010) lasted for 14 months reported in the case report(Golomb et al., 2011). Video-game based rehabilitation holds great promise as an effective means to extending therapy beyond the clinical setting. Currently, however, there is no system which can target specific wrist joint and monitor the patient's exercise in the home environment. To overcome these deficits we introduce a novel low-cost human-computer interface named the Neuroplasticity-targeted Exercise Trainer (NExT) that will provide highly-structured upper limb rehabilitation at home.

Neuroplasticity-targeted Exercise Trainer

System overview

The NExT system is designed to allow patients to repetitively perform therapeutic exercise of their hemiparetic wrist using video game-play. Figure 1 shows the prototype of the NExT, which consists of a personal computer, a custom hand-held controller, an armrest equipped with five sensors, and a friendly graphic user interface (GUI) that permits patients to play a wide range of video games (for example, free online arcade games or commercialized rehabilitative games("www.nanogames.com,").

Figure 1. NExT.

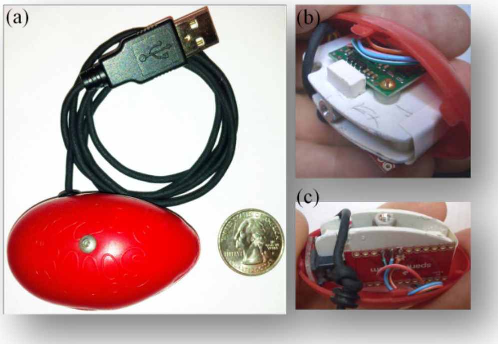
Easy to hold lightweight controller

The controller design had to conform to a number of requirements in order to be compatible with the patients' physical limitations. In another study, a modified wheelchair joystick was interfaced with a computer and other electronic device for wheelchair users (Casas et al., 2012), but such a configuration would not meet our needs, as it does not allow for wrist joint exercises performed in free space. The joystick is restricted in its degrees of freedom and must be used with a mounted based. And the mounted based is not aligned with the axis of wrist joint, this off-axis alignment can restrict wrist movement. A lightweight (<30g) and easy-to-grasp controller (Figure 2) is designed especially for children with brain injury who have insufficient grasp strength and are unable to use off-the-shelf game controllors. An egg-shaped controller provides a spherical surface for palmer grasping for children with weak grip strength. This egg-shaped controller detects prescribed joint motions. It consists of two parts: an inertial measurement unit (MinIMU-9, Pololu) and a microcontroller board (Pro Micro 5V/16MHz, Sparkfun). The 3-axis accelerometer (LSM303DLH) and 3-axis gyroscope (L3G4200D) onboard the MinIMU-9 are used to detect and measure rotations about each of the three axes of the controller. The Pro Micro, utilizing the

ATMega 32U4 microcontroller from Atmel, is used to interface with the IMU and relay the linear acceleration and angular velocity measurements to the computer via UART serial communication protocol over one of the computer's USB ports.

Custom Chair with Posture Control Armrest

Figure 2. The handheld controller and its internal components. (a) The controller as a whole. (b) The IMU. (c) The microcontroller board.



A modified chair is incorporated into the system (Figure 3). The chair has an attached assembly on its right side on which the posture control armrest is positioned. To adjust for variation in size among different patients, the assembly is constructed to permit repositioning of the armrest in all three dimensions. This ensures that the patient can rest their forearm naturally and comfortably.

Figure 3. Chair with armrest assembly.

An essential part of the chair is a digitally equipped armrest (Figure 4). It limits the patient from executing compensatory proximal joint movements while performing his/her exercises. Many patients with motor structure injury make posture changes while performing wrist motions. They have often been observed to rotate their shoulder or elbow instead of their wrist when operating controllers. Importantly the armrest discourages this compensatory movement, ensuring that the affected muscle groups are targeted by the therapy.

Figure 4. Digitally equipped armrest

The armrest is constructed out of a section of PVC pipe (measuring the length of a child's forearm) cut longwise to form a u-shaped platform (cylindania). The inner surface of the half-pipe is lined with a soft rubber sheet (2 mm thick) on which the patient can rest their hemiparetic forearm. Fixed underneath the rubber sheet are five digital pushbutton switches spread out linearly across the platform which become depressed when a patient's forearm is placed on top. With the patient's forearm rested on the armrest, the depressed state of the switches indicates that the patient is using their wrist rather than their proximal joints to operate the controller during game-play. The digital electrical states of the switches are serially communicated to the computer over a different USB port by a separate Pro Micro microcontroller board.

Graphical User Interface

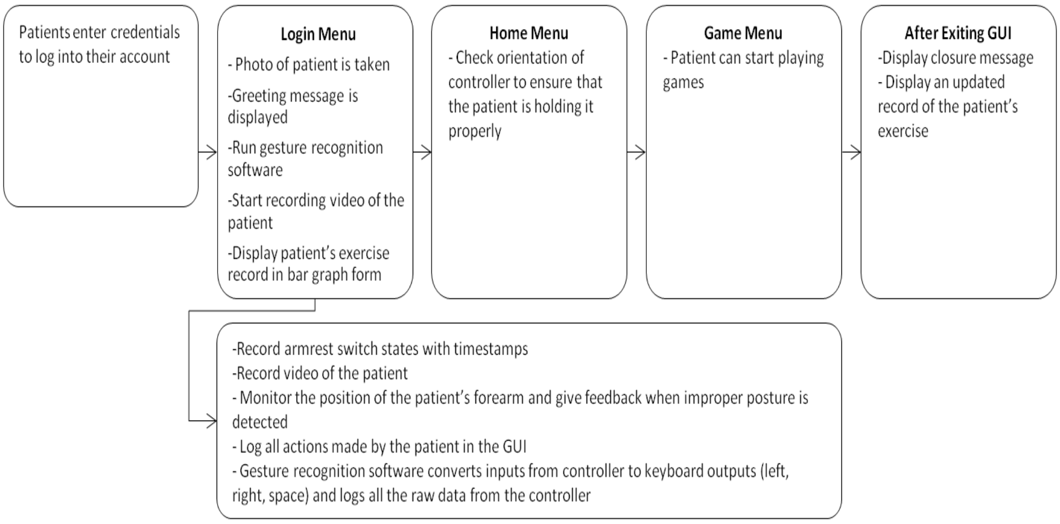
The core of the HCI is a java based program that serves as a graphical user interface (GUI). It guides patients through the exercise, provides them with interactive feedback and logs their usage. Through serial communication, the GUI reads the incoming data from the controller and passes that information to the gesture recognition application, the Wekinator, over Open Sound Control protocol. The Wekinator is an open source software package for gesture recognition which classifies the gestures using input features (the acceleration and angular velocity data from the controller generated by the patient's wrist motions) and patches them to any output parameters determined by the therapist (the control signals for game-play). The gesture classification is done by a machine learning process using K-Nearest Neighbor and Support Vector Machine algorithms. Training examples of controller orientations are submitted to the Wekinator to develop a wrist motion-control signal pairing model which will be loaded at the beginning of each exercise session. Table 1 is an example of the corresponding wrist motions (input features) to the control signals (output parameters) for game-play. For a more detailed explanation of the Wekinator, please see the reference.(Fiebrink, 2011; Morris & Bartlett, 2004)

Table 8. control signals v.s. wrist motion (Right Hand)

Control signal	Wrist motion
Move to the Right	Supination
Move to the Left	Pronation
Right + Action	Supination + Wrist Flexion
Left + Action	Pronation + Wrist Extension
Action	Radial Deviation

The GUI is organized into four menus – the login menu, home menu, games menu, and settings menu. Figure 5 illustrates the process of navigating through the GUI. The patient logs into his/her account using his/her credentials and is then presented with a greeting. Moving on to the home menu, the patient goes through a preparation process. When this is completed, the patient is allowed to start playing games. The settings menu is where the therapist can adjust various GUI settings for the patient. A more detailed explanation of the menus is discussed below.

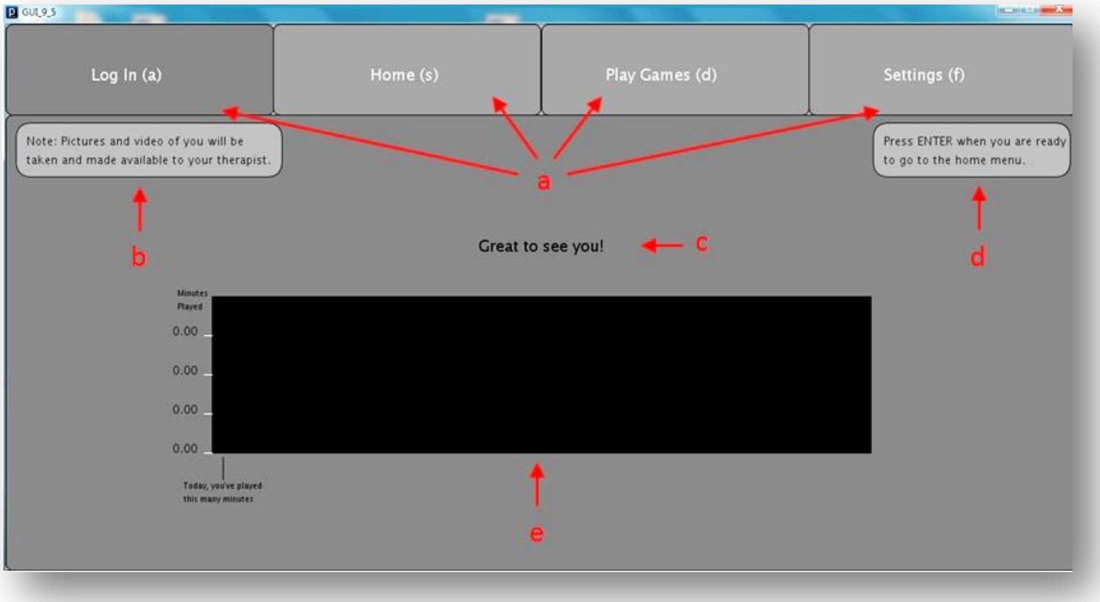
Figure 5. Flowchart illustrating how the GUI operates.



Login and informative greeting

Upon running the GUI, the patient is taken to the login menu (Figure 6) where they are prompted to enter a username and password in order to access their personal account. Once this is accomplished, the GUI takes a photo of the patient for identity verification. As the GUI collects important data related to the patient's exercise, it is important that we know if the patient's sibling(s) log(s) into the patient's account, which would otherwise compromise the legitimacy of the data. An audio greeting is then played depending on the date and time of the previous login, as shown in Figure 7.

Figure 6. Login menu as would appear the first time the patient logs into his/her account. (a) The four menus of the GUI depicted in tab-style. (b) A disclosure informing the patient that pictures and video of the patient will be taken during each exercise session. (c) The greeting message. (d) Tells the patient how to move onto the next menu. (e) A chart depicting how many minutes of game-play the patient has accomplished each day.

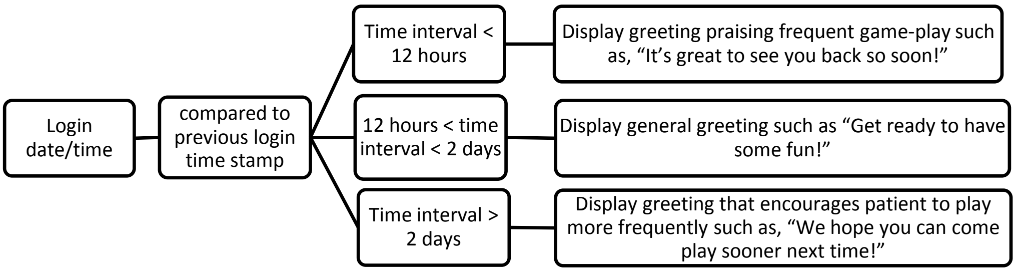


Note: Pictures and video of you will be taken and made available to your therapist.

Great to see you!

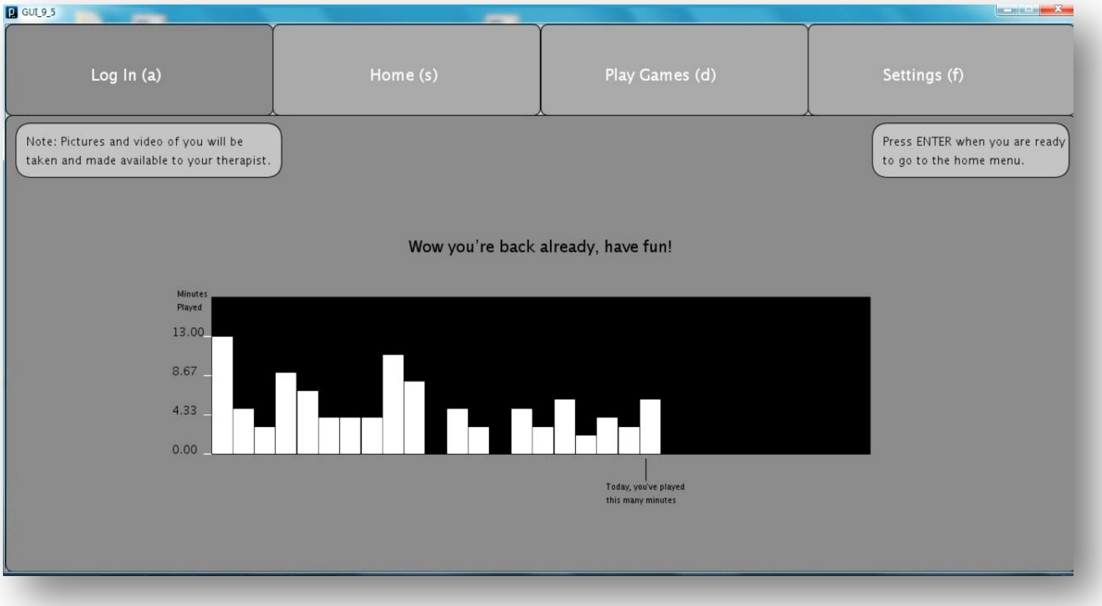
Press ENTER when you are ready to go to the home menu.

Figure 7. Flow chart illustrating the greeting message selection process.



If no longer than twelve hours has elapsed after the previous login, a congratulatory message is generated to praise the patient for their frequent exercise. If the time between logins is greater than two days, a message that encourages the patient to play more frequently is given. For in-between cases, a general greeting is given. The greetings are presented in this manner in order to promote frequent exercise. Furthermore, once logged in, the GUI runs the Wekinator and loads the appropriate wrist motion-control signal pairing model, thereby allowing the controller to emulate the left, right, and spacebar keys for game-play. In addition, the login menu displays a chart depicting the total number of minutes the patient has spent playing games each day. Figure 6 shows the play chart as it would appear the first time the patient logs into his/her account. If they were to play for 7 minutes during that exercise session, for example, upon exiting the GUI, the closure screen (which will be discussed later) would display an updated play chart as in Figure 8. Figure 9 shows what might the play chart look like after 21 days into the home-based therapy. By continually displaying their progress, the chart helps motivate the patients to perform their exercises more frequently and for longer periods of time. Lastly, for offline posture analysis, the GUI starts recording video of the patient at a resolution of 640x480 pixels, 30 frames per second.

Figure 8. Closure screen showing an updated play chart and a goodbye message.

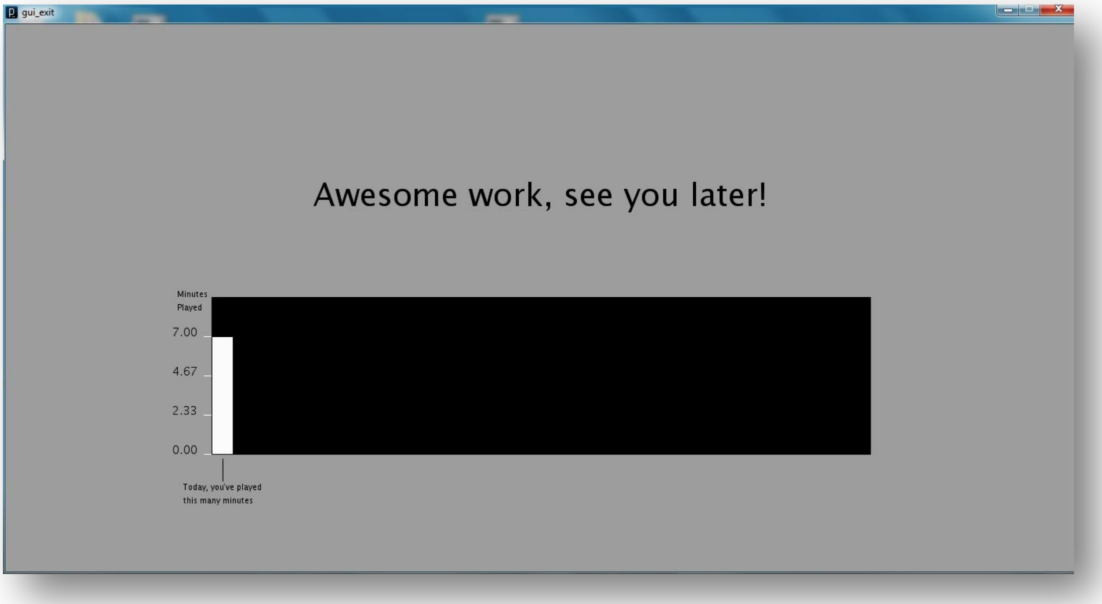


Note: Pictures and video of you will be taken and made available to your therapist.

Press ENTER when you are ready to go to the home menu.

Wow you're back already, have fun!

Figure 9. Login menu as it might appear 21 days into the home-based therapy

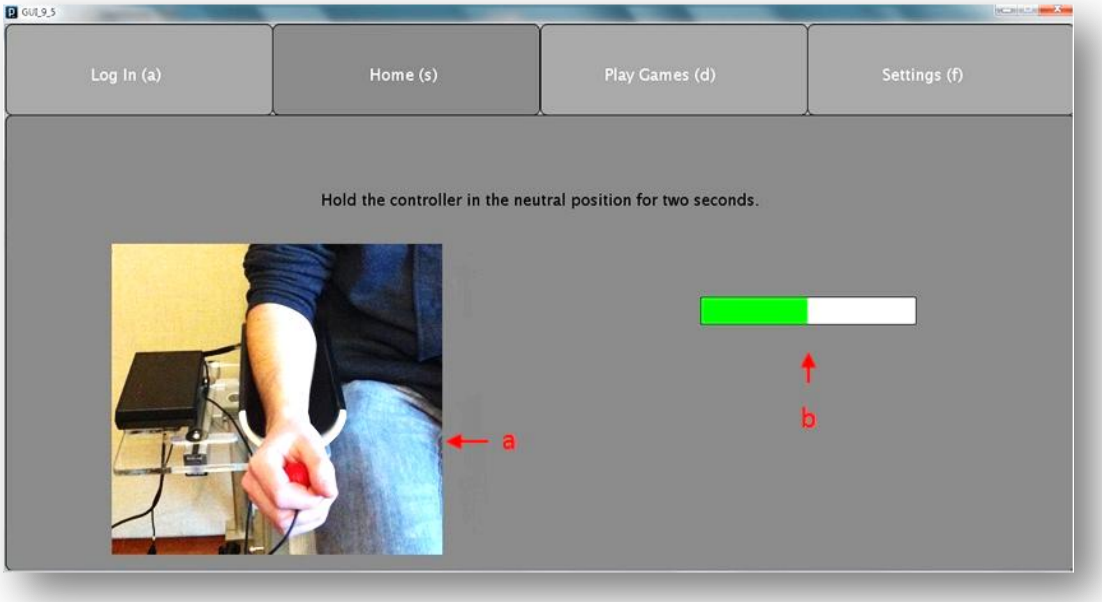


Awesome work, see you later!

Home menu

Once logged in, the patient is free to navigate to the home menu (Figure 10), in which they are shown an image of themselves holding the controller in the starting position (the starting position is the orientation that corresponds to no control signal). They are then told to hold the controller in the same manner as in the picture for a time period of two seconds. Due to the symmetrical shape of the controller, there exists the possibility of the patient holding the controller upside-down. Therefore, to ensure that this does not happen, the GUI reads the accelerations in the x, y, and z axes of the controller and compares these values to what they should be if the controller is held in the neutral orientation. If the two sets of acceleration values agree and the patient maintains this controller orientation for the required two second time period, they are automatically taken to the game menu. If not, a message is voiced informing the patient that they might be holding the controller upside-down.

Figure 10. Figure 10. Home menu. (a) Picture of patient holding the controller in the neutral orientation. (b) Progress bar showing how much longer the patient must maintain this controller orientation.

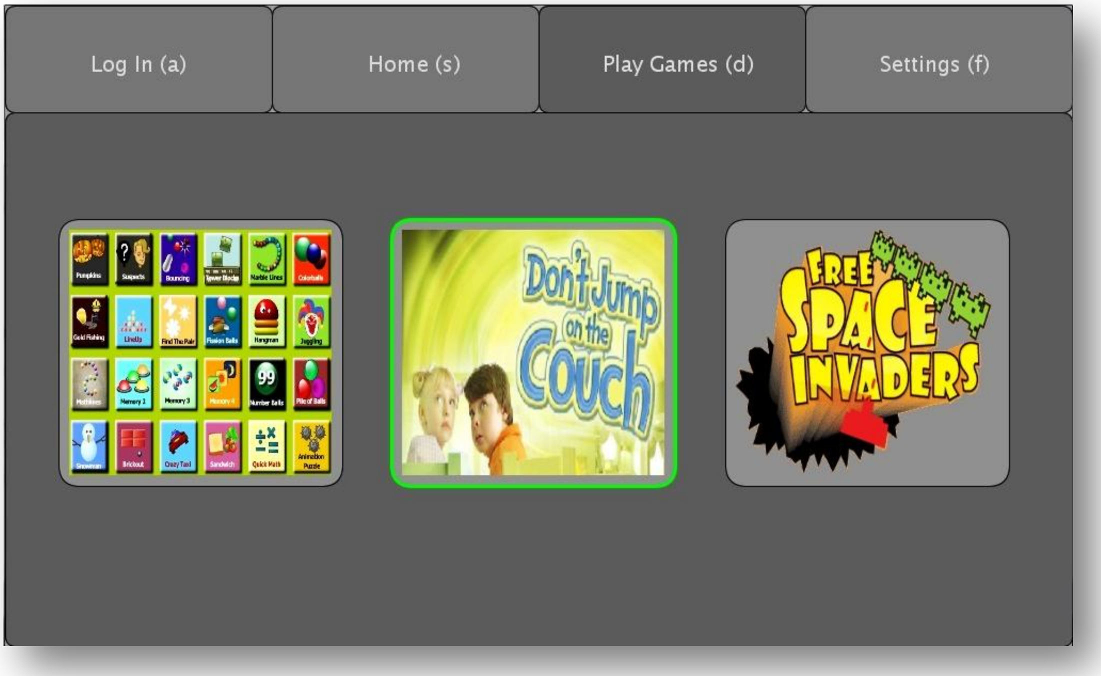


Hold the controller in the neutral position for two seconds.

Settings menu

The fourth menu of the GUI, the settings menu (Figure 12), is accessible only by the therapist. In this menu the therapist is able to modify various HCI related settings particular to the patient. One of the settings the therapist may modify is whether a Skype conversation between patient and therapist is automatically initiated upon patient login. During the early stages of the home-based therapy, the therapist may want to observe the patient's posture in realtime and the Skype video conference would make that possible. This menu also allows the therapist to configure various Wekinator settings, including the pairing model the GUI will load once the patient logs in. This is important as it allows the therapist to adjust the therapy as needed. For example, if the patient shows improvement in their wrist range of motion, the therapist may configure the Wekinator to require wider angles of wrist rotation from the patient in order to operate the controller.

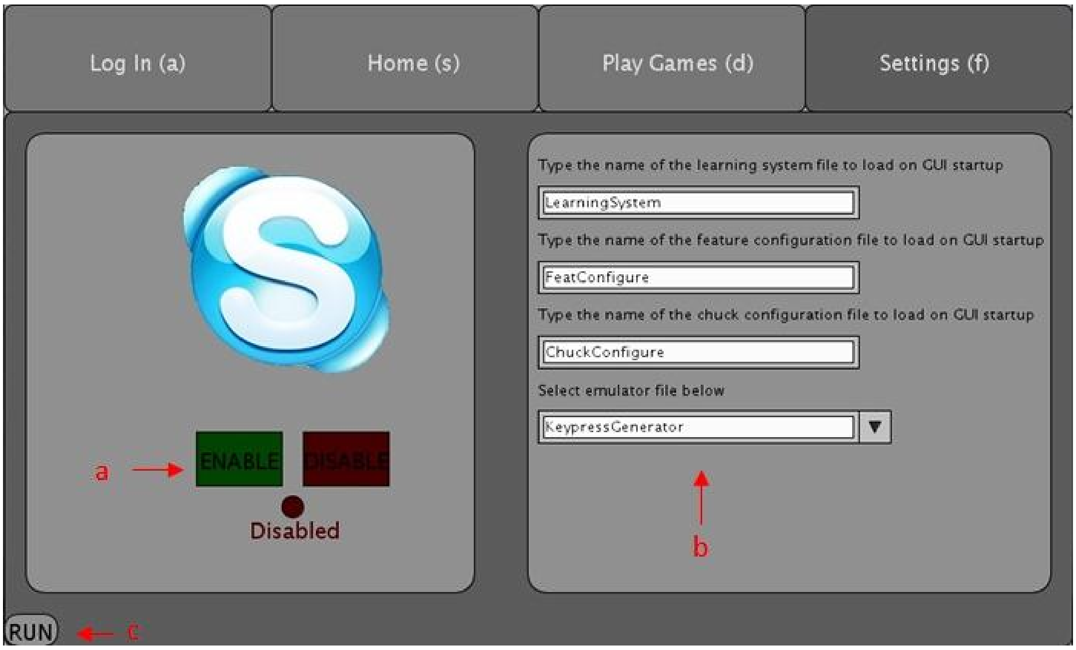
Figure 11. Game menu showing different game options.



Game menu

Once the controller check is completed, the patient is taken to the game menu (Figure 11) where they have access to a variety of puzzle and arcade games. They are free to play the games at their leisure. As the patient is playing, the GUI monitors the switches in the armrest to detect improper posture. If at least three of the five switches are released a voice message is played telling the patients to place their forearm back on the armrest. After the patient has finished playing, they simply exit the GUI. Upon exiting the GUI, a window is displayed containing a good-bye message and updated game-play chart depicting the patient's progress for the day (Figure 8).

Figure 12. Settings menu. (a) Allows the therapist to enable/disable Skype conversations. (b) Allows the therapist to modify the Wekinator pairing model. (c) The therapist can run the model to test it out.



Type the name of the learning system file to load on GUI startup

LearningSystem

Type the name of the feature configuration file to load on GUI startup

FeatConfigure

Type the name of the chuck configuration file to load on GUI startup

ChuckConfigure

Select emulator file below

KeypressGenerator ▼

Other functions for meeting the needs of research and science

In addition to the guidance that it provides to the patient, the application records important data for future analysis. One set of data recorded consists of the acceleration and angular velocity output from the controller, their corresponding control signal, followed by a timestamp. This data is recorded continuously throughout the game-play at a rate of 100 Hz. Concurrently, the digital states of the armrest switches are recorded with timestamps at a rate of 100 Hz. Furthermore, the number of minutes the patient spends playing during each exercise trial is recorded when the patient exits the GUI. Apart from the quantitative data, the application also takes and saves a photo of the patient through the computer's webcam upon login for patient identity verification and records video of the patient during game-play for posture analysis by the therapist.

Potential User Requirement

Although the system can be potentially adapted for other limbs and joints, the setup and functions described here specifically target motions involving the wrist. The system includes video games with varied complexities. However most games can be easily comprehended by most children from the age of 7 years old and older with comparable cognitive ability. This study is geared towards young patients who are in need of wrist or arm rehabilitation. The users must also be able to at least follow basic instructions such as "move your hand to the right".

User validation of the system

NExT was developed to promote massed practice in a controlled and reliable manner. To validate the system, we studied the practice patterns and collected user feedback from children with and without hand impairments.

To study practice patterns using NExT, we recorded muscle activity and joint motions while a subject was playing the video games. By doing so, we can understand whether a patient (1) plays games by the prescribed joint motions/muscles using our system and (2) repeats the prescribed motions as frequently as their typically developing peers do. We recorded activities of flexor carpi radialis (FCR) and extensor carpi ulnaris (ECR) by using electrodes of a commercial surface electromyography (EMG) system (Bagnoli Desktop EMG system, Delsys Inc., USA) with a gain of 1000. The EMG signals were sampled at 1000 Hz and sent to a laptop through an analog-to-digital converter (USB-6343, National Instruments Corp. Austin, TX). In addition, two motion sensors (MTw, Xsens, The Netherlands) were placed across the patients' wrists to capture kinetic data of wrist motions and this data was sent to a 2nd laptop running the Xsens commercial software. A trigger pulse was sent to the laptop on which the EMG was recorded in order to synchronize the two sets of data. The two sets of data were combined and visualized through a LabVIEW VI (National Instruments Corp. Austin, TX), and off-line data processing was conducted in Matlab (MathWorks Inc. Natick, MA).

We recruited seven children with hand impairments, who were diagnosed with hemiplegic cerebral palsy (three girls, four boys; mean age 10y 6mo, SD 1y 4mo) and five typically developing children (four girls, one boy; mean age 8y 9mo, SD 1y 4mo) to use the prototype of our developed system. The children with hand impairments were recruited from the Children's Rehabilitation Center of Hasbro Children's Hospital in Rhode Island, USA. The typically developing children were recruited from the siblings of patients and children of staff in the Pediatric Rehabilitation Center.

Inclusion criteria for the patient group include: (1) Manual Ability Classification System (MACS) levels I-II, ability to handle most kinds of objects independently using one or both hands with or without compromised performance quality, (2) able to actively participate and follow instructions. The exclusion criteria: (1) other neuromusculoskeletal problems, such as hand fracture or peripheral nerve injury, (2) wrist and forearm contracture. The typically developing children were free of any neurological and musculoskeletal impairment while participating in this validation study.

All the participants were asked to play six video games for a total duration of 18 minutes. After they played the video games using our system, we inquired the children two questions: (1) Do you like to play video games using our system? (2) Will you practice every day using our system if we put a device at your home? The children answered our question using a 7 point Likert scale. Seven indicates they like it very much or will practice every day and one indicates that they do not like the game at all or they will not use our system at all.

The signals from the controller generated by the participants were captured by our system. The signals were then classified as different joint motions, such as wrist motion, forearm supination, and forearm pronation (Figure 13.) over time.

Figure 13. The amount of movement made by the targeted joints (a) Typically developing child (b) child with CP

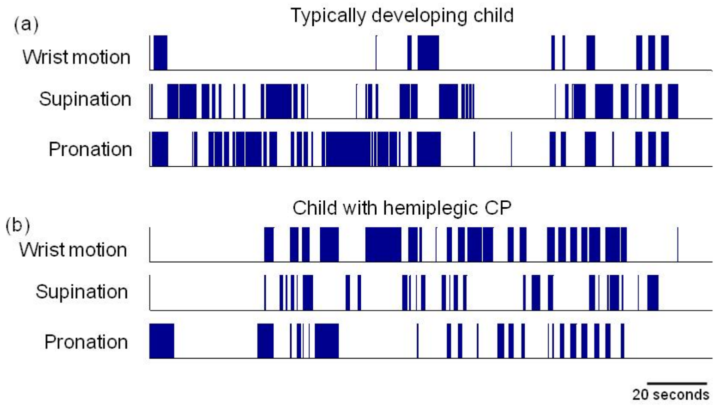
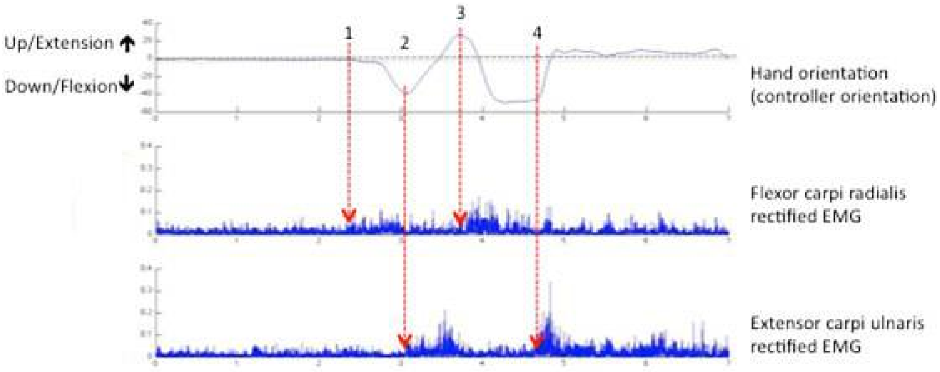


Figure 13 shows an example of the type of data obtained from joint motions measured over a period of 200 seconds of game-play. This example illustrates that a child with brain injury can use this system for repetitive wrist movements which is key to reliable massed practice, although there might be differences from normal usage patterns.

Figure 14 shows representative electromyographic activity and its corresponding joint motions during game-play. The recorded EMG signals were first fed to a notch filter to eliminate 60-Hz line noise and then to a band-pass (10-400 Hz) filter to remove the motion artifacts and high frequency noise. The filtered EMG data were processed in a linear envelope representation (ratification before low pass filtering at 20 Hz).

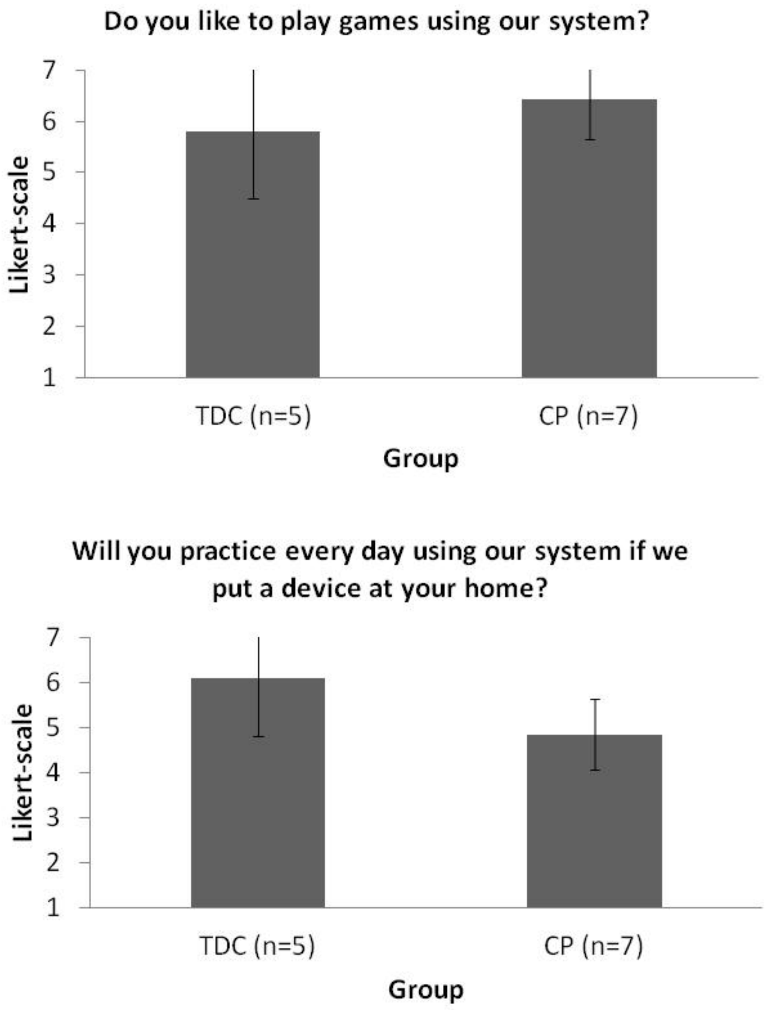
Figure 14. Muscle activation during video game-play: our training system could successfully elicit the target muscle activation during game-play.



We demonstrated that the system can elicit the desired motions by recording EMG during game-play. With initiation of flexion or extension (number 1, 2, 3 and 4 in the first trace of Figure 14), we detected clear corresponding EMG activation of FCR and ECU. This trial confirms the activation of desired joint motions.

The feedback from children with brain injury or typically developing children shows no difference. Both groups could accept our system as an adaptive way to play video games. Only one child with brain injury responded that he would not use it every day but 1-2 times per week, which lowers the Likert scale score in the study shown in Figure 15.

Figure 15. Children's response to our system and willing to practice at home.



Discussion and Conclusion

Our system addressed the needs of efficient neurorehabilitation while providing a complementary tool for upper extremity training in children with cerebral palsy. Our approach was intended to allow children with brain injury to receive rehabilitation therapy more frequently at convenient times and locations. A concern with a hand-held sensor to play games, such as Nintendo's Wii® Sport, is that the desired game motion could be accomplished by moving a combination of many other joints rather than the target joint, in our case, the wrist. Although commercial active video games (Nintendo's Wii® Sport and Wii® Fit) have been studied on balance, reaching or physical fitness with controversial results(Brichetto, Spallarossa, de Carvalho, & Battaglia, 2013; Deutsch et al., 2008; Graf, Pratt, Hester, & Short, 2009; Hurkmans et al., 2010; Ramstrand & Lygnegard, 2012), these approaches may not be ideal for motor training which targets specific joint motion. Microsoft Kinect™ has potential to increase motor training; however, Kinect™ currently cannot register wrist/forearm rotations with sufficient precision. We are incorporating simple switch methods with the capability of using an additional camera to ensure that the posture of other body parts is maintained and unwanted compensatory, maladaptive movements are limited. The system will help to ensure compliance with therapeutic regimens prescribed by clinicians, while promoting massed practice. In future studies, data collected in the home setting will be used to develop a scientific basis for therapy evaluation, including how the frequency and pattern of activation influence motor improvements. The overall goal of the NExT system is to enhance motor performance in children with brain injury while allowing scientists and clinicians to better understand optimal training and therapy approaches.

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