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Development of an MR safe reach and grasp movement evaluation system to study brain activation patterns after stroke

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Abstract—**An MR safe apparatus is important for the for monitoring of tasks in the magnetic resonance (MR) environment. This paper describes the development of an MR safe movement evaluation system to measure the hand grasp and elbow flexion/extension movements. The system will be used to monitor motor performance in the fMRI environment and assess functional and motor impairment level pre and post robot-assisted therapy.**

I. Introduction

The fast development of functional resonance imaging (fMRI) techniques makes it possible to study task related brain activations, such as activations associated with finger tracking [1] and hand gripping [2]. fMRI techniques can measure the blood oxygen level-dependent (BOLD) signal, which reflects changes in cerebral blood volume, cerebral blood flow, and oxygen consumption. Neural activities are closely interacted with these variables [3]. Studying neural activities after stroke is critical to the understanding of stroke recovery mechanisms and individualizing stroke rehabilitation methods such as robot-assisted therapy to each individual. There are several potential neural mechanisms thought to drive stroke recovery and cerebral plasticity. For example, the neural activities around the infarction might be changed [4], neural plasticity might increase in dendritic branching in the contralateral hemisphere [5]. etc. . With the ability to detect brain activities while performing motor tasks, an MR safe device that can monitor movements during the scanning serves as the bridge between tasks, movement performance, and the brain activities. Because of the strong magnetic field and limited space in the scanner, MR safe devices must be developed using MR safe materials as well as be small enough to fit into the scanner's orifice. Several MR safe systems have been developed in the past decades to measure movements in the scanner as well as to produce force and motion to interact with the individual's movement, such as a force/torque sensor [6], a 2-DOF haptic interface [7], and a pneumatic manipulandum [8].

This paper describes a hand glove with an elbow orthosis system designed to capture the elbow flexion/extension movement (defined as elbow reach) and finger flexion/extension (hand grasp) movement in the MR scanner. The system can evaluate the motor performance during tracking tasks completed inside the MR Scanner as well as to correlate the brain activation with the movement performance later on. Section II discusses the design, materials of the device, section III discusses the tasks analysis method, and section IV and V discusses- pilot data and future work.

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II. Methods

A. Designing for MR Safety

The MR environment is defined as the area of influence inside the 5 Gauss line [9]. The term MR safe indicates that a device is safe to use in the MR environment. Specifically, it means that the device will not bring injury to any person or to any other equipment, it will not be affected by the strong magnetic field, and it will not affect the MR image quality. In order to meet this criteria a device cannot contain any materials such as ferrous parts that might lose function in a strong magnetic field; high-impendence sensors that can induce the radio frequency (RF) pulse; dielectric or conductive materials that may attach to the RF probe and affect the property of the antenna or non-RF shielded cables that might introduce transducer noise from the control room. [9].

B. Devices (hardware)

Our main development criterion is to ensure that the upper extremity movement evaluation system with the hand glove and elbow orthosis (Fig. 1) is MR-safe.

1) Hand grasp glove: The hand glove [10] is made from a commercially available hand glove (Sammon Preston inc. IL) with a Velcro pieced added in to make the don on and don off more convenient. Thin and long sleeves are sewed on the index finger and thumb with slices every half inch from tip to

opisthenar. Four bend sensors (Flexpoint® inc. Utah) can be inserted into the slices to cover the index and thumb inter-phalangeal (PIP) and metacarpo-phalangeal (MCP) joints. The bend sensor consists of a polyimide substrate as a plastic film coated with a proprietary carbon/polymer based ink. The bend sensor is a potentiometer that can measure the bend angle from the resistance. Grasp aperture, β is defined as the distance from the tip of index finger to the tip of the thumb. It is calculated using in a two-link robot hand model (Fig. 2. upper figure). The lengths of the index and thumb phalanges, the distance between the MCP of the index finger and thumb, and the four joint angles measured by the sensors are used to define the position of index and thumb tip (Fig. 2, the middle figure). β is calculated from the distance between the tips (Fig. 2 the lower figure). A control circuit including an ATMAG8 microprocessor as the analog to digital converter and a RS232 to transfer signal to serial port of PC is used for the data acquisition (fig. 3 system configuration). A RF shield cable connects the sensors in the scanner room to the circuit placed in the control room through the control panel.

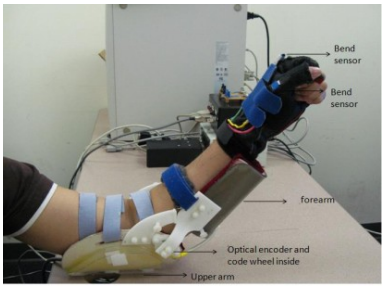
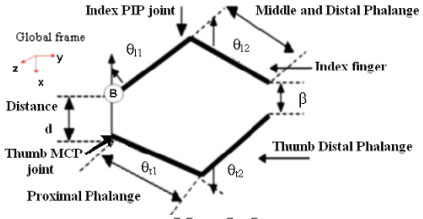


Fig. 1. The elbow orthosis with hand glove



$$\begin{bmatrix} x_{thumb} \\ y_{thumb} \\ z_{thumb} \end{bmatrix} = \begin{bmatrix} c(\theta_{t1}+\theta_{t2})l_{t2} + c(\theta_{t1})l_{t1} + d \\ s(\theta_{t1}+\theta_{t2})l_{t2} + s(\theta_{t1})l_{t1} \\ 1 \end{bmatrix} \begin{bmatrix} x_{index} \\ y_{index} \\ z_{index} \end{bmatrix} = \begin{bmatrix} c(\theta_{i1}+\theta_{i2}-90)l_{i2} + c(\theta_{i1}-90)l_{i1} \\ s(\theta_{i1}+\theta_{i2}-90)l_{i2} + s(\theta_{i1}-90)l_{i1} \\ 1 \end{bmatrix}$$

$$\beta = \sqrt{(x_{index} - x_{thumb})^2 + (y_{index} - y_{thumb})^2}$$

Fig. 2 Grasp aperture calculation. The upper figure is the hand modle: index finger and thumb with MCP, PIP joint and the tip of the finger. d is the distance between index finger and thumb MCP joint; . Li1 is the distance from index MCP to PIP, Li2 is the distance from index PIP to TIP, Lt1 is the distance from thumb MCP to PIP, Lt2 is the distance from thumb MCP to PIP. The middle matrix is the calculation of position of index and thumb finger derived from the hand mode; the lower equation is the calculation of the distance between the tip of index finger and thumb derived from the position of both fingers.

2) Elbow orthosis: The elbow orthosis consists of a forearm part (polycarbornate) and upper arm part (acrylic) with an optical encoder piece (nylon) mounted in the hinge of the two parts. A small reflective optical encoder (AVAGO technology, AEDR 8400 series) is mounted on a custom made PCB board, and placed in a nylon structure. A code wheel made of plastic film is attached to the cover of the encoder structure. Subject will wear the orthosis on their arm with some Velcro straps to keep their arm from slipping backward and forward, the hinge part will be right by the elbow joint. The encoder can sense the rotation movement of the elbow. The encoder reading will be transferred to the PCI-QUAD04 data acquisition board (measurement computing Inc.) installed in the target PC in the control room (Fig.3 system configuration). The orthosis configuration can limit the region of motion between 0-45 degrees. (Larger movement is not allowed in the scanner because of the space limit). Nylon screws with elastic band on are placed on the side and back of the orthosis to help stroke survivor perform flexion or extension movement if they have any disability with either kind of movements.

C. Task Design

Three kinds of tasks are designed with the system, hand grasp tasks, elbow reach tasks and reach to grasp tasks. A custom made MATLAB SIMULINK XPC™ target real-time operating system is built for the real-time task. The host PC and target PC are communicating through TCP/IP protocol; target PC connects to the glove control circuit via serial port; and the encoder connects to the PCI-QUAD04 data acquisition board installed in the target PC. The real time operating system collects and processes data and displays the real time movement and feedback on a screen that can be seen by the subject while they are lying down on the scanner board.

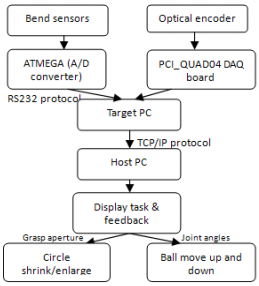


Fig. 3: System configuration

1) Grasp Task: Subjects will be asked to perform opened-close-open movement. For severely impaired subjects with no grasp function, an air-filled balloon will be placed in their hand to help their movement. A blue circle representing the current hand configuration with the radius linearly scaled to the grasp aperture is displayed on the screen. A black target ring with the radius linearly scaled the same way to 125% of their minimal grasp aperture is also shown. The goal for the subject is to close their hand to shrink the circle into the target ring. When the target is hit, it will turn green; when the target is overshoot, it will turn red, providing the accuracy feedback. Then the

subject will open their hand again to the original state for the next task.

2) Reach task Subjects will be asked to perform elbow flexion-to-extension movement. A black ball representing the subject's elbow will move vertically up to the target (another black ball) when subject performs the elbow flexion movements. The elbow angle is transferred to the distance the ball moved in real time. When the ball hits the target, the target will turn green otherwise it will turn red, providing the accuracy feedback. The subject is then asked to move their elbow back to the original state for the next task.

3) Reach to grasp task: Subjects will be asked to perform an elbow extension with an open hand to elbow flexion with a closed hand movement. A ball moving vertically up and a circle shrinking will be displayed at the same time. When the subject hits both the hand and elbow target, the target will turn green; while either the hand or elbow overshoots the target, it will turn red, otherwise, it will keep black. The subject will go back to their original state again once the target is hit. Fig. 4 shows the four states of reach to grasp tracking task. Each task is designed to be finished within 4 seconds; and subjects are encouraged to perform the tasks with a comfortable speed within the time limit. A block of tasks will include 75 task trials and 85 blank trials. The order of the tasks or trials is randomly assigned but designed for the event-related fMRI tasks brain image analysis. Each task will be 4 seconds but the intervals between two real tasks might be 4s, 8s, 12s, etc. All tasks will be performed while subjects lay on the scanner board of the fMRI system with their paretic hand wearing the device and performing tasks. Head movements will be minimized. Subjects will be monitored during the whole scanning session to record any mirror movements.

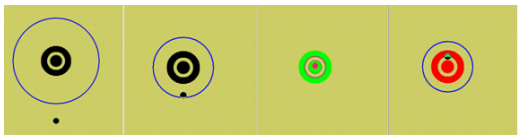
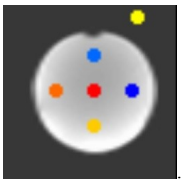


Fig. 4. Four states of the reach to grasp movement. From left to right: first: the task starts; second: subject bend elbow with closing the hand; third: target hit; fourth, target overshoot by elbow movement (this might not happen due to movement);.MR compatibility result and discussion

A. MR compatibility

To determine whether the device is MR-safe, we measured from two perspectives: firstly, the device and motion does not affect the quality of the fMRI data collected from the scanner by defining ROIs and measuring the signal-to-noise ratio (SNR), secondly, the echo planer imaging does not affect the device operation by comparing the device reading from inside and outside of the scanning environment. We used a modified testing procedure developed by Suminiski et al [8]. We tested the MR safety by scanning a phantom (3.0T General Electric (GE) spherical head phantom) placed inside a split transmit/receive quadrature head coil. We selected a gradient echo planar pulse sequence with parameters as follows: 38 continuous axial slices, TE=25ms TR=2s, flip angle = 77˚, FOV=24cm, 64*64 matrix and 3.75*3.75*4 mm spatial resolution We followed the procedure below: scan phantom in the coil only without any devices; placed the glove or the orthosis at 35cm or 50cm from the center of the coil separately; placed both the glove and the orthosis at 35cm or 50cm from the center of the coil; and perform grasp movement with the glove at 50cm from the center of the coil; performed the reach movement with the orthosis at 50cm from the center of the coil; and performed reach to grasp movement with both glove and orthosis at 50cm from the center of the coil. . We collected one run of fMRI data (approximately 2 minutes) for each configuration.

Then we identified 7 Region of interests (ROI) within the phantom and 1 ROI outside of the phantom as the baseline (Fig. 5) Each ROI is approximately 4.5mL in volume. We averaged each voxel's time series winthin each ROIs and calculate the mean/standard deviation as the SNR.



Fig, 5. The ROIs defined within and outside of the phantom. Another ROI is not displayed in the image because it is in the superior part of the phantom.

For the motion/non-motion status, 3 difference distance (35cm/50cm/infinite and we define phantom alone as the device is at infinite place) and 4 device conditions (no device, glove alone, orthosis alone and glove with orthosis together), Separate one-way ANOVA statistical analysis were performed to determine if there are significant difference between each device; distance and the motion and non-motion status (sample size is 70, normally distributed). The results showed that there are no significant difference between the motion and non-motion status (between group mean square 240:99; within group mean square 280.580; F = 0.859 and p value = 0.357,); No significant difference were found between distances (between group mean square 23.278; within group mean square 287.670; F = 0.081 and p value = 0.922). Also, there is no significant difference between different devices (between group mean square 25.231; within group mean square 297.581; F = 0.087 and p value = 0.967).

B. Device compatibility:

We test the glove and the orthosis both inside and outside the scanner and with motion and non-motion status. For the glove sensors, ~~one~~ one-way ANOVA was performed (sample size 25 for each sensor, normally distributed). We consider the sensor data collected outside of the scanner as the distance of infinite. For the non-motion status, no significant difference was found between distances (infinity, 35cm from the center of coil; 50cm from the center of the coil) (p =0.975, 0.991, 0.998, 0.999; F =

0.025, 0.009, 0.002, 0.001). No significant difference was found between devices present (glove outside the scanner, only the glove in the scanner and both glove and orthosis in the scanner, p =0.981, 0.994, 0.998, 1; F=0.02, 0.006, 0.002, 1). For the non-motion status of elbow orthosis, after we apply a low pass RC filter to each channel of the encoder (cutoff frequency: 1592HZ), the angle reading for each condition is 0 degree.

For the motion status, we asked a person to wear the device and perform the grasp and reach-to-grasp movement. Because of the potential difference between people's movement, we are not able to perform the ANOVA test. But we could compare the result from inside and outside of the scanner by looking at the following figure. Fig. 6 is the example of the grasp aperture for ten grasp movements both inside and outside the scanner. Fig. 7 is the example of the joint angles for ten reach movements. The data have been filtered with a Butterworth low pass filter (cut off frequency 10Hz).

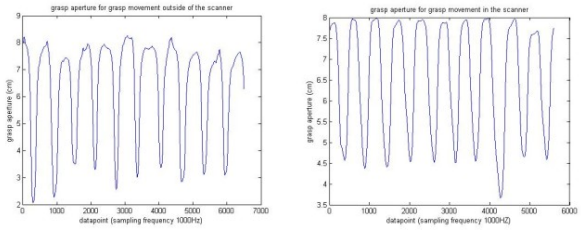


Fig. 6 Grasp aperture for 10 grasp movement outside the scanner (left figure) and inside the scanner (right figure). X axis is the time point with sampling frequency of 1000Hz; Y axis is the grasp aperture (cm)

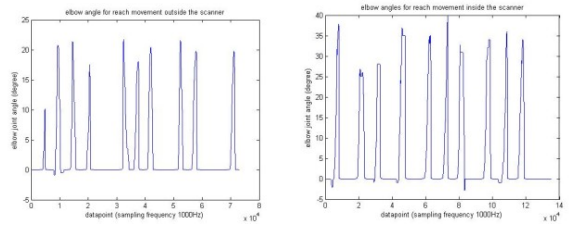


Fig. 7. Joint angle for 10 elbow movement outside (left figure) and inside the scanner (right figure). X axis is the time point with sampling frequency of 1000Hz; Y axis is the joint angles.

Preliminary data suggested that the able-body elder adult was able to perform the tasks with minimum head movements in the scanner. However, due to the high frequency noise, there are larger variation of the displayed grasp tasks then in the scanner due to the variation of sensor reading. Power spectral analysis showed that the noise can be filtered out by a low pass filter. Butterworth low pass filtered will be preformed to the sensor data prior to the task display. Our next step is to test the device on the stroke subject. We will measure the clinical functional level of stroke survivors using standard clinical assessment tools such as the upper-extremity Fugl-Meyer assessment, the Rancho Los Amigos Functional Test [12]. We will then correlate the functional levels with their motor performance measure by our system as well as the brain activation acquire from fMRI images.

III. Conclusions

The system described in the paper is MR safe. The system has been tested at a GE Signa Excite 3.0 Tesla short bore functional magnetic resonance imaging system) for the compatibility test and for 2 age-matched controls and 1 stroke survivors.. Preliminary data suggest that able-bodied older adults were able to perform the tasks with minimum head movements in the scanner ~~[rx1]~~. Additional modification of the system is needed. The next steps are to adjust the task and complete testing with stroke subjects. Ultimately, we will evaluate brain changes (activation patterns and connectivity) after a 4-week upper extremity robot assisted stroke therapy using Activities of daily living exercise robot [13].

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